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Circular Economy Design and Management in the Built Environment

A Critical Review of the State of the Art

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Preface

This book offers a comprehensive exploration of Circular Economy Design and Management within the Built Environment, presenting a critical review of the current state of the art. It thoroughly examines multi-level approaches, ranging from material usage to urban planning, and explores strategies for circular building design, criteria, and indicators for circularity. Additionally, it investigates practical tools and frameworks, as well as the roles and relationships of stakeholders across the entire value chain. Through insightful case studies and critical analysis, readers gain a deep understanding of circularity principles and applications, circularity management models, feedback systems, sustainable practices, and the integration of circularity into technological advancements and digital tools such as BIM.

The importance of this book lies in its response to the pressing challenges faced by contemporary architecture and construction, providing a roadmap for sustainable, circular solutions. It addresses the critical need to transition from linear to circular practices, emphasising resource efficiency, waste reduction, and the longevity of structures.

By offering practical insights and highlighting successful implementations, this book aims to guide architects, civil engineers, designers, sustainability professionals, and policymakers towards informed decision-making in creating environmentally conscious built environments. Designed for these professionals and researchers, it serves as a valuable resource for anyone passionate about reshaping the future of our built spaces with a focus on circularity and environmental responsibility.

The book presents a systematic and cohesive methodology for addressing various facets of Circular Economy design and management within the context of buildings and the built environment, a unique approach not found in existing literature. It begins by exploring general concepts, principles, and strategies of the Circular Economy as they apply to buildings and the built environment. This is achieved through a bottom-up approach, progressing from materials to building components, and eventually to the urban scale.

A dedicated focus is then directed towards individual building scales, emphasising conceptual frameworks and innovative design solutions across different life-cycle stages. The book subsequently addresses essential indicators and criteria for circularity, covering material, component, and system considerations at the scale of individual buildings. It also explores how these criteria can be integrated into tools and frameworks for implementing and monitoring Circular Economy practices in buildings, and how they align with international sustainability schemes.

Furthermore, the book examines the intersection of Circular Economy principles with Industry 4.0 technological advancements. This includes showcasing the automation of diverse strategies and the use of digital tools to enhance circularity in design, monitoring, and value chain management. The relationships among stakeholders involved in circular value chains are also explored, with an emphasis on their roles and responsibilities within feedback systems.

Each chapter of the book is substantiated with illustrative case studies, examples of best practices, and presentations of ongoing efforts. Notably, some of the topics addressed are only partially covered in competing titles, lacking the systematic methodology presented here.

The development of this methodology owes its success to the extensive network of the CircularB COST Action, which convenes researchers from 40 European countries. Their collaborative efforts, expertise, and diverse perspectives were instrumental in shaping this methodology. The meticulous monitoring and guidance ensured the coherence and interconnectedness of information flow throughout the book, making it a valuable contribution to the field.

August 2024

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Contents

Part I
Multi-level Approach from Urban to Buildings to Materials

Viorel Ungureanu and Katerina Tsikaloudaki

In an era that faces the challenges of climate change, environmental degradation and resource scarcity, the built environment stands out as a significant contributor to global energy consumption, greenhouse gas emissions, natural resources' depletion, and waste generation. It is nowadays acknowledged that the conventional linear model of "take-make-use-dispose" used in the construction industry has been considerably attributed to these trends. Within this framework, the circular economy emerges as a paradigm shift towards a more regenerative system, demonstrating its main objectives to minimize waste and maximize the value of resources.

The circular economy in the built environment involves implementing strategies at various levels: urban, building, and materials. Each level contributes to reducing waste, conserving resources, and promoting sustainability.

At the urban level, circular economy strategies focus on planning and designing cities that minimize waste and optimize resource use. Urban planning and zoning encourage mixed-use developments, reducing the need for transportation and promoting efficient land use. Zoning regulations support adaptive reuse of buildings and brownfield redevelopment. Cities establish robust systems for waste collection, sorting, and recycling, and are equipped with facilities for processing construction and demolition waste. Circular urban metabolism designs cities to function like ecosystems, where waste from one process becomes input for another, such as using organic waste for urban agriculture. Shared and multi-use spaces promote the use

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of shared spaces and infrastructure, such as co-working spaces and public amenities, maximizing the utility of built environments and reducing the need for new construction.

At the building level, circular economy principles are integrated into the design, construction, and operation of buildings. Design for disassembly ensures buildings can be easily deconstructed at the end of their life cycle, allowing materials to be salvaged and reused. Modular and prefabricated construction techniques create buildings that can be easily assembled, disassembled, and reconfigured. Implementing energy-efficient designs and systems, and integrating renewable energy sources like solar panels, reduces the building's carbon footprint. Adaptive reuse repurposes existing buildings for new functions rather than demolishing them, preserving the embodied energy and materials of the original structure.

At the materials level, circular economy strategies focus on the recovery, reuse, and recycling of building materials. Material recovery involves implementing practices for the selective demolition of buildings to recover materials that can be reused or recycled, including careful deconstruction and inventory of materials. Using recycled and biodegradable materials reduces waste and the need for virgin materials. Material passports create digital records of materials used in buildings, including their properties and origins, to facilitate their future reuse and recycling. Developing and using innovative materials with a lower environmental impact, such as low-carbon concrete, recycled steel, and sustainable insulation materials, further supports circular economy goals.

By addressing circular economy principles at the urban, building, and materials levels, we can create sustainable, resilient, and resource-efficient built environments. This multi-level approach ensures that every stage of the lifecycle of buildings and materials contributes to reducing waste and conserving resources.

In this chapter, the basic background concerning the theory and the background of implementing the principles of circular economy in the context of the built environment is presented. This entails every aspect of design, construction, management, and end of life of structures, and expands from the basis of materials and building elements, to the whole structure and the urban environment level. The main objectives, strategies and means are discussed in order to set forth the essential theoretical background. Analysis on the materials, components, energy systems and building services follows, accompanied by a detailed presentation of circular manufacturing. Special attention is given to the recovery and reuse of materials and products from existing structures, which is among the core scopes of the circular economy concepts.

Chapter 1
Circular Economy Best Practices in the Built Environment

Genesis Camila Cervantes Puma, Adriana Salles, Janez Turk, Vlatka Rajčić, Almudena Muñoz Puche, Kinga Korniejenko, Themistoklis Tsalkatidis, Vanessa Tavares, Rocio Pineda Martos, Tatiana Ruchinskaya, and Luís Bragança

Abstract This document serves as the opening chapter of a book that addresses the critical issue of resource depletion in the built environment, illustrating the unsustainable trends in current construction and demolition practices that extensively rely on new raw materials. It highlights the significant impact of the building sector on

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global resource consumption, energy utilization, and waste generation, with alarming statistics such as buildings accounting for 40% of the world's extracted materials and a significant source of waste and greenhouse gas emissions. Advocating for a transformative shift towards a circular economy in the built environment, the text emphasizes sustainable and regenerative economic practices that minimize waste and maximize resource efficiency. This approach necessitates the redesign of systems to ensure the durability, reparability, and recyclability of construction materials, thereby promoting a model where waste is systematically eliminated and materials are continually repurposed. The document also discusses the 10R strategy, which centres on minimizing waste and enhancing resource efficiency, and explores various circular practices within the construction sector. It includes examples from case studies and best practices to demonstrate the viability and advantages of adopting circular economy principles. The challenges and success factors in implementing such practices are thoroughly examined, emphasizing the urgent need for increased awareness, supportive policies, and robust stakeholder collaboration to foster a more sustainable and resource-efficient built environment. The first chapter sets the stage for a detailed exploration of these themes throughout the book's subsequent sections.

Keywords Circular economy · Built environment · Sustainable construction · Resource efficiency

1.1 Introduction

Our current society, driven by a culture of disposability, is depleting the Earth's valuable and limited resources at an alarming pace [1]. The built environment is a prime example of this phenomenon, where buildings are frequently stripped down and demolished, only to be replaced by new structures constructed from new raw materials. Unfortunately, little to no regard is given to the significant environmental and social consequences associated with the extraction and processing of construction materials. Equally concerning is the lack of consideration for the eventual fate of our buildings [2].

The built environment is a major contributor to resource consumption, accounting approximately 40% of the world's extracted materials [3]. Buildings and construction account for the consumption of approximately 40% of the natural resources worldwide, 70% of electrical power and 12% of potable water. Moreover, buildings and construction were responsible for consuming 35% of final energy and generating 38% of emissions in 2019. Buildings might have a crucial role in achieving carbon neutrality, circularity, and sustainability of the built environment through the renovation of building stock. For example, 75% of building stock existing in European Union is non-energy efficient and is not in compliance with the current legislation as 90% of building stock was built before 1990 [3].

The demolition and constructions activities associated with it generate the largest waste stream in many countries. For instance, in the European Union (EU27), construction and demolition activities generated 37.5% of the waste produced in all economic activities in 2020, that together with the activities of mining and quarry (mostly intended for the construction industry) totalised 60.9% of waste produced. The extraction of raw materials necessary for construction is becoming increasingly challenging, leading to heightened environmental strain as delicate ecosystems are exploited. In the near future, it is expected that extraction and use of raw materials will be exacerbated considering the actual consumption of these raw materials for construction and urban areas (urban areas currently consumes 75% of existing natural resources and generates 50% of solid waste and 60% of greenhouse emissions on a global scale) and the projected increase of population living in urban areas (68.4% of the projected 9.7 billion inhabitants in 2050).

Additionally, geopolitical factors contribute to price volatility and disruptions in the supply of essential raw materials. Adding to the complexity, the demand for resources is projected to escalate as the global middle class is expected to double in size by 2030. For instance, global steel demand alone is forecasted to surge by 50% by 2025 [4]. These trends highlight the urgent need for sustainable approaches in the built environment to address resource scarcity and minimise environmental impact.

Unfortunately, building design frequently prioritises the immediate needs of current users without considering the future implications. A building is often composed of intricate components, incorporating a wide array of materials and polymers that are intricately fused together. This complex composition poses a significant challenge for future retrieval or separation of these materials [5].

A more forward-looking approach that considers long-term sustainability and resource availability is essential to ensure that valuable resources are effectively conserved and available for the benefit of future communities [5]. To this end, under the different headings, an overview of the basic concepts of circular economy in the built environment is presented, such as circular materials, design, modularity, reuse of existing building etc. The report will then continue with different examples of case studies and best practices for each of these concepts and, finally, a few lessons will be derived, key challenges and success factors from the implementation of the circular economy in the built environment.

1.2 Circular Economy

The circular economy is a ground-breaking economic model that seeks to transform the traditional linear model of “take, make, dispose” into a more sustainable and regenerative system. It emphasises the principles of elimination of waste and pollution, optimization of material use, and regeneration of natural systems to promote the creation of a circular flow of goods in the economy. This involves designing products to be durable, repairable, and recyclable, thus extending their life, see Fig. 1.1.

At the heart of the circular economy lies the idea of valuing products and materials as resources that merit preservation and creating strategies that promote the reuse and regeneration of these resources. This approach can help reduce the depletion of

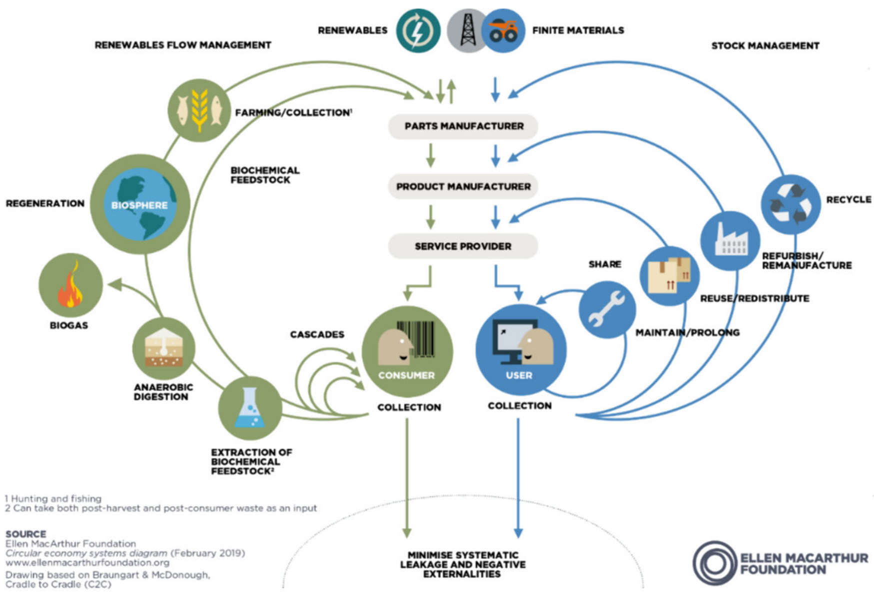

Fig. 1.1 The butterfly diagram: visualising the circular economy [6]

natural resources and minimise the environmental impact of waste generation and disposal, leading to a more sustainable model of economic development [7].

Moreover, the circular economy recognises the need to achieve sustainable development through a triple-bottom-line approach to economic performance, i.e., taking into consideration environmental, social, and economic factors simultaneously. This approach recognises the interconnectedness of these three factors and emphasises the importance of ecological stewardship, social development, and economic growth in achieving sustainable development [8].

The circular economy can have several benefits for businesses and societies that adopt its principles. First, it can lead to increased resource efficiency, reduced waste generation, and the development of innovative business models that promote economic growth. Second, it can contribute to the preservation of ecosystems and the mitigation of climate change, making it a desirable approach for professionals seeking to promote sustainability and resource efficiency in business practices. Third, circular business models can create opportunities for job creation and contribute to social development, particularly in underserved communities that have been disproportionately affected by a non-circular economy [8].

Europe has emerged as a global leader in promoting and implementing the circular economy concept. The EU has adopted several policies and initiatives aimed at supporting its implementation, including the Circular Economy Action Plan [9] and the Circular Economy Package [9], which promote sustainable consumption, production patterns, and waste reduction. EU member states have implemented waste management and recycling targets to minimise landfilling and increase material recovery, and Extended Producer Responsibility schemes hold manufacturers accountable for the end-of-life management of their products, promoting product design for durability, reparability, and recyclability [10].

In conclusion, the circular economy represents a fundamental shift towards sustainability and regenerative economic systems that align with social and environmental goals. By prioritizing the reduction of waste and pollution, optimizing material use, and regenerating natural systems, this model presents an alternative to the traditional linear model, leading to a more sustainable and regenerative system. It promotes an economic growth that considers environmental, social, and economic factors simultaneously, recognizing their interconnection [8]. The circular economy has several benefits for businesses and societies, including job creation and social development, promoting sustainability and resource efficiency in business practices, and ecosystem preservation and climate change mitigation. Europe has emerged as a leader in promoting and implementing this concept, with policies and initiatives aimed at supporting its implementation [11]. The circular economy represents a fundamental shift towards sustainability, which offers a promising future for a more sustainable and inclusive economy.

Principles

The principles of the circular economy are centred around designing out waste by creating a system in which there is no waste. To achieve this goal, products are designed to last, using high-quality materials, and optimised for a cycle of disassembly and reuse that facilitates their transformation and renewal.

The circular economy distinguishes between technical and biological cycles, with consumption only occurring in the biological cycles. Biologically based materials such as food, linen, or cork are designed to feed back into the system through anaerobic digestion and composting to regenerate living systems such as soil and oceans, providing renewable resources for the economy. In contrast, technical cycles focus on recovering and restoring products, components, and materials through strategies such as reuse, repair, remanufacturing, or recycling [12].

The goal of the circular economy is to optimise resource yields by always achieving the highest possible utility of products, components, and materials in use in both technical and biological cycles [13]. This means that products are designed to be used for as long as possible before being disassembled and reused or recycled. By doing so, the circular economy aims to reduce waste and minimise the use of virgin materials.

The final principle of the circular economy seeks to use renewable energies to fuel the system, reducing dependence on finite resources and increasing systems' resilience. This principle emphasises the need to design out negative externalities and develop effective systems that promote sustainability [11]. In review, the circular economy is a production and consumption model that prioritises minimizing waste, reducing resource consumption, and promoting sustainable use of natural resources. It aims to create a sustainable economic system that can support the needs of both current and future generations while minimizing its environmental impact [13].

By adopting design principles that focus on reducing waste and pollution, extending the life of products and materials, regenerating natural systems, optimizing resource yields, using renewable energies, reducing dependence on finite resources, increasing systems' resilience, designing out negative externalities, and developing effective systems that promote sustainability, it can create a sustainable economic system that meets the needs of current and future generations [11].

10R Strategy

The 10R strategy is a pivotal element of the circular economy, providing several sustainability advantages (see Fig. 1.2). This approach involves designing out waste by implementing a waste-free system which concentrates on high-quality products and materials that are optimised for disassembly and utilization [14]. The technique differentiates between technical and biological cycles, with consumption only taking place in the biological cycle [15]. Biologically based items are designed to regenerate living systems such as soil and oceans by feeding back into the system through anaerobic digestion and composting. In contrast, components and materials are recovered and restored through strategies like reuse, repair, remanufacturing, or recycling in the technical cycles [14].

The goal is to optimise resource yields by obtaining the highest possible utility of products, components, and materials in both technical and biological cycles [16]. Products are designed to be of highest use for a long time before being disassembled and reused or recycled, minimizing waste, and decreasing the reliance on virgin materials [14]. As a result, businesses can achieve triple bottom line sustainability benefits that include economic, social, and environmental advantages [16].

By following the 10R strategy, businesses can reduce their environmental impact, create new opportunities for growth and cost savings, promote the circular economy, and drive innovation [14]. By adopting a sustainable future, businesses can play their role in lessening reliance on virgin materials and resources, contributing positively towards a sustainable future.

The 10R strategy offers numerous sustainability benefits, including reducing waste and improving efficiency throughout the product life cycle, promoting the circular economy, and driving innovation [15]. By adopting the 10R strategy, businesses can reduce their environmental impact and boost their bottom line by creating new opportunities for growth and cost savings.

For example, by reducing the number of materials used in manufacturing and packaging, businesses can save on costs associated with raw materials, transportation, and disposal. Furthermore, by adopting a circular economy approach, businesses can reduce their reliance on virgin materials and resources, which can help to conserve natural resources, reduce greenhouse gas emissions, and mitigate climate change [15].

Overall, adopting the 10R strategy can help businesses to achieve triple bottom line sustainability benefits, which include economic, social, and environmental benefits. By reducing waste and improving efficiency throughout the product life cycle, businesses can reduce their environmental impact while also creating new opportunities for growth and cost savings [16]. By promoting the circular economy and

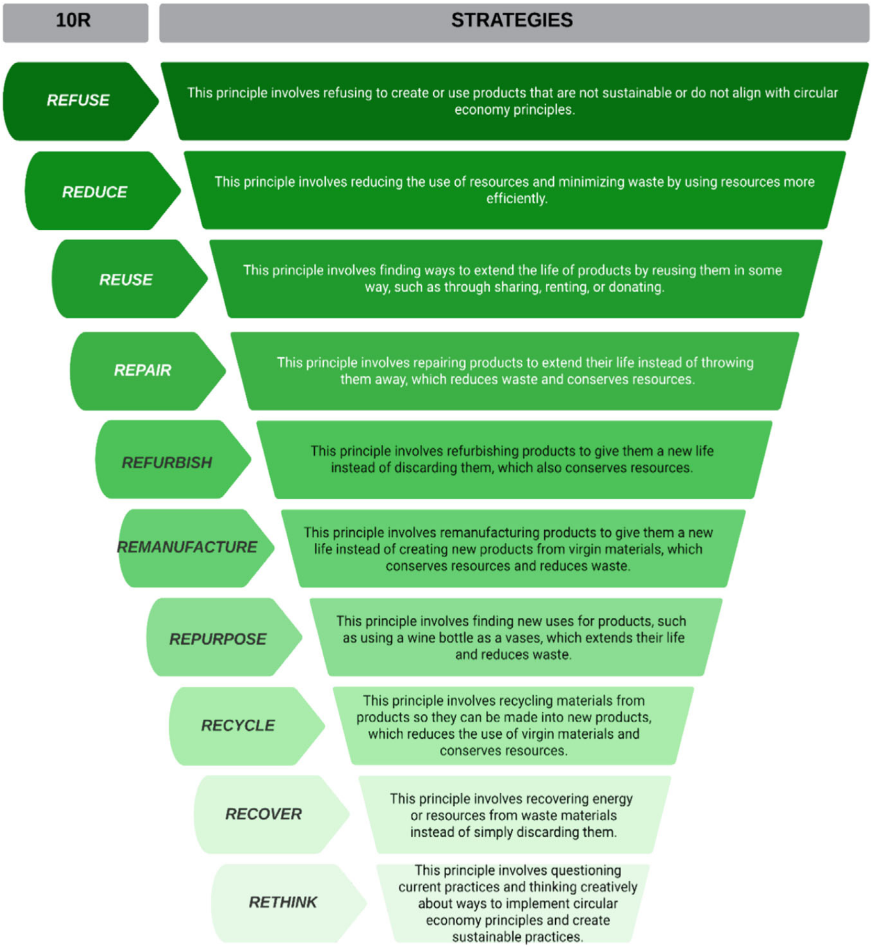

Fig. 1.2 10R strategy [16]

driving innovation, businesses can further reduce their reliance on virgin materials and resources while also contributing to a more sustainable future.

Benefits of Circular Economy

The circular economy offers numerous benefits that make it an attractive solution for promoting sustainability and reducing waste. These benefits (see Fig. 1.3) include environmental sustainability, economic opportunities, and social benefits [8]. By adopting circular practices, stakeholders can minimise the environmental impact of production and consumption, stimulate innovation and economic growth, create job opportunities, improve resource access and affordability, and enhance community resilience.

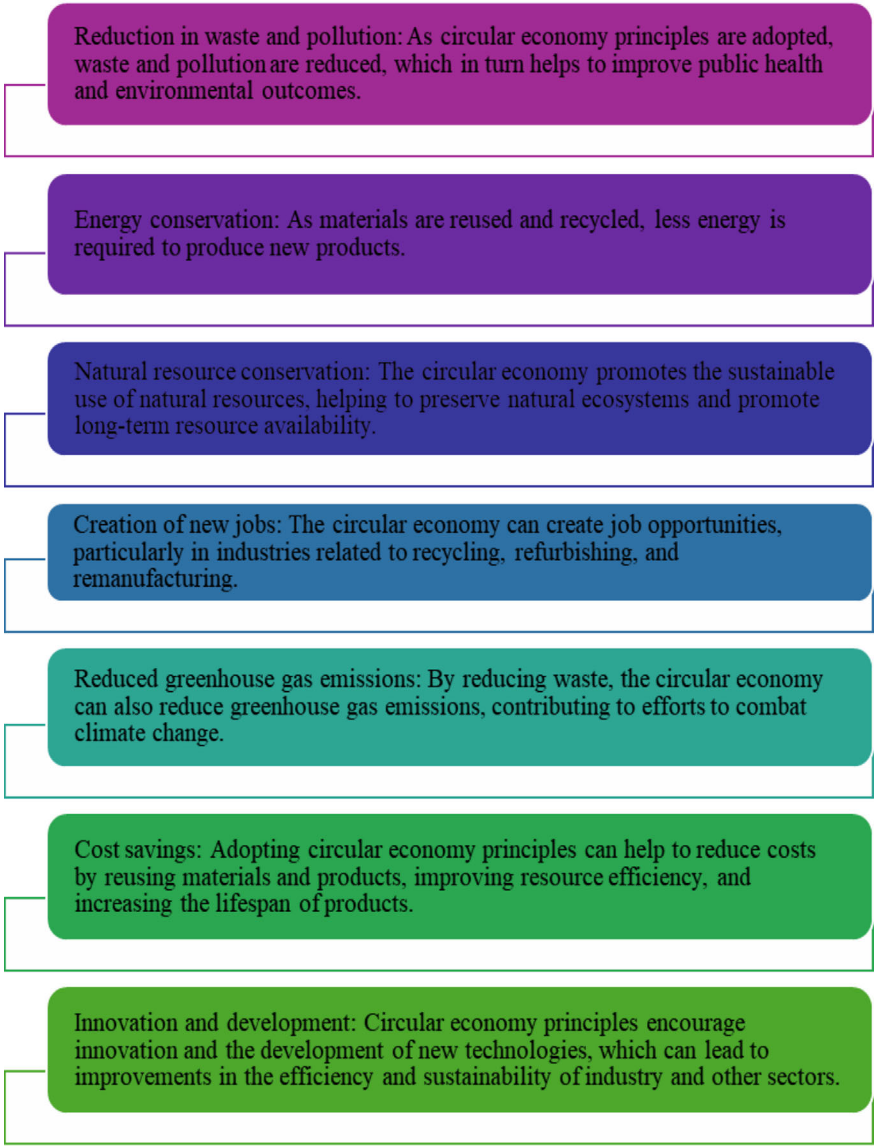

Fig. 1.3 Benefits of circular economy

One of the significant environmental benefits of implementing circular economy principles is that it can lead to a reduction in greenhouse gas emissions [5]. By promoting the reuse of existing products and materials, the circular economy can curtail the need for extracting natural resources, reducing the associated carbon footprint [8]. Additionally, by minimizing the use of virgin materials, the circular economy can help conserve natural resources and protect vital ecosystems such as soil, air, and water bodies. Moreover, circular practices and processes can lead to significant energy savings by reducing the need for resource extraction, manufacturing, and transportation of new products [8].

Another environmental benefit of the circular economy is that it can help to limit waste generation and reduce pollution. Circular economy practices such as recycling and remanufacturing can divert waste from landfills and incineration, thus promoting resource efficiency [17]. This, in turn, can help protect ecosystems, limit biodiversity loss, reduce landscape and habitat disruption, and contribute to the global effort to combat climate change.

By adopting these principles, the circular economy can create a sustainable economic system that meets the needs of current and future generations while minimizing its environmental impact [8].

1.3 Circular Economy in the Built Environment

The circular economy is an industrial economy that aims to restore materials and resources, relies on renewable energy, reduces toxic chemical use, and eliminates waste through careful design. It presents a tremendous opportunity to capture more value in the built environment. To tackle the complex nature of the built environment, the Ellen MacArthur Foundation worked with Arup to develop a roadmap towards a circular economy for building construction [18]. Courses, research frameworks, and reports, such as TU Delft's MOOC: Circular Economy for a Sustainable Built Environment, Circular Economy for the Built Environment: A Research Framework, and WorldGBC's Circular Built Environment Playbook, respectively, are available. The built environment industry has a crucial role to play (see Fig. 1.4) in transitioning towards a sustainable, circular economy.

Recovery and reuse of salvaged building materials and products from existing structures

Recovery and Reuse of Salvaged Building Materials in the Construction Industry

The recovery and reuse of salvaged building materials and products from existing structures is an essential practice in the context of circular material usage in the construction industry. Instead of demolishing buildings and sending the debris to landfills, salvaging materials by disassembly allows for their reuse in new construction projects, reducing waste and conserving resources [19].

Key Aspects of Recovery and Reuse of Salvaged Building Materials

Salvage operations involve carefully deconstructing or dismantling existing buildings to recover reusable materials, requiring skilled labour, proper tools, and techniques for safe removal and preservation. Materials are then identified, sorted, and assessed for usability and potential applications, including evaluating condition, quality, and

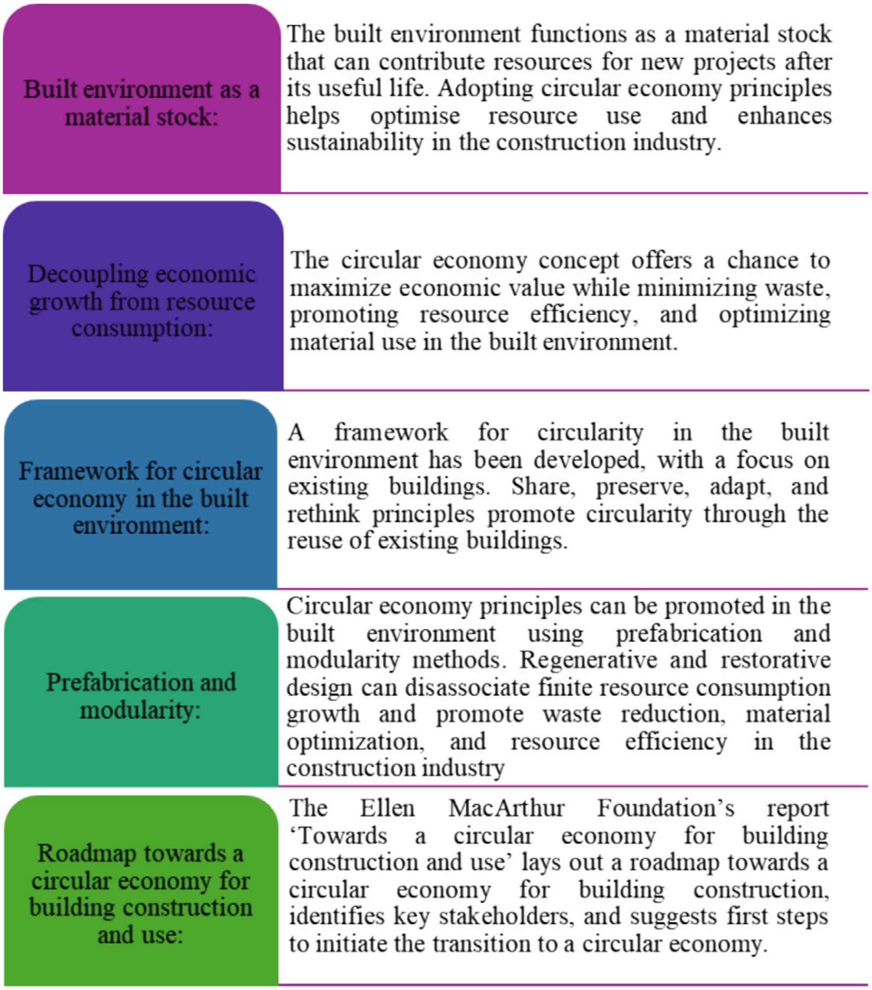

Fig. 1.4 Circular economy in built environment

compatibility [7]. Proper preservation and storage are necessary to maintain their quality, involving cleaning, repairing, treating, or storing materials appropriately. Salvaged materials should be assessed and tested to meet safety and quality standards, evaluating structural integrity, durability, and performance. Establishing an inventory and cataloguing system streamlines the reuse process, facilitating integration into new construction projects [19]. Designers and architects must consider characteristics, limitations, and aesthetics when incorporating salvaged materials while ensuring structural integrity and meeting regulatory requirements. Building networks and partnerships among stakeholders enhance reuse, allowing for exchange of information, expertise, and creation of marketplaces. By adopting these principles, the construction industry significantly contributes to sustainable practices by reducing waste, conserving resources, and promoting circular material usage [20]. See more information in Chap. 5, 'Recovery and Reuse of Salvaged Building Materials and Products from Existing Structures'.

Design for circularity

Design for circularity is a deliberate and systemic design approach that incorporates the fundamental principles of the circular economy. This approach is centred on minimizing waste, maximizing resource efficiency and promoting the reuse, recycling and regeneration of materials [21]. To achieve these objectives, design for circularity involves considering the entire life cycle of a product, from the sourcing of materials and the manufacturing process to the disposal of waste, with an emphasis on creating sustainable products and systems in a regenerative manner [21].

Key elements of design for circularity include the creation of products that are durable, easily repairable, and designed for disassembly, allowing for the recovery and repurposing of materials in a closed-loop system. Designers achieve this by adopting a range of techniques, including the use of recycled or renewable materials, building modularity and adaptability into designs, implementing product-service systems, and exploring opportunities for remanufacturing or refurbishment [21].

Material Selection and Management

The European Union (EU) emphasises the importance of applying circular economy (CE) principles across all economic sectors, including the construction sector. The criteria for selecting circular materials in the construction sector include:

1. Water and energy conservation: Circular materials should contribute to reducing water and energy consumption in the construction process.
2. Waste prevention: Circular materials should help minimise waste generation during construction and demolition activities.
3. Material recycling: Circular materials should be recyclable, allowing for their reuse in future construction projects.
4. Promotion of reuse and repair: Circular materials should be designed to facilitate reuse and repair, extending their useful life and reducing the need for new materials.
5. Utilisation of secondary raw materials: Circular materials should incorporate secondary raw materials derived from recycling or recovery processes.

By selecting materials that meet these criteria, the construction sector can contribute to the transition towards a less resource-intensive economy and promote circularity [12].

In the context of circularity, the European Union (EU) recognises the importance of critical raw materials, which are economically significant, sensitive to supply interruption, and have a significant environmental impact during extraction [22]. The EU aims to incorporate these materials into reduction, reuse, and recycling practices while seeking diversified and undistorted access to global raw materials markets and reducing external dependence and associated environmental pressures [23].

To achieve a less resource-intensive economy, it is recommended to prioritise the adoption of circular economy principles from the beginning of the production process. This includes designing production systems that efficiently use materials and enable recycling and reconversion of waste [12]. By incorporating circularity principles into the production process, economic models can be transformed, and the transition towards a less resource-intensive economy can be facilitated.

Selecting circular materials involves considering water and energy conservation, waste prevention, material recycling, promotion of reuse and repair, and utilisation of secondary raw materials [23]. The EU also emphasises the importance of incorporating critical raw materials into reduction, reuse, and recycling practices. Material efficiency, recycling techniques, waste prevention, and lifecycle assessment are key aspects of achieving circularity in material management and production systems [12].

Material recovery involves retrieving and reusing valuable materials from construction and demolition waste (CDW) [24]. This process includes activities such as deconstruction, which carefully disassembles structures to preserve valuable components [25]. Recovered materials can include lumber, cross-laminated timber, bricks, and other items that can be repurposed in future construction projects. The goal of material recovery is to reduce waste generation, conserve resources, and minimise the environmental impact associated with extracting new raw materials [25].

Recycling is an end-of-use strategy that involves reprocessing materials to be used in another product, thereby avoiding waste and the extraction of raw materials. In the construction sector, recycling often involves converting CDW into reusable materials, such as recycled aggregates, concrete, mortars, plastics, and gypsum Recycling CDW and other waste materials can contribute to resource conservation, waste reduction, and the promotion of sustainable material use [24]. More information is presented in Chap. 7 ‘Circular Material Usage Strategies/Principles’.

Modularity/prefabrication

Modularity and prefabrication bear immense significance in furthering the Circular Economy within the built environment. The integration of Circular Economy principles into modular construction allows for the development of a strategic framework that takes into consideration the entire life cycle of construction, ranging from design and production to use and end-of-life considerations [26]. The synergy of modularity and prefabrication with restorative and regenerative design can effectively overcome the trend of resource consumption growth, promoting the reuse of building components and aligning with the principle of decoupling economic growth from resource consumption. While the existing literature on the link between modularity and the Circular Economy remains limited, evidence suggests that these concepts augment resource efficiency, mitigate waste, and optimise material use, leading to a sustainable and Circular construction sector [26].

The benefits of integrating modularity and prefabrication into construction are manifold and significant for the Circular Economy in the built environment. Offsite manufacturing and assembly of building components have the potential to reduce material waste, maximise the utilisation of building materials and curtail transportation-related carbon emissions compared to traditional construction techniques [26]. Furthermore, prefabrication of building components offsite simplifies construction at the job site, expediting the construction timeline and minimizing the presence of workers on-site. Controlled factory environments enhance quality and consistency, leading to better-functioning and more durable buildings. Offsite construction can also improve job site safety by reducing hazardous conditions and minimizing work performed at high elevations [27]. Overall, modularity and prefabrication play an integral role in delivering higher quality, more durable structures while promoting environmental benefits and resource efficiency within the sector [27].

Prefabrication and modular construction offer several benefits for the Circular Economy within the built environment, some of which include shorter project durations, cost savings, enhanced site protection, superior product quality, reduced waste, and a closed-loop supply chain. Prefabrication and modular construction allow for faster and more precise manufacturing, leading to shorter project timelines, reduced construction costs, and economic sustainability [27]. Additionally, they minimise the impact of construction on the environment and surrounding communities, enhancing site protection while also improving product quality and promoting resource efficiency through optimised material use and waste reduction [26]. The closed-loop supply chain resulting from these practices further decreases the demand for virgin materials, as components are reused and recycled. Overall, the integration of prefabrication and modular construction techniques into Circular Economy principles offers numerous benefits and is crucial to advancing sustainability in the built environment (see more information in Chap. 8, 'Modularity/Prefabrication').

Reversible and transformable buildings

In a building context, the term "reversible" describes the process of transforming or dismantling a building's systems, products, and materials without incurring damages. A reversible building can, therefore, be dismantled, and its components can be reused, repurposed, or recycled. Similarly, reversible products can be designed and manufactured to enable the easy disassembly and reuse or recycling of their components. Reversible design is a fundamental principle of the circular economy, which seeks to keep resources in use for extended periods and eliminate waste [28].

Reversible building represents a strategic approach to architecture and construction aimed at creating buildings with reusable, repurposable, or recyclable materials, enabling them to be disassembled without causing damage [29]. This philosophy emphasises resource productivity and supports the ability of a building's components to revert to an earlier state, making the space easily adaptable to changing user needs [29]. Reversible design considers the technical and spatial dimensions, enabling efficient refurbishments and the disassembly, reuse, and/or recycling of the building's components [29].

Reversible products are of paramount importance to the circular economy, as they allow for the deconstruction and reuse of components, reducing waste and carbon emissions. "Reversible building" represents the backbone of circular building and the circular economy, involving the design of buildings and products that are easily disassembled and reused [29].

Reversibility and durability are potential indicators of circular economy design, highlighting the importance of designing easily disassembled, recyclable, or repurposable products, promoting sustainability in the industry [30]. Reverse logistics, which refers to the collection, repair, refurbishment, and recycling of products at the end of their useful life, is a crucial aspect of the circular economy. Manufacturers can use circular business models, whereby they maintain ownership of the product and are responsible for its upkeep throughout its life cycle, regardless of who possesses it [30].

The importance of reversible design is gradually becoming prevalent in calls for projects as reversible design allows products to be reconfigured, adapted, and repurposed to promote circularity in the production industry [30]. Overall, reversible products are instrumental to the circular economy, enabling the reuse and repurposing of materials and promoting sustainability in the production industry while reducing waste and carbon emissions (see more information in Chap. 10 'Reversible and Transformable Buildings').

1.4 Case Studies and Best Practice Examples

The construction industry has long been recognised as a significant contributor to natural resource depletion and environmental pollution [31]. As a result, designers and manufacturers are increasingly focusing on sustainability and circularity in their operations to minimise waste and promote resource efficiency. This requires the adoption of various design concepts, including circular materials, modularity/prefabrication, design for circularity, and reversible building/products. However, to effectively implement these design concepts, it is essential to establish and follow best practices [31]. Best practices provide a consistent framework for achieving successful outcomes, optimizing performance, and ensuring regulatory compliance, among other benefits. In this article, we delve into the importance of best practices in achieving sustainable and circular design, highlighting their benefits and their critical role in successful implementation. Table 1.1 outlines the case studies in the next chapters.

Table 1.1 Case studies in the next chapters

Chapter Nº	Case studies
Chapter 2 'Recovery and Reuse of Salvaged Building Materials and Products from Existing Structures'	1. Project ReCreate 2. Temporary market hall
Chapter 7 'Circular Material Usage Strategies/Principles'	1. Gonsi Sócrates bio-building 2. Urban Mining and Recycling (UMAR) experimental unit 3. Open-spaced apartment 4. Escuela Politécnica superior
Chapter 4 'Modularity/Prefabrication'	1. Vertical timber extensions on existing building 2. FrameUp—optimisation of frames for effective assembling 3. SUPRIM case study
Chapter 5 'Reversible and Transformable Buildings'	1. People's Pavilion 2. Brasserie 2050 3. Triodos Bank 4. Koodaaram Kochi-Muziris Pavilion 5. Stadium 974

1.5 Challenges Faced in Implementing Circular Economy Practices in the Built Environment

The construction industry encounters economic challenges in adopting circular economy practices. A major roadblock is the insufficient level of awareness and knowledge of circular economy principles and practices among industry stakeholders. Additionally, there is an absence of incentives to design and construct buildings and products that can be easily disassembled and repurposed at the end of their operational life. These barriers pose significant obstacles to the adoption of circular design in the construction industry [32]. The implementation of circular economy practices in the built environment can also be impeded by technical obstacles. These challenges include a lack of standardization, complicated building systems, and the difficulty of disassembling and reusing materials. These technical barriers can pose significant difficulties for designers and constructors seeking to adopt circular economy practices in the built environment [33].

The implementation of circular economy practices in the construction industry can be impeded by several economic challenges. One such challenge is the limited research and application of circular economy concepts, which results in a lack of understanding of its full potential. Furthermore, the absence of a circular economy culture among stakeholders and resistance to change hinder the adoption of circular practices. Stakeholders may perceive implementation of such practices as costly due to insufficient regulatory frameworks and limited awareness of the benefits of circular practices [34]. Addressing these challenges involves collaborative efforts between stakeholders and government support, including the creation of new business models and metrics, adoption of innovative technologies, and establishment of economic incentives for circular products. Standardised metrics and increased demand for circular products are also important in overcoming economic barriers [35]. The design of buildings and products for disassembly and reuse at the end of their lifecycle is vital, but stakeholders may lack awareness and knowledge of circular economy principles and practices. In summary, there is a need for stakeholder collaboration, government support, and novel approaches to overcome economic obstacles and make the implementation of circular economy practices a reality in the construction industry [35].

The implementation of circular economy principles throughout the supply chain necessitates a clear economic justification, reinforced by metrics, tools, and guidance [36]. Technical barriers, such as absence of standardization, building system complexity, and the intricacies of disassembly and reutilisation of materials, pose significant challenges to the adoption of circular practices in the built environment. Moreover, a dearth of research and development in the circular economy concept limits comprehension of its vast potential within the construction industry [34].

Resistance to change alongside the lack of a circular economy culture among stakeholders presents another major obstacle to the circular economy's adoption. These impediments relate to stakeholders perceiving the high costs of implementing circular practices, inadequate regulatory frameworks, and insufficient awareness of the advantage of embracing circular practices [35].

Effective strategies to surmount these economic challenges require multi-party collaboration, innovative business models and metrics, and technology adoption [35]. This collective effort should produce clear economic incentives, practical solutions, standardised metrics, and increased market demand for circular products. Thus, through collaborative efforts between stakeholders and government support, circular economy implementation can become a tangible reality in the built environment [37].

1.6 Success Factors for Circular Economy Implementations in the Built Environment

The transition towards a more sustainable and circular future in the built environment requires addressing various factors that minimise waste generation, resource depletion, and environmental impacts. Collaboration and stakeholder engagement are crucial, involving architects, designers, contractors, legislators, manufacturers, and communities at every stage of the value chain [12]. Design for adaptability and modularity is essential, building flexibility and modularity into designs to make disassembly, reconfiguration, and reuse easier, avoiding total demolition and reconstruction for future adjustments and additions [35].

Careful consideration in material selection is critical, prioritizing durable, highly recyclable, and environmentally friendly materials.

Resource-saving practices such as energy-efficient systems, sustainable landscaping, and water-saving technology further enhance the circularity of built environments. Taking a lifecycle approach to building, from planning and construction through use and eventual destruction, is crucial. Efficient asset management measures such as routine maintenance, monitoring, and upgrading increase the lifespan and value of buildings [12].

Creating circular business models that incentivise recycling, renovation, and remanufacturing of building materials promote longer product lifecycles and decreased waste production using leasing, sharing, and product-as-a-service models. These circular practices may be financially incentivised through tax breaks or subsidies [35].

Data management and digitalization play a pivotal role in promoting effective decision-making throughout the building lifespan, reducing waste, and allocating resources better. Building Information Modelling (BIM), Internet of Things (IoT), and data analytics are some digital technologies that can be used [38].

Governments and regulatory agencies promote circular economy adoption through supportive policies, laws, and standards, such as waste management regulations, green construction accreditations, and procurement policies that prioritise circular practices [39]. Encouraging public education and knowledge about the benefits and significance of the circular economy in the built environment among experts, decision-makers, and the public is critical in promoting a culture of sustainability and embracing circular practices.

1.7 General Conclusions and Future Trends in Circular Economy Practices for the Built Environment

The built environment industry is exploring the circular economy concept as a way to reduce resource consumption and move away from the traditional linear take-make-dispose model. The circular economy aims to create maximum economic value while minimizing waste by applying circular principles to both existing and new buildings. These principles include adaptive reuse, prefabrication, and modular construction. According to a report by the Ellen MacArthur Foundation, the circular economy offers significant investment opportunities of 115 billion euros for Europe's built environment sector. These opportunities involve designing and building circular structures, establishing closed-loop systems for construction and demolition materials, and creating circular cities [23].

However, the implementation of circular economy practices in the built environment faces several challenges, such as policy and regulatory barriers, information and awareness gaps, and the need for more collaboration across the supply chain. Despite these challenges, several trends are emerging in the circular economy practices of the built environment industry, such as increased awareness, technological and material innovation, stakeholder collaboration, and policy support from governments and regulatory bodies [5].

The built environment industry is moving towards a more sustainable and circular future, with several promising aspects emerging. These include the increased use of modular and prefabricated construction methods that enable easy disassembly, reuse of components, and repair instead of replacement [34]. These methods can reduce waste and resource consumption, as well as increase flexibility and adaptability. Another aspect is the integration of circular principles into energy, water, and waste systems for entire buildings and neighbourhoods. This can create more efficient and resilient systems that minimise environmental impacts and optimise resource flows. A third aspect is the availability of recycled, repurposed, and reclaimed building materials that can reduce the demand for virgin materials and extend the life cycle of existing materials. A fourth aspect is the application of digital technologies to support circularity, such as building information modelling (BIM), material passports, and blockchain-based supply chain management [35]. These technologies can enhance transparency, traceability, and quality of building materials and components, as well as facilitate circular design and decision making. A fifth aspect is the incorporation of circularity into disaster recovery and resilience planning in the face of climate change [12]. This can help the built environment industry to prepare for and respond to natural disasters, as well as to recover and rebuild in a more sustainable and circular way. The adoption of circular economy practices in the built environment is essential for promoting sustainability and reducing waste. Continued innovation and collaboration across the industry will be necessary for these practices to become the norm and create a more sustainable future for us all.

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Chapter 2
Circular Materials—A Multiscale Approach to Circularity at a Building, Components and Materials Level

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Abstract Sustainable practices and strategies to enhance resource efficiency while minimising waste in buildings and their constituent elements are key towards circularity at the urban built environment. In this chapter three implementation scales, under the paradigm of the circular economy (CE), are measured—*i.e.*, buildings, components and materials—, considering both new and existing buildings' implementations. Aspects such as design for adaptability and flexibility, modular and flexible spaces and concepts, energy and water efficiency are discussed. By implementing CE strategies at the component-level using a multipronged approach would extend the lifespan and contribute to environmental and economic sustainability. This includes the refurbishment and upgrading of components and the adoption of modular construction techniques, among other techniques and solutions. The last part

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of the chapter presents the concept of circular materials and its circularity potential at promote extended product lifecycles and transforming waste into valuable resources. Integrating sustainable and circular design principles within construction practices is proposed towards more sustainable and resource-efficient industries' transformations.

Keywords Circular economy · Urban built environment · Buildings · Construction materials · Design for disassembly · Modularity

2.1 Introduction

Circular economy (CE) principles find application across various levels within the built environment, encompassing buildings, components and materials. In a framework for CE, a core tenant is the continuous circulation of products and materials, aiming to minimise waste and optimise resource utilisation throughout their lifecycle. This is accomplished through various strategies, including (i) routine maintenance to prevent early deterioration, (ii) reuse of products in their original form, (iii) refurbishment to upgrade functionality, (iv) remanufacturing to create like-new products from used components, and (v) recycling to convert used materials into new products. The essential purpose is to optimise resource efficiency, minimise waste, and advocate for sustainable practices throughout the entire lifecycle of buildings and their constituent elements.

2.2 Building Level

The principles of the CE offer a transformative approach to building design, construction, and operation. These principles encourage consideration of a building's entire life cycle; including designing for disassembly and adaptability to future uses, as well as incorporating materials with high reuse and recycling potential. By designing buildings with circularity in mind, it becomes possible to extend their lifespan and reduce waste. The application of CE principles at the building level necessitates a holistic approach that considers the total life cycle of the structure. This approach promotes strategies to minimise resource consumption and waste generation throughout all stages, from design and construction to operation, renovation, and end-of-life. Whether it is a new building or an existing one, different approaches need to be considered.

New Buildings

When it comes to new buildings, the goal is to build for long-term use, build efficiently and use materials resourcefully in order to minimise waste. Careful design and planning are crucial, alongside adopting resource-efficient construction techniques like prefabrication and modularisation, to minimise waste and enhance resource utilisation. Increasing the building utilisation and designing for durability and adaptability are also crucial strategies, considering the future needs of the generations to come. The latter is also associated with using circular materials with high recyclability and recycled content, low environmental impact and non-hazardous components.

Existing Buildings

For existing buildings, the focus is on adaptive reuse, giving new purposes and functions to existing structures. This helps towards extending the lifespan of the building and avoiding unnecessary demolition and waste generation. Building renovations and retrofits should prioritise incorporating energy efficiency goals to enhance the building's overall performance and optimise energy consumption. Additionally, deconstruction techniques can be employed to carefully dismantle the building and recover materials for reuse, remake or recycling.

At the buildings level, the application of CE principles translates to designing, constructing, and operating buildings with a comprehensive life-cycle approach. This means focusing on minimising resource consumption and waste generation across the building's life cycle, from design and construction to operation, renovation, and deconstruction.

There are some key steps to follow, as explained in the four sub-sections below:

Design for Adaptability and Flexibility. In the twenty-first century, the dominant feature is rapid technological advancement. The advent of new technologies and smart building concepts is reshaping people's lifestyles. Although buildings are constructed with the intention of serving for many years, it is clear that in just a decade, the needs of occupants can evolve significantly. To address this challenge, buildings must be designed with a long-term perspective, minimising the need for frequent replacements or demolitions. The emphasis is on creating designs that allow easy modifications or repurposing as evolving needs arise. This adaptability is crucial because the social, economic, and environmental conditions are constantly changing, necessitating a corresponding evolution in the functions and purposes of buildings.

Besides aligning with circularity, this approach offers distinct advantages. Designing for adaptability and flexibility is a pivotal step in ensuring that buildings can respond effectively to changing circumstances. By proactively considering future requirements and potential changes, the lifespan of buildings can be extended, hence reducing waste, and curtailing the necessity for extensive renovations or demolitions.

Modular and Flexible Spaces. The concept of flexibility and adaptability in architecture has been present since the emergence of modernism and continues to be highly relevant in our daily lives. According to Kronenburg [1], flexible design aims to create spaces that can be adjusted to unforeseen circumstances, evolving user needs, and new operational requirements. The twentieth century witnessed a progressive adoption of modular design principles, both in building structures and individual products, marking a development in industrial history [2].

The term "flexible housing" is a more appropriate phrase to describe flexibility in the built environment, as explained by Schneider and Till [3]. They broaden the definition of flexibility to encompass all design choices that depart from rigid functionality. This highlights the criticality of creating spaces capable of adapting to accommodate diverse needs and functions over time.

In summary, flexibility and adaptability are crucial considerations in architecture and engineering at the built environment. They enable spaces to respond to changing requirements and operations, and the use of modular structures and flexible design approaches can facilitate this adaptability. The term "flexible housing" encompasses the range of design decisions that allow for the transformation and reconfiguration of spaces, moving away from rigid functionality.

Energy Efficiency. Sustainable building design prioritises energy efficiency, a critical strategy for minimising energy consumption, lowering greenhouse gas (GHG)) emissions, and contributing to environmental well-being. To achieve this, several key considerations should be weighed, such as:

Passive Design Strategies. Implementing passive design strategies is important to optimise energy flows, natural lighting, infiltration, and ventilation. Minimising heat loss through the building's envelope using effective insulation, and reducing the effect of thermal bridges, along with the management of solar heat gains can also significantly lower the heating and cooling energy needs.

Efficient HVAC (Heating, Ventilation, and Air Conditioning) Equipment. Integrating high-performance HVAC systems within a holistic building design fosters significant energy savings and improved indoor thermal comfort. In addition, adopting energy-efficient lighting solutions, such as LED bulbs and harnessing daylighting strategies, further minimises the reliance on artificial lighting.

Smart Controls and Energy Management Systems. Using occupancy sensors, thermostats, and smart controls can automatically adjust energy use according to occupancy, daylight, or other factors; thus, optimising energy consumption. While energy management systems offer the ability to leverage data from connected devices, ensuring effective control and management relies on the implementation of a user-friendly interface.

Renewable Energy Systems. Incorporating renewable energy systems such as geothermal systems, solar power, wind power, biomass, or biogas can greatly contribute to sustainable performance targets. Installing solar photovoltaic (PV) systems on rooftops or vacant land can generate clean electricity, offsetting the building's energy demand and reducing reliance on grid power. Integration of small-scale wind turbines or utilising geothermal heat pumps for heating and cooling purposes are also viable options.

It is important to consider user-friendliness when implementing energy-efficient systems. Complexity can hinder effective management and usage, so the systems should have a basic interface that is easily understandable and manageable by users. Additionally, integrating energy-efficient equipment and systems throughout the building, such as HVAC systems, will contribute to overall energy efficiency.

By incorporating these strategies and technologies, buildings can significantly improve the prevailing comfort conditions and, at the same time, reduce their energy consumption, reduce carbon emissions, and advance a more sustainable future. It is essentially important that designers prioritise energy efficiency in building design and construction to create environmentally responsible and resource-efficient structures.

Water Efficiency. Water management in buildings encompasses the implementation of strategies and technologies to optimise the utilisation, conservation, and overall management of water resources. The goals of effective water management include eliminating wasteful practices and unnecessary expenses associated with the use of clean water, reducing the reliance on freshwater resources to preserve ecological balance, and ensuring adequate water supply in areas facing water scarcity. By implementing efficient water management practices, buildings contribute to achieving sustainable water use, conservation, and resilience in the face of growing challenges of water scarcity. This can be achieved through the adoption of water-efficient appliances such as dishwashers and washing machines, and fixtures—e.g., toilets, showerheads, and faucets.

Grey water recycling provides water savings of up to 50% in residences. For commercial purposes such as hotels and dormitories, this rate exceeds 60%. The water used to bathe and wash hands accounts for 50–60% of total greywater, the greywater from the washing machine accounts for 25–35% of total greywater, and the greywater from the kitchen accounts for 50–60% of total greywater.

Rainwater harvesting systems have huge potential to reduce water consumption in buildings.

2.3 Component Level

The principles of the CE extend beyond the building itself, encompassing the individual components that form itself. This includes the use of components that are designed for disassembly, facilitating their seamless separation and subsequent reuse or recycling. By incorporating circular design principles into the selection and use of components, it becomes possible to minimise waste and maximise resource efficiency. At the component level, several key strategies can be used to promote circularity:

(1) Encouraging Product-as-a-Service (PaaS) Business Model: Emphasising the PaaS model can facilitate the sharing and reusing of components, promote resource efficiency, and reduce waste.
(2) Supporting Reverse Logistics and Take-Back Programmes: Smart take-back systems and efficient reverse logistics keep resources in the loop, enabling recycling and repurposing of materials at their end-of-life.
(3) Designing for Repairability: Emphasising repairability in component design extends their lifespan and reduces the need for replacements. This can include using easily replaceable parts or providing access to repairs.

(4) Promoting Remanufactured Components: Encouraging the use of remanufactured components instead of new ones contributes to resource conservation and reduces the demand for new production.
(5) Facilitating Component-Sharing Platforms: Providing platforms for individuals or organisations to share components fosters resource sharing and reduces the overall demand for new production.
(6) Collaborating for Resource and Component Sharing: Collaborating with others to share resources and components further reduces the requirement for new production and upholds circularity.
(7) Encouraging Innovation in Sustainable Materials and Technologies: The support of research and development in the component field promotes the development of innovative materials and technologies that enable sustainable and circular components.
(8) Raising Awareness and Demonstrating the Benefits: Educating consumers, producers, and policy makers about the advantages of implementing component-level circularity can elevate public awareness and drive responsible consumption behaviours.
(9) Advocating for Supportive Policies and Regulations: Advocating for policies and regulations such as tax incentives or extended producer responsibility laws that support CE practices at the component level can further drive adoption and implementation.

In the built environment, implementing CE strategies at the component level necessitates a multipronged approach, encompassing the reuse of building elements, the refurbishment and upgrading of components, and the adoption of modular construction techniques. These strategies extend the lifespan of components, reduce waste, and contribute to environmental sustainability.

Reusing Components

While the term of CE may be recent, the underlying principles of resource recovery and component reuse have a long history, dating back to pre-industrial times and practised extensively then [4]. Material recovery is a complex process influenced by numerous factors, encompassing economic changes, technological advancements, and evolving trends such as fashion. In particular, the reuse and recycling of metals have been practised since their very first utilisation [5]. The landscape of decision-making is evolving, with environmental considerations gaining significant weight alongside traditional economic and social factors. Due to this importance and increasing material costs, the disassembly and reuse of components is attracting more attention [6]. Recognising the importance of sustainable practices, the Environmental Protection Agency (EPA) developed a tool to measure the energy savings from responsible material management. Their findings demonstrate that recycling and source reduction can conserve significant energy and minimise greenhouse gas emissions, contributing to a healthier planet [7]. Achieving seamless deconstruction hinges on two key factors: (1) incorporating the right technologies into the design process; and (2) developing innovative building systems and technologies that prioritise component reusability. By combining these approaches, we get closer to a circular construction model where materials have multiple lives.

The Canadian Standards Association (CSA) has released a draft guide outlining principles and strategies for Design for Disassembly and Adaptability (DfDA) in buildings, offering valuable guidance for architects, engineers, and construction professionals [8]. This research uses life cycle assessment (LCA) methodologies to comprehensively evaluate various approaches toward reuse of materials and components in the built environment. By providing designers with robust data and insights, the study aims to develop a practical evaluation tool for selecting building layers and components that optimise both environmental performance and reusability potential [6].

The practice of recovering and incorporating individual components salvaged from previous construction projects into new buildings is called “component reuse”. This can encompass structural elements like beams and columns, or nonstructural components like cladding panels, bricks, and even staircases. Compared to recycling, reusing building components or entire structures typically requires less reprocessing, leading to a more significant reduction in environmental impact [6]. The U.S. (United States) Environmental Protection Agency (EPA) study revealed that component reuse offers significantly greater environmental benefits than recycling, with waste reduction efforts leading to more than 60% higher energy and GHG emissions savings [7].

Implementing a materials reuse strategy requires significant flexibility from design teams, necessitating an openness to adapting plans as components become available. Timely access to accurate information throughout the design process is highly important. Having precise dimensions of reclaimed components readily available in the early stages of the design empowers informed decision-making.

Reuse of structural components enjoys greater feasibility when the intended new purpose aligns with the original function. Incorporating such as components into a new project is facilitated by similar structural layouts and preservation of the original span sizes in the new design. Client engagement plays an important role in driving the success of deconstruction and reuse strategies. Their decisions regarding budget, design goals, and level of risk tolerance significantly impact the feasibility and success of such projects. The decision to reuse materials in a project demands a nuanced approach, considering the unique characteristics of each site and the context of the project. Factors such as location, available space, project timelines, and specific design requirements all have a significant impact on the feasibility and suitability of utilising previously used materials.

Refurbishment (Repair-Repaint-Retrofit) and Upgrading

The environmental footprint of the construction industry can be significantly reduced through refurbishment, solidifying its position as a vital facet of the CE. Alongside repair, remanufacturing, and direct reuse, refurbishment empowers the industry to prioritise resource conservation and waste reduction.

Refurbishment involves the process of improving buildings by cleaning, decorating, and reequipping them to achieve energy efficiency and sustainability goals. It often includes elements of retrofitting, which focusses on upgrading existing building components and systems to enhance their performance.

Refurbishment encompasses the targeted intervention on defective or outdated elements, such as components and surfaces. This involves repair or replacement while preserving the core structure. This approach promotes the conservation of existing buildings while simultaneously enhancing their functionality and aesthetics. Furthermore, refurbishment can extend to upgrades in fire protection, acoustics, and thermal performance, ultimately leading to an overall increase in the building's quality and sustainability.

Retrofits, on the other hand, refer to the process of strengthening, upgrading, or adding additional equipment to a building after its initial construction. This often includes improved thermal insulation, energy-efficient HVAC systems, or even renewable energy sources, together with the aim of improving building performance and minimising environmental impact.

By implementing refurbishment and retrofitting practices, the construction sector can contribute to resource conservation, waste reduction, and the promotion of sustainable building practices. These approaches allow for extending the lifespan of existing buildings, significantly reducing the need for construction projects made with elements from new materials, thereby minimising the associated environmental impacts.

2.4 Material Level

The construction industry can unlock significant environmental benefits by embracing the principles of CE. Prioritising recycled materials in buildings reduces the dependence on virgin resources, minimising waste and GHG emissions. This paves the way for a more sustainable and resource-efficient future for the built environment.

The concept of circular materials revolves around the reusing, recycling, or transforming of materials within a closed-loop system. This approach represents a paradigm shift, transitioning from the traditional "use and throw away" model towards a more efficient paradigm of utilising existing resources through reuse. Additionally, the development of new construction materials based on zero carbon principles can also be considered part of the circular materials approach, as they lower costs, speed up construction, improve quality and safety, and extend the lifespan of buildings.

The use of circular materials in construction offers several benefits. It reduces waste, conserves resources, and lowers the environmental impact of the built environment. Some innovative construction materials and systems that contribute to circularity include self-healing concrete, concrete canvas, topmix permeable, aerogel, and nanomaterials. These materials offer improved durability, strength, and sustainability.

To promote circularity at the materials level, several strategies can be implemented:

(1) Material Recovery and Recycling: Implementing strategies to recover and recycle materials from demolition or renovation of buildings, such as concrete, metals, or wood, reduces waste and conserves resources.
(2) Closed-Loop Material Systems: Encouraging the adoption of circular materials within construction and manufacturing processes. These materials prioritise ease of separation, recycling, and reuse.
(3) Extended Producer Responsibility (EPR): Encouraging manufacturers to take ownership of their components beyond the point of sale, including responsible recycling, repurposing, or alternative end-of-life solutions.
(4) Digital Platforms and Material Passports: Using digital platforms and material passports provides information about the origin, composition, and recyclability of building materials, facilitating their future reuse or recycling.
(5) Optimise Material Usage: Practices such as reducing overdesign, decreasing the weight of products, and eliminating waste in production processes help optimise material usage and minimise waste.
(6) Bio-based Materials: Exploring the development and use of bio-based materials that are renewable and biodegradable contributes to circularity and sustainability.
(7) Advanced Recycling Technologies: The implementation of advanced recycling technologies, including chemical recycling and upcycling, facilitates the extraction of valuable materials from waste streams.
(8) Collaboration with Product Designers: Collaborating with product designers to select materials that align with principles of CE, such as ease of disassembly and recyclability, promotes circularity.
(9) LCAs: Conducting LCAs to evaluate the environmental impact of materials and products, considering factors from extraction to disposal.
(10) Lean Manufacturing Practices: Promoting lean manufacturing practices to minimise material waste during production.
(11) Stakeholder Engagement: Fostering multi-stakeholder collaboration, including manufacturers, consumers, and policymakers, to educate and advocate for the use of circular materials and responsible consumption practices.
(12) Supportive Regulations: Advocating for regulations that mandate minimum recycled content in products.
(13) Innovation and Collaboration: Collaborating with research institutions, startups, and industry partners to drive innovation in materials and circularity.

Sustainable Materials Selection

Evaluating the sustainability of building materials can be guided by standards like EN 15,804:2012 + A2:2019, which establishes foundational principles for Environmental Product Declarations (EPDs) in the construction sector. EPDs play a key role in green building assessment tools, offering insight into a product's environmental impact throughout its entire life cycle. EPDs rely on LCAs to provide information on various environmental impacts of products. By meticulously analysing resource consumption, energy usage, emissions released, and waste generated at every stage of a product's life cycle, LCAs offer a holistic perspective on their true sustainability.

The Waste Framework Directive (2008/98/EC) establishes distinct definitions for recycling and recovery within waste management. Recycling involves the reprocessing of waste materials into entirely new products, materials, or substances. On the contrary, recovery refers to operations that fulfil a valuable purpose by replacing other materials or preparing waste for a specific function.

The term "reuse" refers to sending the output material from a resource-consuming unit to other operations without re-entering the processes from which it was emitted. In contrast, the recycling scheme allows the effluent to re-enter the processes where it was generated. By prioritising materials that can be recycled, reused, or transformed within a closed-loop system, the construction industry can reduce waste, conserve resources, and minimise environmental impact. This includes using materials with high recycled content and designing for disassembly to facilitate material recovery and recycling.

Beyond selecting sustainable materials, innovative practices such as digital platforms and material passports offer deeper insights into the origin, composition, and recyclability of building components. Additionally, EPR motivates manufacturers to take ownership of their products' end-of-life, promoting recycling and repurposing strategies. Collaboration with product designers, conducting LCAs, promoting lean manufacturing practices, and active stakeholder engagement work hand-in-hand to propel the adoption of sustainable materials and facilitate the implementation of CE practices within the built environment.

Closed-Loop

At the heart of the CE are closed-loop material systems, where materials or products are designed for iterative use, recycling, and transforming into new offerings without compromising quality. This approach minimises waste generation, promotes resource conservation, and paves the way for a more sustainable and resource-efficient future.

Key characteristics and principles of closed-loop material systems include:

(1) Material Reuse: Emphasising the reuse of materials involves extending their lifespan by using them in multiple cycles or repurposing them for different applications. This approach mitigates the demand for virgin materials and simultaneously minimises the generation of waste.
(2) Material Recycling: Closed-loop systems prioritise the resource recovery of materials at the end of their designed use phase. This involves meticulous collection, sorting, and processing to transform them into new products or materials, ultimately decreasing the reliance on virgin resources.
(3) Remanufacturing: Remanufacturing involves a meticulous process of refurbishing or repairing products or components, restoring them to their original performance specifications or even exceeding them. This approach significantly

extends the product lifespan, contributing to a reduction in the demand for new manufacturing endeavours.

(4) Reverse Logistics: Reverse logistics is the "return journey" of products or materials. This system involves managing the flow of used items from consumers back to manufacturers or recycling facilities, where they can be refurbished or recycled. This ensures that the materials are properly collected, sorted, and reintegrated into the closed-loop system.

(5) Resource Efficiency: Closed-loop material systems aim to optimise resource usage by minimising waste, reducing energy consumption, and maximising the resource efficiency and economic benefit derived from materials during their lifespan.

(6) Waste Reduction: By designing products and systems with closed-loop principles in mind, waste generation can be minimised. This includes reducing packaging waste, optimising material usage, and implementing efficient production processes.

(7) Transparency and Traceability: Closed-loop systems benefit from transparency and traceability, which involve tracking the origin, composition, and flow of materials across the value chain, including acquisition, transportation, storage, processing, and eventual delivery to the end user. This ensures accountability and enables informed decision-making about material selection and recycling processes.

2.5 Circular Materials

Circular materials are materials that have undergone processes such as collection, sorting, and reprocessing after their initial use. These materials, which can include plastics, natural fibres, metals, and more, are prepared to be used in new products or applications. The concept of circular materials is closely linked to the CE, which aims to transform linear material flows into circular ones by prioritising regenerative resources, designing for the future, promoting extended product lifecycles, and fostering the transformation of waste into valuable resources.

Circular materials are essential to achieve sustainability goals as they help reduce the consumption of virgin resources, lower emissions from the production of new materials, and minimise waste and environmental impact. By reusing materials and incorporating them into new products, circular materials contribute to a more efficient and sustainable use of resources.

In the context of construction, the principles of circular design can be applied to buildings and constructed areas. This involves focussing on the design and assembly process of the various components, such as walls, columns, slabs, roofs, foundations, floors, pipes, partitions, and furniture. The goal is to ensure that the materials used in these structures can be easily reused or repurposed in future generations of construction. It is important to consider the lifespan of each component and plan accordingly to maximise their potential for reuse. Integrating circular design principles into construction practices has the potential to transform the industry towards a more sustainable and resource-efficient future.

Concrete

Concrete is undoubtedly one of highly utilised construction materials due to its versatility, durability, and low cost [9]. Concrete contains natural ingredients such as cement, water, aggregates (sand and gravel), and admixtures [10]. Environmental concerns surrounding the production and disposal of concrete have spurred the development of more sustainable practices within the industry.

Recycling concrete boasts a multitude of benefits, most notably the reduction in dependence on primary raw materials and the substantial decrease in waste that ends up in landfills [11]. Recycled concrete offers a sustainable approach in construction and infrastructure by being reused as aggregate in new concrete and providing, in this way, a closed-loop solution. Alternatively, it can be used in road construction and earthworks, reducing the demand for virgin material. The ideal application depends on balancing environmental benefits, local accessibility, and engineering requirements [10]. The lifespan of concrete structures depends on factors such as the type of concrete used, structural design, quality of workmanship, exposure conditions, and maintenance practices. In general, concrete structures can last 50 to 100 years, although some last longer or shorter periods.

One of the main factors that ensures the durability of concrete is the strength of the steel reinforcement. Maintenance practices are essential to extend the lifespan of structures. Using circular materials such as slag in cement production can reduce resource use and waste generation, while improving the properties of concrete [12]. The co-processing of recycled concrete scraps in cement manufacturing presents a significant opportunity to advance the CE in construction. This approach effectively uses waste as a valuable resource, minimising the landfill burden and resource extraction.

Steel

The steel industry plays a crucial role in various human activities, including construction, transportation, consumer goods, and machinery. It is known for its remarkable strength, durability, and recyclability, making it a valuable material for a wide range of applications. However, the production of steel is associated with significant environmental challenges.

Steel production has steadily increased over time, driven by population growth and economic development. The industry is global, with China being the largest producer, followed by the European Union (EU), India, and the U.S. These regions also consume a significant portion of the global steel output.

Unfortunately, the steel production methods currently in use are heavily relying on fossil fuels, contributing to carbon emissions. With roughly 7% of global energy-related CO_2 emissions, the iron and steel sectors represent significant drivers of climate change [13]. To address this problem, there is a need for infrastructure and regulatory frameworks that promote the development and adoption of new technologies to reduce CO_2 emissions.

A positive aspect of steel is its recyclability without any loss of quality. About 30% of the world's steel is born from recycled scrap. This recycled steel can be used for various construction products, such as structural steel and roofing materials, contributing to a more CE [13].

To make the steel industry more circular and sustainable, several pillars can underpin this transition, including material efficiency, steel scrap recycling, process efficiency, and steel production based on renewable sources [14]. These measures involve producing lighter steel products, reusing steel items, improving energy efficiency, and transitioning to renewable energy sources.

To achieve carbon neutrality and a circular steel economy, public policies in the EU and elsewhere need to be updated and expanded. The creation of agencies to promote the maintenance, repair, and reuse of steel in various industries can be a step in the right direction.

Timber

Wood is an attractive and environmentally friendly material that aligns well with the principles of the CE. Sustainably sourced wood, obtained from responsibly managed forests, can play a decisive role in construction and various products, offering numerous environmental advantages. These include lower energy requirements for processing and the ability to sequester carbon from the atmosphere [14].

Sustainably sourced wood is used in a wide range of construction products, such as structural wood, flooring, and cladding. It offers advantages in terms of sustainability, workability, aesthetic qualities, and physical qualities. It can be adapted to various layouts, built quickly with dry construction techniques, mass-produced efficiently, and all at a cost-effective price point.

The emergence of engineered wood products has further expanded the use of wood in the construction sector. Products such as glue-laminated wood (GLULAM), veneered laminated wood (LVL), and cross-laminated timber (CLT), are strong, durable, and fire-resistant. Not only reduce construction time, but they also contribute to the environment by replacing high-impact materials such as concrete [15].

Wood recycling and reuse, while not as straightforward as materials like steel or aluminium, are still possible [16]. Wood can be repurposed into lower-quality products, used as biomass for energy production or in applications such as wood chipboard and mulch. As landfill taxes increase, the recycling and reuse rates for wood are expected to improve [17]. Engineered bamboo is also a promising material with sustainability potential, capable of replacing traditional cladding and structural materials in construction [18].

The concept of "off-site construction" is a noteworthy technique from a CE perspective. It involves planning, designing, fabricating and assembling building elements at the installation site, with the aim of minimal waste and efficient utilisation of resources [17].

The increased use of wood in construction presents challenges, such as the need for larger, longer-growing trees, land availability for planting, and the imperative for public policy interventions that will accelerate the transition to a CE [19]. Additionally, changing social perceptions and accelerating the development of mass wood construction are crucial to industry growth and environmental benefits.

Masonry

Masonry, the age-old technique of building structures with materials such as bricks and stone, has evolved into a technology that plays an important role in modern construction. Sustainable practices in Masonry construction go beyond recycling and carbon-free materials; they encompass the entire lifetime energy consumption of products. Although bricks are durable and can last for centuries with proper maintenance, they also present environmental challenges at various stages of their production [20].

The environmental drawbacks of traditional bricks include high water and energy consumption, substantial GHG emissions during the firing process, inadequate raw material management leading to soil degradation, brittleness that requires additional materials, and excess solid waste generation.

To address these issues and promote more ecological alternatives, innovative approaches in masonry are emerging: (i) Masonry with Waste—The application of industrial or agricultural by-products such as rice husk ash, fly ash, or slag to create bricks or mortar with a lower carbon footprint and greater durability; and (ii) Light Masonry—Incorporates aerated or porous materials to reduce the weight and density of units, saving resources, transportation costs, and improving thermal and acoustic insulation.

To improve brick sustainability, various strategies can be implemented:

(1) Use alternative energy sources or waste materials for production, significantly reducing the environmental impact [21].
(2) Reduce the size and weight of bricks to conserve resources and reduce transportation costs.
(3) Incorporate additives or coatings to enhance performance and durability.
(4) Develop new types of brick, such as biobased or recycled bricks, to create more sustainable options.

Furthermore, research and innovation are paving the way for the development of groundbreaking technologies to make bricks eco-friendlier and more functional, aligning with CE principles:

(1) Hollow Bricks: Made from clay or concrete and can incorporate recycled waste materials such as coal ash or rice husks. Their thermal insulation properties reduce heating and cooling energy consumption in buildings.
(2) K-Briq: Made from 90% construction waste, it does not require firing in a kiln, cement, or mortar for laying. It can reduce carbon emissions from brick production by up to 90%.
(3) Biomineralised Brick: Grown from bacteria and CO_2 using photosynthesis and calcium carbonate, this self-replicating material can be repaired, extending its use lifespan.

(4) Air Purifier Brick: Designed to filter pollutants and dust using a cyclone filtration system and a microalgae liner to capture and store contaminants. Its porous concrete block design enhances airflow.

The use of salvaged bricks, while sustainable, faces challenges related to standardisation and verification of strength, safety, and durability [22]. Legislation in some EU countries is moving towards reducing construction and demolition waste sent to landfills. However, the construction industry is slow to adapt, and legislative changes often lag behind innovative practices and materials.

Additive Manufacturing

Additive manufacturing (AM), more commonly known as 3D printing, is a critical component of Industry 4.0, contributing to the realisation of the CE. This technology involves creating objects layer by layer from digital design data, resulting in minimal material waste. Although AM offers substantial benefits, its adoption in the construction industry lags behind other sectors. AM reduces material waste and energy consumption by using only the necessary amount of material, enabling the closed-loop production of products through the use of recycled materials. The main steps in the AM process include modelling, converting 3D models into executable procedures for 3D printers, actual printing, and post-processing [23].

There are three primary methods in AM related to construction: extrusion, powder bonding, and additive welding, each with its materials and challenges. Cement-based materials are commonly studied for additive construction and often involve a combination of bulk materials, binders, and chemical additives.

Polymers and metals are also explored in AM construction, with various materials like photosensitive resin, nylon, elastomers, and wax for polymers and metals for metal structures. The potential for AM to impact sustainability by 2025 includes reduced production costs, energy consumption, and CO_2 emissions by approximately 5% [24].

AM contributes to the CE by reducing material waste, energy consumption, and transport costs, extending product lifecycles, and offering innovative on-demand products and services and unique one-off components. Challenges in AM sustainability include understanding the AM lifecycle, adapting Design for the Environment (DfE) to Design for AM (DfAM), improving material recycling, addressing intellectual property concerns, and exploring hidden costs [25].

Barriers in the construction sector include the cost of AM machines, customisation expenses, size limitations, post-processing requirements, and material properties [26]. Despite these challenges, there is growing interest and investment in AM in construction, with the development of materials, processes, design strategies and applications, as well as the emergence of large-format 3D printing machines [27].

To realise the sustainability potential of AM in construction, standardisation in materials, layer bonding, and structural design is crucial, along with a focus on resource efficiency and environmental sustainability [26]. AM adoption within the CE model promises to streamline localised value chains, increase resource efficiency, include recycled materials, and reduce transportation costs.

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Chapter 3
Energy Systems and Building Services Level

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Abstract Research and technological developments have mainly focused on increasing the energy efficiency of buildings, improving the thermal properties of the envelope and reducing energy consumption. Another critical issue is related to waste reduction and implementation of circular economy frameworks. Moreover, building services have a significant impact upon the health of users and any application of the circular economy has to consider the effect on the occupants' well-being. In this chapter, two aspects are considered: the first relates to the building systems which utilise energy for heating, cooling, ventilation, electrical supply; the second concerns the systems converting the energy from the sun, wind, and soil. Regarding the usage of energy in buildings, the types of materials applied in building services are categorised including metals, plastics, electronic components, etc. The barriers to the adoption of circular supply chain management are illustrated collecting information from the literature, especially in the air conditioning sector. Then, the electricity and thermal energy production from renewable sources are presented in the light of implementing a circular economy at the building and urban scale. Solar, both PV and thermal, wind, and geothermal technologies are illustrated in terms of trends in installation and prediction of waste production. Best practices of recycling are illustrated from projects, industrial processes, and companies. The collected information highlights the need for closer collaboration between the involved stakeholders, starting from the citizens and extending to all members of the design, construction, and building management professions.

Keywords Circular economy · Building energy services · MEP · Solar panels · Wind energy · Geothermal energy

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3.1 Introduction

Energy systems in and supplying buildings are an integral part of achieving a circular economy. Energy is a significant enabler and is essential if buildings are to deliver comfortable and healthy indoor environments.

The generation of electricity through the conversion of various energy streams is outside the remit of this book, however, the move from finite fossil and fission fuels, which require materials being 'won' from the earth's crust to the rise of renewable energy sources from sun, wind and water, aligns with circular economy principles. This reduces the release of greenhouse gases, the growth of which in the atmosphere is leading to climate change and the disruption of traditional circular agricultural processes.

There are two aspects related to the implementation of circular principles to energy systems and buildings, the first are the systems which utilise energy in the building for heating, cooling, ventilation, electrical supply distribution systems. The second is the circularity of the systems which convert the energy from the sun, wind and water.

It should be noted that when discussing building services this also includes public health systems in buildings such as sanitary waste disposal systems. While not directly related to energy, they fall within the design remit of the building service engineer, and so are grouped with space and hot water heating, cooling, ventilation and electrical supply.

Communication cabling, building security and protection systems and building transportation systems are also subsets of building services engineering, but due to space are not considered in this chapter.

3.2 Building Services Engineering

Building Services Engineering encompasses the design, installation and maintenance of the systems which make buildings habitable and comfortable. This includes heating, ventilation, air conditioning, lighting, hot water and sanitation systems. Sometimes this area is referred to as MEP (Mechanical, Electrical and Public Health Engineering).

Brand [1] describes a building as a series of layers. The services form a layer within the structure, see Fig. 3.1.

The building services can have a significant impact upon the health of building users, as evidenced by the rise of sick building syndrome, legionnaires disease [2]. Hence any application of the circular economy to building services has to consider the impact upon the occupants' health and well-being [3].

Such systems are integral to the construction of a building, but often separate from the structure, with projected lifetimes often less than the building itself. For example, a gas boiler may have a design life of 20 years, while a slate or concrete tiled roof

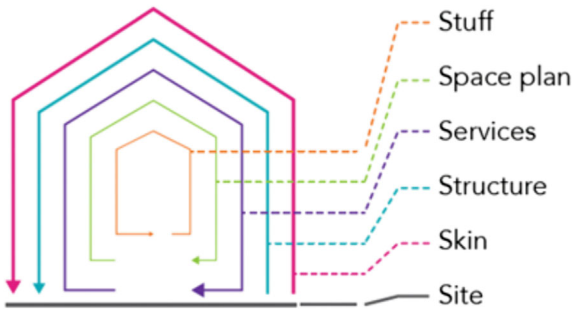

Fig. 3.1 Building in layers [1]

may have a lifetime of 60 years but survive significantly longer without maintenance. Often the building services are replaced several times in a building's lifetime. This can result in the building services having the largest overall embodied energy within a building over its lifetime, while for some aspects such as sanitary systems, their end-of-life value is considered negligible. Hence the potential for achieving circularity within building services is critical for future resource use and material sustainability. However, it can also pose the greater barriers with advanced technologies such as photovoltaics and LED lighting.

3.2.1 Energy Efficiency and Energy Sources

Considerable research and technological developments have been undertaken to improve the energy efficiency of buildings since the oil crises of the 1970s. There have been two aspects of this, the first is improvements to the building fabric to reduce heat loss and overheating, though the latter continues to be a problem. The second aspect is the improved energy performance of heating, cooling and ventilation systems. Both aspects have led to a reduction in energy consumption, however, this has been partly offset by increased energy use in buildings in Brand's 'stuff' layer. The largest improvements have been in lighting, initially with the adoption of fluorescent lighting technology, and since 2010, the introduction of the white LED. In 2000 lighting represented 10% of UK domestic building energy use, in 2023 that was around 3%. Alongside energy efficiency, the oil crises led the western world to initiate research into alternatives to oil-based energy sources. With the rise in awareness of climate change resulting from carbon emissions there is currently a shift to non-fossil fuel energy sources.

3.2.2 Waste and Water Management

Other initiatives to reduce waste in buildings have included water management. Low flow systems and grey water use are useful in reducing water demand. Reducing water demand and sewage throughput reduces energy costs for public sanitation authorities, plus reduces the stress on the environment in providing water sources or coping with treated water outflows. However, low flow sewage systems need to be installed correctly otherwise there are un-intended consequences [4].

In the UK it is estimated that 10–15% of building material is wasted during construction, while 54% of demolition materials are sent to a landfill. In Australia, construction and demolition waste makes up 40% of total waste generation [5], while the authors of [6] estimates that for the EU it is 35%. Current estimates suggest that most materials are unsuitable for reuse as containing toxic elements, so end up in landfill.

3.2.3 Building Services—Materials, Use and Reuse

The types of materials used in building services include metals (such as copper, aluminium, steel, iron), plastics, electronic components, etc. Most of these materials are readily convertible so may be remade into other materials. For example, copper is already extracted from buildings undergoing demolition for recycling, as to the high cost of the raw material makes material recovery economically viable. However, the circular economy assessment must commence with extending the life of a component or potential use elsewhere, thereby maintaining a high value for longer. That copper wire is melted down, instead of being reused as copper wire. There may be good reason for this, health and safety of installers and electrical system users is at the heart of electrical design principles, see for example British Standard 7671—Requirements for Electrical Installations. Due to the product cycle of building services equipment being considerably shorter than the rest of the building, there is significant opportunities and sustainability advantages through the adoption of circularity. However, MEP equipment can also be complex. Large plant such as heat pumps and chillers are constructed from many smaller components that are difficult to break down, components have plastic as well as metal parts and may also have coatings to protect surfaces from corrosion.

Within the UK and Ireland, the Chartered Institution of Building Services Engineers (CIBSE) is leading the review and development of Circularity within Building Services Engineering. TM56: Resource efficiency of building services [7] is a technical memorandum covering material use. In 2019, a research agenda was commissioned to consider circularity in the profession, using a University College London (UCL) building. The targets set included avoiding early obsolescence of installations through futureproofing, addressing performance gap issues between design and as built and overcoming initial cost barriers for equipment which gave better life-time performance. Digital technology was also seen as unlocking potential by tracking material flows. In the UCL project the whole life cost and carbon reductions were used to demonstrate the benefit of a circular approach to the building services installation. The project concluded that each project is unique, and each lends itself to different approaches and solutions, while consideration of the maintenance strategy is important in the design stages.

Poppelwell et al. [8] concluded that early engagement of everyone in the value chain was essential, and the adoption of a total expenditure (TOTEX) approach to funding projects was required. They also highlighted the need for close collaboration and open communication between all members of the design, construction and building management team. This would require an evolution of the industry. They proposed five scenarios for facilitating circular building services:

1. Joint Venture
2. Universal building
3. Passive
4. Pre-loved
5. Recover.

The **Joint Venture** is where all the stakeholders in a building—from client to parts suppliers operate under a single financial umbrella. By doing this, the incentives for everyone involved is aligned to optimising the performance. This requires a 'product as a service' approach to systems, with performance being what is paid for instead of design and equipment.

In the **Universal Building** the building uses are defined, and during the design account is taken of the most onerous use that the building may be put to. This allows for easy or simple adaption to meet a change of use. Installations are designed to last as long as possible. This also requires a building to be defined in terms of the type of building it cannot become. There can sometimes be arguments in terms of capital expenditure (CAPEX) versus operational expenditure (OPEX). It requires the market to recognise this future flexibility.

Marks and Spencer, a UK retailer of food and clothing, took such an approach when building a new store near Manchester. The Cheshire Oaks store was designed and constructed with sustainability at the forefront of all decisions. Amongst the goals they set was a zero-waste policy during construction, but most importantly the building was designed so that if it no longer suited the company to use it as a store, it could be converted into other uses.

The **Passive** building's focus is to reduce if not eliminate the active MEP systems and instead use natural ventilation, maximising daylight, and passive shading techniques. Such buildings can be unique and make them difficult to convert. One such example was the Sainsburys supermarket, in Greenwich, London. It was the first retail building to achieve a BREEAM Excellent rating and received plaudits for both its sustainability credentials and architecture, being nominated for the Stirling Prize [9]. It was demolished only 17 years after it was constructed. Sainburys moved out because it was impossible to enlarge the store, instead a new store was constructed nearby. Nobody came forward to use the store as was, instead the building was demolished to make way for a large flat pack furniture warehouse. This demonstrates that when developers decide to construct a passive building, the length of its occupancy is considered, so that it does not become a stranded asset. The failing of this supermarket building was the uniqueness of the design solutions to achieve a low energy passive building which did not translate to other uses.

The **Pre-loved Building** seeks to reuse equipment no longer needed in other buildings, and then ensuring that equipment and components can be recycled at EoL.

Finally, **Recover** where the MEP plant is designed to use considerably fewer resources, and waste from plant is eliminated. An example of this can be found in Victoria Square, Belfast, where waste heat ejected from the cooling equipment is used to heat the floor slab in the outdoor food seating areas.

In 2021, CIBSE published TM66: Creating a circular economy in the lighting industry [10]. Authored by design consultants, lighting consultants, industrial designers, and representatives from lighting manufacturers. It acknowledged that considerable gains had been made since 2010 regarding in-use lighting energy efficiency, especially through the adoption of LEDs. However, there have been unintended consequences such as the unmaintainable luminaire with no ability to replace the light source if it fails. The capacitors in the light source driver have been identified as the component most likely to fail, giving a mean lifetime of 5–10 years, with the unit only useful for recycling at best. Also, the speed of development of LEDs has led to short product life cycles and hence it is difficult to get spare parts, or components are not backwards compatible. Hence this technical memorandum set out to establish checklists as means of assessment a product's circularity. It also provided real-world examples of good practice.

Alongside this publication, CIBSE launched the Circular Economy Assessment Method (CEAM). Its objective is "… to is to give information to all, enable supply push by creating a 'nuts and bolts' tool for manufacturers, and to stimulate demand by giving specifiers and clients the questions they need to ask" [10]. It contains two Excel based tools. The first is CEAM-Make which allows manufacturers to assess the performance of their luminaire and the supporting ecosystem. The second tool, CEAM-Specify, is to support specifiers when seeking to identify equipment, a bit like a briefing list of the questions to ask a manufacturer.

The UK's Green Building Council (UKGBC) have created a Circular Economy Forum. They are investigating current circular economy metrics. While these apply to the wider construction industry, they have relevance for building services. They have narrowed published research to seven metrics:

1. Dematerialisation (Upfront), kg m^{-2} GIA
2. Dematerialisation (Life Cycle), kg m^{-2} GIA
3. Design for Disassembly and Re-use, % (tonnes)
4. Material:

    a. Re-used % (tonnes)
    b. Remanufactured % (tonnes)

   c. Recycled % (tonnes)

5. Material Database and Passport % (tonnes)
6. Design for adaptability % (Area)
7. Embodied Carbon (kg CO_2 e m^{-2} GIA).

The metrics were chosen so that incremental as well as absolute circularity of projects could be measured. They proposed that the metrics are reported according to the layers of a building as defined by Brand [1], see Fig. 3.1. They did this because there tends to be a discipline lead for each layer and the related supply chains, each layer is aligned with the Royal Institute of Chartered Surveyors (RICS) Whole Life Carbon Assessment [11], and each layer tends to have different design lives [12].

In Sweden, Climecon [13] have implemented descriptions to help specifiers adopt circular economy principles when choosing equipment. They have adopted wool instead of plastic for their acoustical attenuation systems. Outside systems have been coated to improve their life-time and protect from corrosion, with UV-resistance plastics used to reduce the need for replacement. Chen et al. [14] undertook a review of papers on life cycle analysis (LCA) and the circular economy in construction. They looked at various techniques such as lean construction. They proposed applying building information modelling (BIM) to enhance the information exchange and decision-making processes. They concluded that LCA is critical to validate the potential of recycled and reused materials regarding their environmental impact and mechanical properties.

The authors of [15] examined barriers to the adoption of circular supply chain management (CSCM) in the air conditioning sector. CSCM is a process used to design the supply chain by recycling, remanufacturing or refurbishing, repairing, and reusing products. Through a literature review and interviews they identified six main barriers and 21 sub-barriers which were rated by an Analytical Hierarchy Process (AHP) method.

Their ranking of the barriers is from most to least critical was:

1. "Regulatory" barriers, primarily insufficient environmental laws
2. The high cost of circular supply chain management
3. Market competition limiting CSCM adoption
4. Obligations to comply with refrigeration gas regulations
5. A lack of tax breaks when using CSCM
6. "Operational" barriers.

Their overall conclusion was that the legal issues are the greatest barrier to CE adoption in the air conditioning industry. Mohebbi et al. [16] investigated cradle-to-grave carbon assessment of a typical UK supermarket, as the use of refrigerators and other appliances represents a suitable field for the implementation of CE principles. They point out that the use of circular economy methodologies is an appropriate solution for managing waste from electrical and electronic equipment (WEEE).

3.3 Energy Transition and Circular Economy

The Nearly Zero Energy Buildings (NZEB) concept is a real solution to reduce energy consumption, promote energy transition and decarbonization of the constructions sector according to the Energy Performance of Buildings Directive [17]. The use of renewable energy systems contributes to achieving net positive energy balance of buildings and can also promote circular material flows if well planned and harmonised. On the other hand, pivotal technologies to the energy transition, such as wind farms and PV systems, still utilise raw materials from natural resources instead from processing of waste. Well experienced EoL management strategies are not developed for these materials and components, and renewable energy manufacturing could encounter a significant reduction of metal reserves [18]. The electricity and thermal energy production from renewable sources are presented in the following sections in the light of implementing a circular economy at the building and city scale. Solar, both PV and thermal, wind, and geothermal technology are illustrated in terms of trend in installation and prediction of materials usage and recycling.

3.3.1 Photovoltaic—Trend in Installation

Photovoltaic (PV) technology is recognised as one of the most promising solutions for contrasting climate change and improving energy security. The diffusion of PV systems recorded a constant growing as reported by the International Energy Agency (IEA), from 4 GW in 2005 to 100 GW in 2012, and 942 GW in 2021 [19]. China dominates with a cumulative capacity of 308 GW, followed by the European Union (179 GW), the USA (123 GW), Japan (78 GW), India (60 GW), Australia reached (25 GW), and Korea (22 GW).

In the European Union (EU), Germany leads with 59 GW, followed by Italy (23 GW), Spain (19 GW), France (14 GW), and the Netherlands (13 GW). In 2022 Europe continued the increasing trend with 39 GW installed, led by Spain (8 GW), Germany (8 GW), Poland (5 GW) and the Netherlands (4 GW). High electricity market prices have reinforced the competitiveness of PV and several countries have acted policies to further accelerate PV installations. On the contrary, other countries reduced supports for this technology because of grid congestion.

It is expected that countries with the most ambitious PV targets will have the largest shares of PV waste in the future. The IRENA–IEAPVPS report [20] outlines that by 2030 the top three countries, for cumulative projected PV waste, will be China, Germany, and Japan. The accumulative global PV panels at EoL is predicted to reach 1.7–8 million tonnes by 2030 and 60–78 million tonnes by 2050. Only the European Union (EU) has adopted PV-specific waste regulations at the time of writing (2024). In the rest of the world, most countries classify PVs as general or industrial waste. The EU has pioneered PV electronic waste (e-waste) regulations including PV-specific collection, recovery and recycling targets. Based on the extended-producer responsibility principle, the EU Waste Electrical and Electronic Equipment Directive [21] requires all producers supplying PV panels to the EU market (wherever their manufacturing be based) to finance the costs of collecting and recycling EoL PVs in EU market. This experience can offer useful examples of how EoL management can be a positive component in the PV value chain [20]. The recovered material can be used to produce new PV panels or be sold into global commodity markets. It is predicted (2016) that PV panels could produce a value of up to US$ 450 million by 2030. This is equivalent to the amount of raw materials necessary to produce about 60 million new panels. By 2050, the recoverable value could reach US$ 15 billion, corresponding to 2 billion panels.

Type of PV collectors and materials. A PV panel is a combination of PV modules that convert the solar radiation in electrical current. A PV module consists of solar cells, which are the smallest generating units. A solar cell is mainly made by doping semiconductor materials like Silicon (Si) and Cadmium (Cd) [22]. PV panels are wired in series, like DC batteries, this is referred to as a string and these are mounted in panels. Figure 3.2 shows the diffusion into the market of the different PV types. The first-generation PV technologies have reached commercial maturity. Copper indium gallium selenide (CIGS or CIS) technology have just entered the market, while the cadmium telluride (CdTe) technology has reached the market penetration stage. The recent technologies are still under investigation and further research is needed to enter the market commercially.

In 2021, Europe contributed to the total cumulative PV installations for almost 22%. Si-wafer based PVs accounted for more than 95% of the total production, and mono-crystalline PVs represented about 84% of total crystalline Si manufacturing [23].

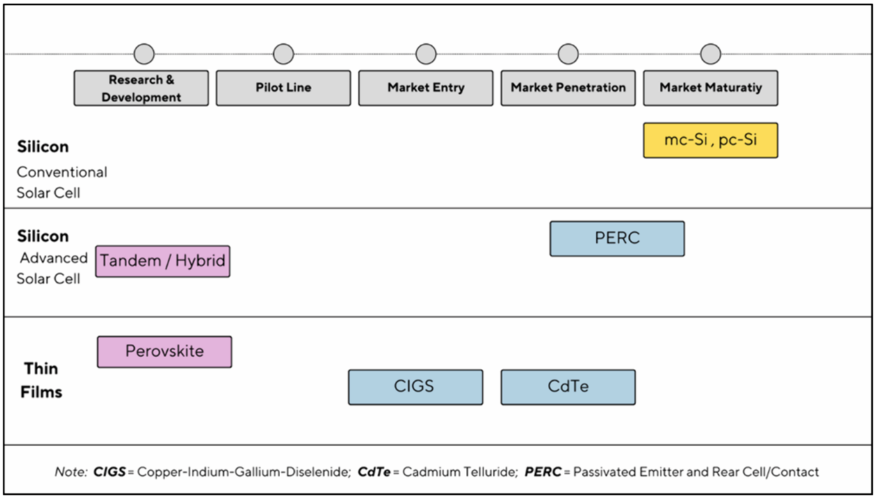

Fig. 3.2 Solar PV technology status. *Source* IRENA [24]

A PV module is expected to have an average lifetime of 30 years, but some of them can be considered waste in earlier stages for diverse reasons: optical failure, power loss, defect in junction-box, glass breakage, interconnection defects, delamination, and damages during transportation [22]. The DC-AC inverter can also fail and need replaced before the PV string requires replacing.

Crystalline silicon photovoltaics require silver, quartz, copper, metallurgical silicon, aluminium, and tin. Photovoltaic thin-films made of CdTe require tellurium, cadmium, molybdenum, or tin. Thin-films made from CIGS require copper, indium, gallium, selenium, cadmium, tin, or zinc depending on the buffer layer used. Perovskites PV cells depend on the calcium titanium oxide mineral, lead and tin compounds.

Recovered materials from EoL photovoltaic includes glass cullet, silicon wafers and granulates, silver, indium, tin, molybdenum, nickel, zinc, copper, aluminium, steel, tellurium, cadmium, selenium, gallium, ruthenium, and plastic components. PV panels can also be used as a source of smelter flux [18].

End of life of PV panels. PV collectors are designed to minimise the moisture that can come in contact with the solar cells and standard c-Si modules are bonded using two layers of ethylene vinyl acetate (EVA). This technical solution makes solar modules recycling a complex process [25]. The Ostfalia University of Applied Sciences (Germany) has proposed a guideline highlighting problematic aspects in module design: irreversible fixing of the frame, scarce recyclability of the junction boxes, inclusion of toxic materials such as lead, an ample variety of materials, and the fusion of wafers with EVA.

The separation of the glazed cover and backsheet from the PV cells is still a critical task. A popular strategy to free the cells from encapsulation is incineration, that is an energy-intensive process emitting dangerous gases such as hydrogen fluoride (HF), fluoroacetate and furans (C_4H_4O) due to the burning of fluorinated polymer [26]. PV Cycle (2007) created a process commercially available in the European market for recycling mono or multi crystalline silicon modules that starts from the separation of the aluminium frame and the junction boxes. A secondary step is the mechanical process for the extraction of the remaining materials, such as glass. It is a downcycling process that provides about the 80% of recovered materials. Thin film processes are under development in Italy, Japan, and South Korea, but the costs are still expensive. In fact, 90% recovery of materials is not sufficient considering the initial production costs [25].

Moreover, studies show that the impurity level is another crucial issue in recycling. Pre-treatments (physical, chemical, thermal, and hybrid) play a key role in impurity removal and metal recovery. Other problems are the uniform collection, the efficiency in recovery processes, and energy-saving. Comparing different types of PV, those in Si crystals are the ones that possess high economic value. One ton of mixed PVs (first and second generation) can produce about 9.32 kg of Cu, 0.30 kg of Ag, 33.48 kg of Si, 1.12 kg of Sn, 1.12 kg of Pb, 4.9 g of Cd, 2.5 g of Te, and 3.4 g of In [27].

In the UK, RecycleSolar [28] uses physical and chemical processes on EoL PV. The metal frame is removed first along with the electrical connections. The panels are then shredded and crushed to break the lamination bonds. An acid leach is then used to recover the semiconductor films from the glass, and physical processes separate the glass from the EVA. The metal compounds are precipitated using increasing levels of pH, and the various materials are collected. The process can recover material suitable for processing into semiconductor grade raw material for use in the manufacturing of new PV. They claim to recover 90% of the glass and 95% of the semiconductor layers. They also recycle the inverters.

Environmental, economic, and social impacts of a circular economy for PV. There are opportunities and challenges related to PV recycling processes. Several studies have analysed the impacts of PV recycling on the environment [25].

An investigation conducted in The European Full Recovery End-of-Life Photovoltaic [29] project, for instance, showed that environmental impacts from c-Si recycling processes come from plastic incineration and chemical and mechanical treatments for the recovery of metals.

On the other hand, PV Cycle [30] highlighted a significant decrease in Global Warming Potential impact compared to the process of making cells. Moreover, an environmental benefit can be obtained from the glass and copper recycling for CdTe modules.

Other studies found that the environmental effects related to the recycling process are lower than for landfill, if the recycled resources are used in modules manufacturing. Overall, recycling of PV modules retain harmful substances (e.g. lead, cadmium, and selenium), recover rare materials (e.g. silver, tellurium, and indium) and make them available to the market for future applications.

A positive social impact of PV recycling is reflected by its potential to create new job positions. In fact, according to the report of the European Commission, if all residential and commercial PVs are collected, pre-treated, and recycled in Europe, it would create 20,000 jobs by the 2050.

The EU has promoted several projects in synergy with the various solar waste recycling companies scattered across its territory. The Ramp-PV project (2020–2022) [31] was coordinated by the French company ROSI [32]. Another project that has received funding from the European Institute of Innovation and Technology (EIT) is the ReSiELP (2017–2020) [33] that includes 8 companies and several European research institutes including the French CEA with the lead role, ENEA, CETMA, Relight SRL ITO srl, the university of Padova in Italy, MAGY and Bay Zoltan Nonprofit Ltd in Hungary, PROJEKTkompetenz.eu in Germany. The goal of ReSiELP is to bring together technologies from different fields with the aim of recovering critical and valuable raw materials also present in PV waste through innovative technologies based on the concept of circular economy aiming for a zero-waste approach [34].

The project is based on three pillars:

1. The recovery of EoL modules;
2. The reuse of silicon after the purification stage;
3. The reuse of glass for the development of building materials.

Recovered materials are fed back into various production systems, except for copper, aluminium and silver which are directly sold, recovered glass is incorporated into mortars and concretes and then tested with the aim of producing environmentally sustainable solutions, while silicon is processed to generate high-quality solar silicon so that it can be reintroduced into the photovoltaic chain and thus become a closed loop. The PHOTORAMA project [35] is a three-year EU-funded project (2021–2024) with the goal of mapping out a circular and sustainable chain to have a carbon-neutral photovoltaic industry, and develop, recycle and recover useful materials from photovoltaic panels. Figure 3.3 represents the distribution of the European companies.

The list of the companies' website follows:

Italy

https://www.9tech.it/.

https://www.compton-industriale.it/index.html.

https://www.frelp.info/chi-siamo/.

France

https://www.veolia.com/en/veolia-group/profile.

https://www.rosi-solar.com/kerf-recycling/.

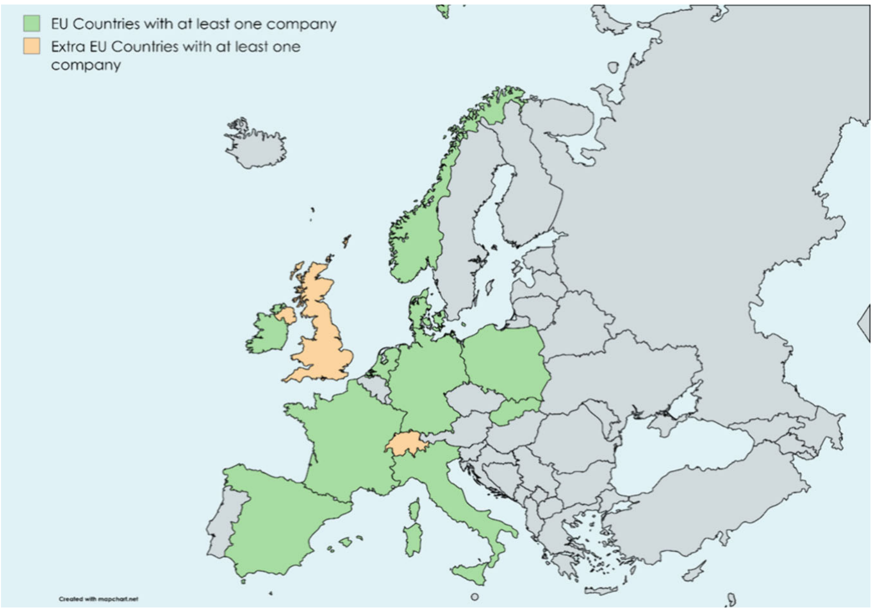

Fig. 3.3 Location of solar waste recycling companies in Europe

Germany

https://www.antec.solar/de_DE/turnkey-anlagen/.

Slovakia

https://aerisoul.com/.

Denmark

https://orsted.com/en/who-we-are/sustainability/nature/circular-resource-use.

Poland

https://jamko.eu/recykling-modulow-fotowoltaicznych/.

The Netherlands

https://www.rinovasol.de/unternehmensgruppe.

Ireland

https://recyclesolar.ie/.

https://www.purevolt.ie/resources/solar/solar-panel-recycling.php#intro.

Norway

https://www.sintef.no/en/sintef-research-areas/solar/.

Spain

http://solucciona.com/solrecycle/.

Swiss

https://immark.ch/de/unternehmen/prozesse.

http://www.kwbplanreal.ch/index.php?type=web&lang=de&show=315&mhs=0.

https://www.erecycling.ch/it/sens.html.

United Kingdom

https://www.hnhpro.co.uk/solar.

https://www.recyclesolar.co.uk/.

3.3.2 Wind Energy—Installation Trend and Materials

The wind turbines market is constantly in evolution and its expansion entails a growing installation with a consequent increase in waste. About 36,000 blades in Europe are expected to be dismantled by 2025, which corresponds to 240,000 tonnes of polymer composite waste [36].

Turbines components are also made of concrete, stainless, high-grade steel, cast iron, thermoplastics, rare earth elements (REEs), copper, zinc, aluminium, silver, and gold [18]. Blades include composite material, and their recycling is still costly and without high volume recycling solutions. Using blades in a second life construction is a solution that is gaining in popularity, but it presents problems such as: a sensed lower quality of used materials and of their structural properties, scarcity of end markets, unfamiliarity with recycled products and doubts about the environmental benefits of repurposing [37]. Moreover, wind turbines use rare earth components that are on the verge of depletion and their recovery could be of significant importance. The materials that make up a wind turbine are different and their quantities depend on the type of turbine, and manufacturer. According to Jensen [38, 39] the components and materials of a wind turbine can be represented in Table 3.1.

Considering a 60 MW turbine, the quantities expressed in kg of potentially recyclable materials are summarised in Table 3.2.

According to the American Chemical Society, nine elements are in serious threat of extinction in the next 100 years, seven are in rising threat from increasing use, and 28 are in future risk of supply [40]. Moreover, the JRC Science for policy report (2020) explains the important role of REEs in wind energy [41]. An analysis of future balances supply/demand is useful to understand the high and low demand scenarios and the maximum expected recycling inputs based on current recycling input rates of some REE used in the wind turbines like Neodymium, Praseodymium and Dysprosium (see Fig. 3.4).

Future scenarios for the production of waste material from wind farms in Europe can be found in [42] considering four time snapshots:

- In 2020, the majority of the blades waste material is concentrated in the central east and North of Germany. Some regions in the central part of Spain also have a high amount of waste material.

Table 3.1 Turbine parts, materials, and potential disposal methods (an elaboration from Jensen [39])

Part of turbine	Main material(s)	EoL handling
Hub	Iron	Recycling (foundry)
Canopy	Glass fibre/epoxy or steel	Recycling, incineration or landfill
Nacelle	Steel, permanent magnets, PCB, batteries	Recycling (as filler), incineration or landfill
Platforms and ladders	Aluminium	Recycling (foundry)
Blades	Glass fibre, epoxy and balsa wood	Recycling (as filler), incineration or landfill
Cables and busbars	Plastic, copper and aluminium	Recycling (foundry)
Tower	Steel	Recycling (foundry)
Miscellaneous	Lubricants, grease, paint, rubber, plastic	Recycling, incineration or landfill

Table 3.2 Approximate recyclable materials from 60 MW wind turbines (an elaboration from Jensen et al. [38])

Material	Material quantity (kg)	% of material/Tot
Ferrous metal	6,560,000	
Aluminium	104,000	
Copper	292,000	
METALS	6,956,000	88
Polyethylene	32,000	
Polypropylene	6600	
Polyvinylchloride	6000	
POLYMERS	44,600	0.6
Electronics	124,000	
Batteries	36,000	
Balsa wood	29,000	
NdFeB Magnet	40,000	
Miscellaneous	–	
Others	229,000	3
Total	7,923,400	

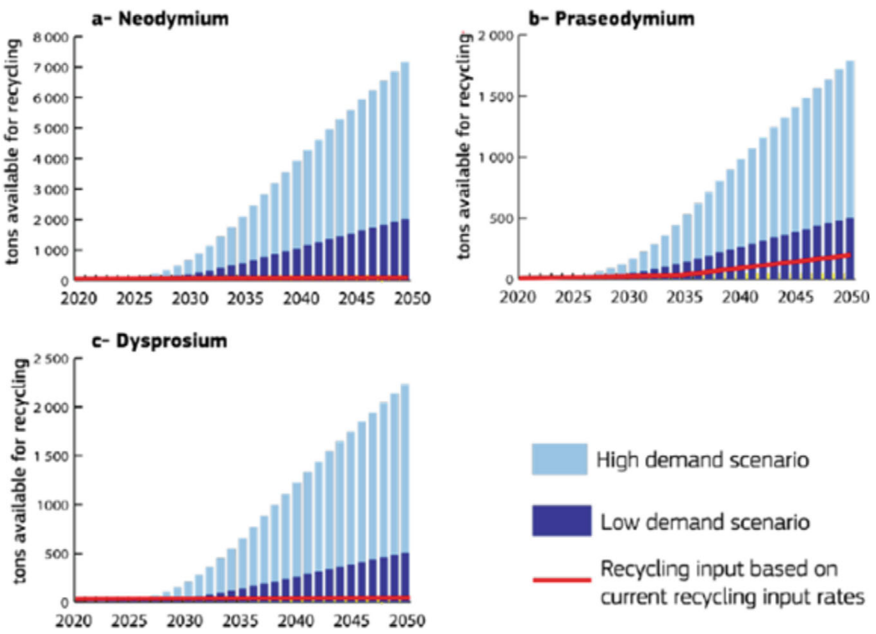

Fig. 3.4 Tonnes of **a** neodymium, **b** praseodymium and **c** dysprosium potentially available for recycling up to 2050 (EU-27 and the United Kingdom) and the maximum expected recycling inputs based on current recycling input rates. *Source* JRC [41]

- In 2030, the waste blade material increases around Europe. In particular, it will increase in the Northwest of Spain and in the North of France. Moreover, other countries such as Scotland, Ireland, Finland, Romania, and Sweden will experience an increment. Less intense hotspots could be observed in Poland, central Greece, Baltic regions and Southern Italy.
- In 2040, wind turbine waste increases in Spain, France, Finland and in central Greece.
- In 2050, a small increase of waste material hotspots is observed in the Bal-tic countries and in Northern UK, France, and Poland.

End of life of wind turbines. Blades are composite structure, consisting of various elements and materials: reinforcement fibres (glass, carbon, aramid or basalt) polymer matrix (thermosets such as epoxies, polyesters, vinyl esters, polyurethane or thermoplastics), sandwich core (balsa wood or foams, polyethylene terephthalate), coatings (polyethylene, polyurethane), metals (copper wiring, steel bolts) [38]. Different techniques for the treatment of waste deriving from wind turbines are proposed, such as: landfill and incineration or other finer treatments called secondary applications (mechanical recycling, thermal recycling, chemical recycling, co-processing). The methods of treating materials are described below.

Landfill is the most common disposal solution for decommissioned turbine blades. Landfill options are prohibited in some countries, such as Germany and the Netherlands. In fact, landfill is unsuitable in countries with long term prediction of restricted spaces, such as Ireland [43].

In secondary applications, we find recycling treatments of different nature such as: mechanical, thermal, chemical, and co-processing. Mechanical recycling involves cutting, shredding or grinding the material into smaller pieces to be included as aggregate in concrete or combined with resin to be made into panels.

Mechanical grinding can preserve some of the mechanical properties of the composite, but it often results in losses of polymer length and contamination for additives or other materials that leads to a lower polymer quality than the original.

Mechanical recycling has limits: plastics must be large enough to be treated, furthermore, in the shredding/melting phase some plastics have high temperature sensitivity and composite structures or thermosetting qualities that make treatment difficult [18, 37, 43]. Thermal recycling methods such as Pyrolysis or Fluidised Bed Combustion (FBC) require the use of high temperatures to recover resins, reinforced fibres and thermal energy [43]. Pyrolysis is not economically feasible for Glass Reinforced Polymer (GFRP) as recovered glass fibres can be degraded, instead raw materials are available at a low cost. The advantage is highlighted through a technical-economic evaluation which indicates that this process has lower environmental impacts than other treatments [37]. Chemical recycling consists in converting the material to be treated to its monomer state/lower molecular weight raw material and is used when mechanical recycling is not feasible. As an example, solvolysis is used to recover fibres from resins using solvent mixtures, or thermal, catalytic and biological deconstruction which are more commercially available processes [18, 43].

In co-processing, the material is mixed with other waste material and sent to a cement kiln where the shovel waste replaces a portion of the processing fuel and raw materials, the mechanical properties are destroyed impeding third life applications [37].

Recycling wind turbines in urban environment. This section describes case studies and projects concerning the recovery and reuse in urban environment of wind turbines, from blades to foundations. Turbines' components can be used for various purposes including commemorative installations, pedestrian and cycle bridges, noise barriers, construction site delimitation barriers, urban and domestic furniture and more. The ongoing experiences help people understand that decommissioned turbines are not only bulky and potentially toxic waste but opportunities for reducing the extraction of raw materials if a second life can be provided.

Wind turbine blades can be reused for the structural part of pedestrian, cycle, and vehicle bridges and recent studies have shown that disused wind turbines can support loads of 33 tonnes [44]. Bridges that use wind turbine blades as their primary load-carrying structural members are investigated in the project "Re-wind Network blade repurposing solutions" [45]. Bridges have variable length spans between 5 and 23 m and variable widths between 3 and 6 m. Four blade models were considered: N29 (Nordex), V44 (Vestas), GE37 (General Electric), C96 (Clipper). The wind turbine blades are typically placed on the sides or underneath the bridge deck that can be made of timber plank, poured-in-place concrete, precast concrete panel, steel grid, steel panel, FRP panel, or any proprietary decking system. According to Re-Wind Network, BladeBridges are durable, sustainable, and have a unique aesthetic as shown in the catalogues and websites [44, 45]. Two-girder BladeBridges are bridges supported by two blades along their facing in the same direction (symmetric) or in opposite directions (asymmetrical). Two BladeBridges were designed and constructed by the ReWind Network in 2022:

- In January, a two-girder BladeBridge was constructed on a greenway between Midleton and Youghal in County Cork, Ireland;
- In May, a two-girder experimental test bridge was constructed in a quarry in Draperstown, Northern Ireland, UK.

The Re-Wind Network BladePoles are wind blades repurposed as poles with diverse uses:

- power line poles;
- cell phone towers;
- lighting poles;
- sign support poles.

Depending on the size of the wind turbine blade, they can be used in urban or suburban neighbourhoods. Blades can also be used as cell-phone towers to replace the classic towers. Smaller blades can be used in urban and suburban neighbourhoods for new 5G cell-phone towers. The BladePoles have the advantage of being electromagnetically transparent and can host communication devices.

Barrier structures designed from wind blades can perform various uses:

- construction site boundary barriers: the objective is to prevent access to unauthorised people and avoid risks;
- noise barrier: reduce noise pollution and limit access alongside highways;
- traffic barrier (Jersey barrier).

The Re-Wind Network presented different types of construction site delimitation barriers. The first type is "Vertical full sections" that are wind turbine blades cut into regular or irregular strips. Sections can be arranged irregularly to create a variegated wall.

These constructions can also be used for wave and wind attenuating and sea-wall barriers of different design depending on the requirements, replacing timber or steel posts currently used to make construction barriers. The advantage of these barriers is that they can be reused many times. Moreover, arc-shaped segments cut from the large blades can be installed vertically or horizontally to create both highway and construction site barriers. Panels of irregular geometry conform to the urban context and can be covered with plants.

Some companies used turbines for noise attenuation barriers, such as the Danish company Miljøskærm [46] that builds barriers with a sound-absorbent material made of recycled fibreglass.

Superuse Studios Rotterdam [47] designed a new playground on a 1200 m^2 plot for the 'Children's Paradise Hawthorn' foundation. Five discarded wind turbine blades were placed around an existing concrete circle and used to create a maze-like space.

The municipality of Terneuzen in Oland commissioned Superuse Studios Rotterdam for an iconic playground built in 2016 [48]. Two wind turbine blades were cut, and some parts were placed lying down others standing up to create interior spaces to climb to the slide mouth.

Blades, nacelles, and hubs can be transformed into street, indoor, and garden furniture to serve households, schools, and offices.

These elements create an eye-catching and modern design such as in the examples that can be find on the websites:

https://projects.superuse-studios.com/projects/rewind-willemsplein/.
https://projects.superuse-studios.com/projects/rewind-willemsplein-lgbtqi/.
https://projects.superuse-studios.com/projects/rewind-oost-pier-terneuzen/.

Another successful experience is offered by GP Renewables Groups [49], a company that aims to make completely circular the wind energy technology.

Turbine blades are also used for a variety of purposes, such as bus and bike shade, canopies, roofing parking-lot. The initiatives involved companies, such as Siemens Gamesa Renewable Energy S.A. and Superuse Studio. The durable shelter design uses four 30 m rotor blades. Scrap rotor blades are easy to find in Almere. Two 30 m blades are used to create a large shelter and every part of the blade is used to make up the structure.

The installations can be found consulting:

https://www.energy-supply.dk/article/view/699757/.
https://re-use.eu/blade-made/.

Blades can also be used to build glamping pods. Small shelters utilise different sized blades and can be constructed in diverse configurations. Roofs can also be created either with a single curved piece and simulate a single pitched roof or simulate an almost flat roof by cutting the wind turbine blade into strips. Bus shelters can be made from sections of a wind turbine. The shape of blades allows water to flow out easily. Moreover, the material is durable offering a valid alternative to the traditional polycarbonate [45]. Circular or foldable tent and fencing are suitable for farmers or private landowners that would like to build a holiday glamping business. Sandwich panels were reused for a picnic table with two seats, mounted to two frames. The effect of the blade's curvature was explored using 1:20 scale models before the design phase and successive manufacturing [50].

3.3.3 *Thermal Solar Collectors*

In Europe, solar thermal systems (ST) technology and industry is well-established. Despite this favourable position in the market, ST installations have recorded a decline since 2010 due to less attractive incentives and the current economic crisis [51]. The trends of market take up and predictions for the solar thermal technologies from 2013 to 2030 are presented in Fig. 3.5. The main types of solar thermal collectors can be classified as glazed flat-plate solar collectors, unglazed solar collectors, and evacuated heat pipe solar collectors, with the latter having higher efficiency and complex technology. The variety of materials involved in ST systems is limited (mostly metals and glass), and recovery and recycling appear as possible alternatives to landfill or incineration [52].

Hybrid systems, photovoltaic and thermal PV/T, could be effective solutions to integrate renewable energy technologies in buildings based on solar energy [53]. Further developments of PV/T systems are necessary to improve efficiency

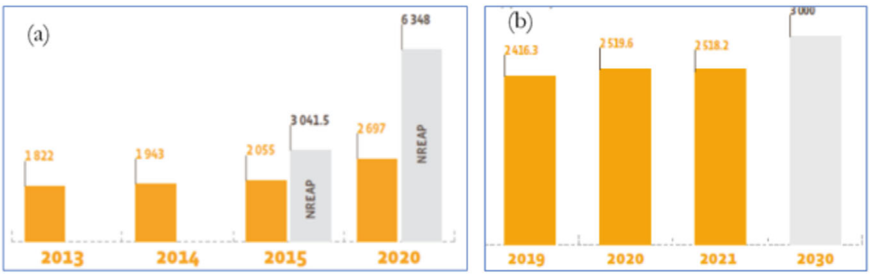

Fig. 3.5 **a** Comparison of the trend of thermal solar systems (in ktoe) from 2013 through 2015 and predictions against the NREAP (National Renewable Energy Action Plans) roadmap. *Source* EurObserv'ER [51]. **b** Comparison of the current trend and prediction for 2030. *Source* EurObserv'ER [57]

and reduce unit costs. As an example, different PV/T configurations have been investigated by simulation [54] or experimental approach [55].

In the light of a circular economy, the advantages of combining ST into PV panels were illustrated in [56]. The author suggests the integration in manufacturing and retrofitting of deployed panels, obtaining an extension of the productive life of PV and the increase of the performances of the heat production and storage, also using phase change materials.

3.3.4 Geothermal Energy—Trend in Installation

Geothermal energy is used for heating and cooling of buildings especially in North America and Europe [58]. The most reliable and detailed source of information comes from updates provided every five years by IGA-IRENA. Considering the most recent report [59], the countries that mostly use geothermal energy for heating and cooling are Indonesia, New Zealand, the Philippines, China, Turkey, Iceland, Japan, Hungary and the United States.

These countries have systems in operation for decades, others such as Belgium, Chile, Colombia, Croatia, Honduras and Hungary have recent plants and experience an early stage of development. About 88% of plants dedicated to district heating are located in China, Iceland, Turkey, France and Germany. Some territories, such as Iceland and the Azores archipelago (Portugal), have a high availability of geothermal resources and markets where demand for energy is low, therefore, demand is satisfied by installing low temperature geothermal plants. The electricity production from geothermal installation in European countries is shown in Fig. 3.6.

There are 10 plants installed in Germany and operate at low temperatures. In Iceland the first geothermal plant dates back to 1969, and there are currently eight installations with a total capacity of 754 MWe. In Italy, the first plant was constructed in 1995 and today there are some industrial plants in Tuscany Region. In Portugal, the plants are mostly installed in the Azores archipelago which provides 23% of the total electricity consumption of the islands. Other power plants are located in Belgium, Hungary, and Austria. Geothermal energy in Turkey has spread over the last ten years. In Croatia the first plant was installed in 2019, while very small plants are located in Romania. Overall, over the last 20 years, the growth of geothermal capacity in the Eurozone has occurred much more rapidly (with an average annual rate of 5.2%) compared to the rest of the world (3.2%).

The use of geothermal energy for heating and cooling is much more widespread in Europe than the use of geothermal for electricity production. The top five countries in the world that have installed geothermal capacity for heating and cooling are Iceland, Sweden, Finland, Switzerland and Norway. 90% of this geothermal energy produced is used to heat or cool buildings.

The use of heat pumps is also considered in other countries such as Germany and France. Turkey stands out in terms of geothermal cooling/heating used both in buildings and in recreational activities and heating of greenhouses with 3488 MWth installed. Other notable countries are: Slovenia with 31 plants (266 MWth), Greece with 25 plants (259 MWth), and Romania with 40 plants (245 MWth).

Materials for geothermal installations. The pipes used in geothermal heat exchangers (GHEs) can be made of conventional or innovative materials.

Figure 3.7 shows the percentages of the different types of conventional pipe materials applied in GHE. The most commonly used material is polyethylene (PE) followed by steel, but copper and polyvinyl chloride (PVC) are also used frequently. In smaller quantities, we have polybutylene (PB), polyurethane (PU), plastic and polypropylene (PP). PVC is better than steel because it is cheap, lightweight, easy to assemble and shapeable [60].

HDPE (high density polyethylene) is a material commonly used in Europe due to its convenience, corrosion resistance and cost. To decrease soil resistance during drilling and ensure good thermal efficiency, thermally improved thermoplastic polymers are used, namely combinations of PE or HPDE, where HPDE is thermally enhanced with carbon nanoparticles or with graphene or aluminum wires.

Mortar is used to ensure heat transfer between the geothermal heat exchanger and the soil. There are two types of mortars used as filling material in geothermal plants: conventional grout (bentonite and cement) and additive (to the mortar are added materials such as sand, graphite, aluminium chips or composite materials).

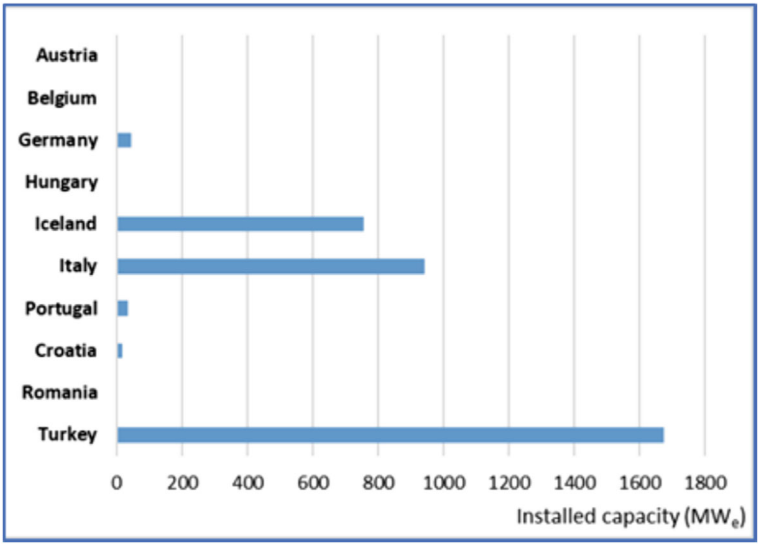

Fig. 3.6 Installed geothermal electricity capacity by country—2021. *Source* IRENA and IGA [59]

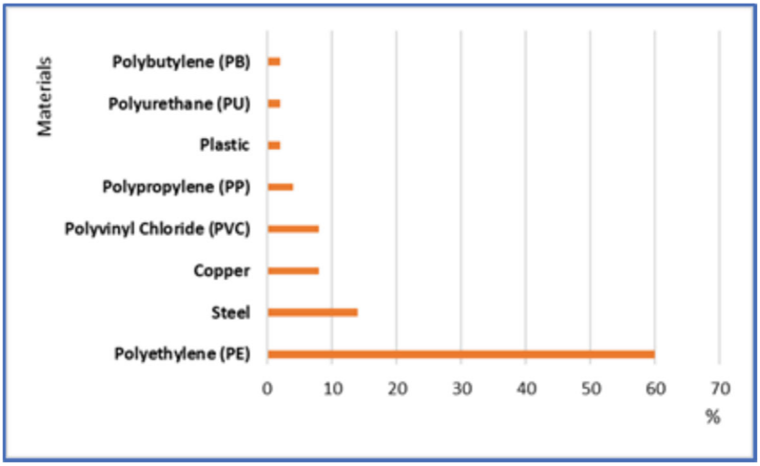

Fig. 3.7 Conventional pipe materials used in GHEs from 2010 to 2018 [61]

Phase change materials (PCMs) are rarely used despite offering the possibility to improve the thermal autonomy that affects the occupation of the soil, important in urban areas. The properties of PCMs are incremented using nanoparticles are incorporated, usually metals, metal oxides, and carbon-based particles.

Regarding the heat transfer fluid, R410A is the most widely used refrigerant in the field of heat pumps and air conditioning even if it needs to be replaced. Several authors in recent years have studied different mixtures and natural refrigerants (such as CO_2, ammonia, water, propane and isobutane) with the aim of increasing their thermal efficiency and reducing the environmental impact. Water is a good solution, but because of its low freezing point it is mixed with other compounds such as glycol, propylene glycol and ethylene [62].

End of Life of Geothermal plants. The authors of [63] proposed the "R strategy" as a guideline to implement the circular economy of geothermal plants:

- Reduce: hybrid systems that couple a geothermal plant with other renewable energy systems can increase efficiency and reduce the raw materials needed;
- Repair, Refurbish and Remanufacture: to extend the life of components through maintenance. Heat exchangers, pumps and condensers could be repaired by decreasing the downstream waste stream. Current literature, however, finds no cases of such activities;
- Repurpose: by converting abandoned wells (of oil or gas) or coal mines into geothermal plants. The conversion of these abandoned sites into geothermal plants are usually located in non-urban environments;
- Recycling: allows the input of waste materials into supply chains. In addition to the classic recyclable materials (steel and plastic), geothermal brine can also be recycled. It contains several elements such as lithium, lead and boron. These elements can be recovered from the geothermal fluid even if the major obstacle is

the costs associated with the recovery phase. If the heat transfer fluid is not brine, it can be recycled and used in heating systems;

- Recovery: it is based on the incineration of waste material to produce energy. In these materials, however, there are high concentrations of carbon, nitrogen, sulphur, heavy metals and other potentially toxic elements.

3.4 Conclusions

Many papers discuss the role of circular economy in the built environment, and particularly buildings, concentrating on the building as a whole and not on specific elements of the building, for example in [64, 65]. Some papers mention circular economy in their key words but neither mention circular economy or its principles in the text. From this it can be concluded that while there has been good research into the principles of circular economy in buildings around deconstruction and recovery, however, there is a need for focused research into the barriers that exist in achieving circularity in building services equipment. The current prediction that MEP services in buildings have the highest embodied carbon can be countered if circular economy principles are applied to the design, installation, use/maintenance and EoL principles. Potentialities and issues concerning the implementation of a circular economy for renewable energy technologies in buildings and cities were also highlighted. The production of electricity by PV and wind involves a large variety of material that can be recovered, reused and treated. PV systems, especially, require attention as the new generations of panels include rare metals with an elevate economic value. Despite this important aspect and the indications of the European Directives, suitable EoL strategies are still neglected in the design phase and at the EoL. Best practices can be found in some companies that tested new recycling processes targeted to reduce the environmental impacts, increment the quantity and quality of recoverable materials, and reuse of components (such as wind turbine blades) avoiding raw materials usage.

Scarce scientific literature and initiatives support the inclusion of solar thermal systems in the circular economy, despite of the significant usage of glass and metals. An extension of the productive life of solar systems could be obtained by PV/T panels. The literature on geothermal energy is lacking studies that analyse the circular economy contextualised to buildings and cities [63], this does not allow for an extensive knowledge. This shortage could be attributed to fewer urban scale geothermal plant installations.

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Chapter 4
Circular Manufacturing

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Abstract Circular Manufacturing (CM), understood as CE strategies adopted in manufacturing, takes a key position in decoupling industry growth from environmental impacts. To achieve a transition into circular economy in construction, a clear view on the state-of-the art is crucial. Construction materials such as concrete, cross-laminated timber or steel have an environmental impact during their production and circularity is not always given. Knowing that the design phase of a product defines a big part of its overall environmental footprint, this chapter discusses CM principles and most commonly pursued CM strategies for steel, concrete and timber. Effects and impacts on buildings and eventual challenges are discussed. Furthermore, Additive Manufacturing (AM), as a possible key driver of circularity is analysed. The

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reduction of material use is identified as key driver in order to reduce material flows, however structural safety and durability needs to be assured. The design and mixture of construction products and materials itself together with an efficient design process in the projects are essential pillars of CM. Prefabrication, modular construction as well as DfD and DfA are key principles that can be achieved with all the analysed construction materials but are more widespread in steel construction today.

Keywords Circular manufacturing · Construction materials · Additive manufacturing · Reduce · Reuse · Recycling

4.1 Definition and Principles

The past century has witnessed an alarming trend within industry: unbridled resource consumption coupled with a steep rise in CO_2 emissions. The negative impacts of resource depletion and the emission of greenhouse gases are obvious and numerous and could lead to planet collapse [1]. As described in the OECD, the scarcity of resources will exacerbate, while the consumption of those will double to 167 gigatonnes in 2060 [2]. Decoupling industry growth from environmental impacts is a major challenge and one of the key pillars to achieve the climate goals set in the EU Green Deal. Adopting CE principles in manufacturing represents an opportunity for industry stakeholders to reduce material consumption as well as resource toxicity, while maintaining and pursuing their business activities.

The implementation of CE concepts, which aim to minimise the use of (primary) resources, energy, and waste flows, hence narrowing down and closing material loops, is strongly encouraged by policy makers. In the EU, the recently updated Circular Economy Action Plan (CEAP) underlines the importance of this concept and the will to transition towards a regenerative growth model. The design phase holds critical influence over a product's environmental impact, with studies suggesting up to 80% of its detrimental footprint being determined at this stage (not specific for construction products). This emphasises the importance of the participation of the manufacturer in circular economy concepts [3]. When the CE philosophy is adopted in the manufacturing sector, it transforms into Circular Manufacturing (CM), highlighting the specific strategies and practices employed in production to minimise waste and maximise resource reuse. Acerbi and Taisch define CM as follows [4]: *"The concurrent adoption of different CM strategies, which enable to reduce resources consumption, to extend resources lifecycles and to close the resources loops, by relying on manufacturers' internal and external activities that are shaped to meet stakeholders' needs"*.

Circular manufacturing in construction refers to an approach that aims to minimise waste, reduce resource consumption, and increase the lifespan of construction materials and products through a circular economy model. This approach builds on the broader framework of the circular economy, which emphasises the elimination of waste by extending the lifespan of products and materials and keeping them in use for as long as possible.

Table 4.1 summarises circular manufacturing principles been adopted in construction and described in further detail in the text below (non-exhaustive list).

To drive the manufacturing sector's transition towards a circular economy, numerous strategies can be implemented, including circular design, disassembly, remanufacture, reuse, recycle, servitisation (manufacturing firms offering innovative services alongside their products), cleaner production, industrial symbiosis, resource efficiency, waste management, reverse logistics, and closed-loop supply chain.

Design for Recycling and Reuse: Sustainable construction practices prioritise designing and manufacturing materials and products with their end-of-life in mind (Fig. 4.1). This entails ensuring easy disassembly of components and facilitating their recycling or repurposing for other projects, thereby minimising the demand for virgin raw materials.

Moreover, the key sustainable construction principle for reducing the quantity of new materials used in the industry is to build less. This is most easily achieved by reusing existing building stock. Existing buildings have the potential to be refurbished by retaining existing building elements and improving them to suit future uses. If we have to build new buildings, we must consider how many of the materials can be from reused products, components or buildings. For example, where there are buildings being demolished on site or locally, materials can be sourced from these buildings, refurbished, and then used in the new building. Alternatively, a national circular economy should be developed to enable the sharing of good quality reused products.

Many structural elements, such as steel beams or concrete prefabricated floor slabs, have a life expectancy which far outlasts a building's lifespan. By knowing these products are going to waste through the demolition of existing buildings, designers can incorporate these components into their design from the outset, using fewer new natural resources and raw materials. Instead of breaking components into smaller pieces and recycling the individual materials, reusing a component in its primary form has a higher value for sustainable construction. It results in fewer

Table 4.1 Circular manufacturing principles in construction

1. Design for Reuse and Recycling Design with the EoL in mind	**5. Long-Term Building Planning** Lifespan of structures, Design for Adaptability (DfA)
2. Material Selection Choosing the right material	**6. Digital Technologies** 3D printing
3. Prefabrication and Modular Construction Reversible construction, Design for Deconstruction (DfD)	**7. Resource efficiency in manufacturing stage** Efficient use of raw materials
4. Resource Recovery and Recycling Salvage of materials, DfD	

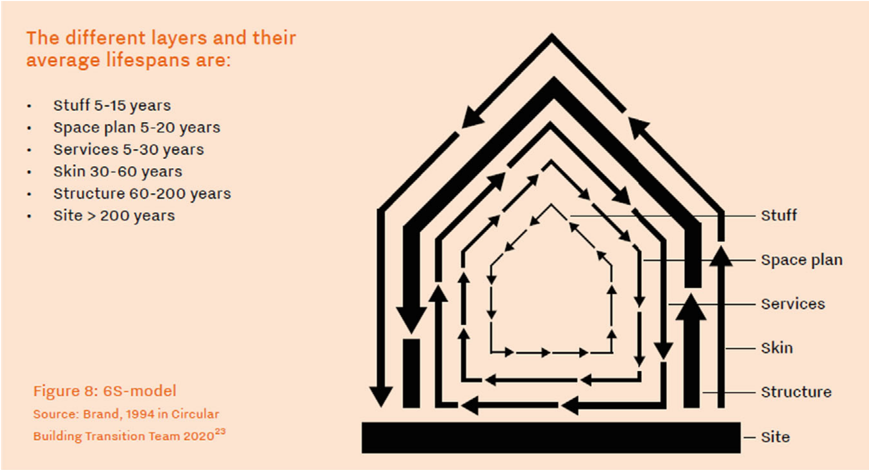

Fig. 4.1 Average lifespan of building layers [5]

modifications, and less manufacturing and construction. This uses fewer materials, less energy and minimises environmental impacts. The value of the item is retained with the potential to reuse it again in the future, thus enabling circular principles to continue in the future.

Material Selection: Choosing sustainable, renewable, and low-impact materials plays a vital role in circular manufacturing. Materials that are durable, easily repairable, and recyclable are preferred over those with limited lifespan and high environmental impact. Prioritise low-maintenance materials throughout the entire building to ensure long-term structural integrity and facilitate future reuse or recycling of valuable components. Implement distinct material strategies for each building layer, considering their individual lifespans (see Fig. 4.2).

Prefabrication and Modular Construction: Prefabricated and modular construction methods can enhance circular manufacturing by enabling easier disassembly and reassembly of building components, allowing for faster construction, and reducing waste during the building process. The design should accommodate reversible connections.

Resource Recovery and Recycling: Construction sites can integrate waste sorting and recycling processes to ensure that materials are recovered and reused whenever possible. This includes salvaging materials from deconstructed buildings and using recycled materials in new construction. Additionally, the use of recycled materials must be maximised without compromising the technical performance of the material. This can be achieved through innovative and efficient design solutions that minimise waste. The growing commercial interest in waste signifies a paradigm shift: waste is no longer solely viewed as a burden, but increasingly regarded as a potential "co-product" with considerable implications for environmental impact assessment. This

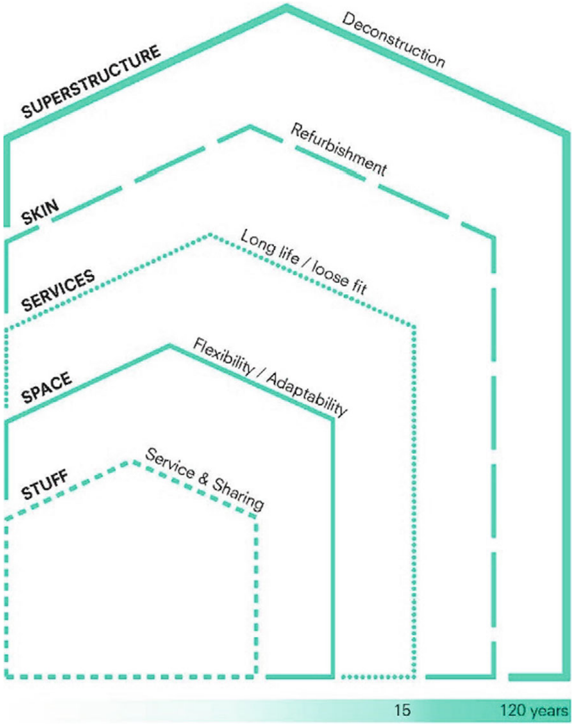

Fig. 4.2 Strategy needs to fit to the life expectancy of the layer [6]

is evident in the cement and concrete industry, where companies actively explore waste-based alternatives, such as industrial by-products, to replace Portland cement, with the aim of decreasing the environmental footprint of construction materials.

Long-Term Building Planning: Circular manufacturing also involves considering the long-term use and adaptability of structures. Designing buildings that can be easily modified or repurposed for different uses increases their lifespan and reduces the need for new construction. Sustainable construction extends the lifespan of buildings by prioritising flexible and adaptable design. This means considering potential future uses and designing features that can easily accommodate them, thereby minimising future material consumption and construction waste.

Digital Technologies: Building Information Modelling (BIM) and other digital technologies unlock a new era of construction efficiency. By streamlining processes, facilitating precise material tracking, and enabling optimised resource allocation, these advances contribute to a sustainable and cost-effective building environment. Integrating digital design tools into a sustainable construction strategy facilitates the precise calculation of material quantities, including the individual screws and bolts needed for a building. This meticulous approach minimises material ordering, resulting in reduced waste and a more environmentally responsible construction process.

By assigning each material in a building a digital "passport" containing its environmental and technical specifications, decision-makers can select materials based on their environmental impact. This transparency extends beyond construction, as material passports facilitate accurate identification and responsible reuse or disposal at the building's end-of-life, promoting a circular economy and minimising waste. 3D printing enables the manufacture of building components with precise, customised shapes, eliminating the need for excess material and reducing waste generation. Virtual Reality (VR) technology offers the ability to generate immersive replicas of buildings and spaces, allowing clients and users to virtually experience them before construction begins. This immersive experience facilitates informed decision-making and enables design modifications prior to physical construction, thereby minimising costly and resource-intensive post-completion changes.

Resource efficiency in the manufacturing stage: efficient use of raw materials and energy for the production of construction materials (e.g. cement, steel) is a main pillar of circular manufacturing. Circular manufacturing in construction has the potential to contribute to environmental sustainability, reduce the carbon footprint, and foster the development of a built environment characterised by enhanced resilience and resource efficiency. However, its successful implementation requires collaboration among all stakeholders, including designers, contractors, suppliers, and policymakers, to address challenges such as standardisation, regulation, and industry-wide adoption.

4.2 Steel

The most relevant CM strategies for steel in construction are presented in Table 4.2.

Steel is widely used in construction and infrastructure, as load bearing elements, façades or foundations. Due to its inherent properties, several CE strategies can be easily applied on steel elements in the built environment such as circular design, reduce, remanufacture, reuse, recycle, servitisation, industrial symbiosis, just to name some of them. In a first step, the use of material should always be avoided. If this is not possible, the use of materials should be reduced.

The reduction of material use is relevant mainly in the following stages of a steel element: 1. Design phase of product 2. Design phase of project. Resource efficiency

Table 4.2 CM strategies for steel

Steel	
1. **Reduction of material use** On product by project basis, DfA	3. **Recycling** Scrap-based steel production
2. **Reuse** Circular design and traceability, DfD	4. **Industrial symbiosis and efficient waste treatment**

for steel elements starts with efficient design of products. They should be designed to be lightweight and long-lasting, while still meeting the same structural and safety requirements. Over the last decades steel products were continuously improved and further developed. In general, high strength steel grades allow the choice of lighter sections, when talking about structural elements. The choice of lighter sections by designers results 1:1 in a reduction of required steel production, reducing the need for virgin raw materials and minimising greenhouse gas emissions during construction and operation. Hence, designers wield significant influence during the project's initial phase, as the decisions made then heavily impact its success and sustainability. Choosing the right solutions and implementing them efficiently are therefore critical for a positive outcome. Steel elements are prefabricated, hence allow a fast installation on the construction site. Further, steel elements can be designed to be modular and easy to dismantle. Design for Adaptability (DfA) represents a core strategy within the CE framework that allows to keep building stock longer in use, hence reduce the use of new raw materials. It has to be underlined that steel structures offer opportunities to follow this strategy, due to possibility of long spans and related opportunities on modularity.

Reuse, to extend the lifecycle of a product, is closely linked to circular design. Circular design strategy is one of the game changers in the construction industry, as the decisions in the Beginning-of-Life (BoL) of a product, influence the environmental impacts during the lifecycle and in the End-of-Life (EoL). To promote circular design in construction, manufacturers need to focus on product functionalities and features, efficiency, reuse possibility as well as durability and modularity. Availability of information and traceability of the products is crucial. Most of steel elements can be disassembled from the existing structures after their service life. In general, disassembly is straightforward when mechanical connections are used. (Read more about reuse of salvaged steel elements in chapter 5). Only if CE principles, especially circular design, are considered already in the manufacturing stage, a shift to CE in the construction industry is possible. Again, the design phase of a steel product, as well as the design phase of a project are relevant. Besides product specifications, the management at the end of life of these products needs to be considered. According to Acerbi et al., one of the main barriers for circular design in the construction sector are agency and ownership issues in the End-of-Life of materials [1].

Recycling of a construction material becomes relevant at its EoL. Strategies like reuse or remanufacturing should be chosen first, as they represent a higher level of circularity. Steel is infinitely recyclable and can be recycled to 100%. Besides reuse, recycling is the most adopted CE strategy for steel. The European Steel Association conducted a survey in 2012 that quantified the steel recovery rate from representative building demolition projects. The average recycling rate for steel across all products, was found to be 92% [7]. Taking all steel products into account, also those products that are not used in construction, a recycling rate of 85% is realised [8]. These numbers show that the recycling chain for steel is well established. The magnetic properties of steel allow an easy separation from other construction materials during the demolition or dismantling stage. Every steel plant that produces steel, is a recycling plant for End-of-Life steel. Two main production routes are currently used in steel production. The first one is the mainly iron-ore based production in a two-stage process—Blast Furnace/Basic Oxygen Furnace (BF/BOF). In the blast furnace, iron ore is turned into iron. In the second stage, iron is turned into steel. The second route is a scrap-based production in an Electric Arc Furnace (EAF). The iron-ore based steel production, called the primary route, relies on iron ore, coke (coal), limestone and up to 30% scrap input. Scrap-based steel production, called secondary production, uses up to 100% of scrap [9]. Scrap plays a major role in circular steel manufacturing, while each tonne of scrap used avoids 1.5 tons of CO_2 emissions, but also conserves critical resources such as iron ore (1.4 tonnes), coal (740 kg), and limestone (120 kg). End-of-Life scrap is a limited resource. Knowing that the average lifetime of a steel product is around 40 years, the End-of-Life scrap that is available today as a resource for new production, was produced around 40 years ago. Scrap availability will further increase in the next decades; hence double from around 450 Mt in 2023 to 900 Mt in 2050. In order to achieve complete circular manufacturing in steel, scrap recycling needs to be maximised, however due to limitations in scrap availability and a rising steel demand, a primary steel production will be needed until 2100 according to today's forecasts. Steel production over the (primary) Blast Furnace route currently accounts for 71% of the global steel production, which is mainly led by Chinese production. In Europe, 56% of the crude steel production is based on the primary route, which means that 44% is produced on the secondary route [8, 10].

Industrial symbiosis and efficient waste treatment are strategies that are closely linked to the recycling strategy in CE. Besides maximising scrap use in the steel production, there are also other ways to reduce environmental impacts of the primary production route and increase the circularity: (1) Biomass to replace fossil coal, (2) Direct reduced iron, (3) Use of renewable energy, (4) Carbon capture and usage, (5) Use of by-products. Steel manufacturers in Europe are currently undergoing a fundamental change by replacing Blast Furnaces into Direct Reduced Iron plants, in order to meet the targets, set by the Paris Agreement and the EU Green Deal. This cuts the GHG emissions by around 50% per ton of steel, while still meeting the steel demand. Direct Reduced Iron is a viable and already existing technology, that is used on industrial scale. Currently the iron ore is reduced with natural gas. In the future, this could be done with hydrogen, leading to a chemical reaction that only emits water as by-product, besides the iron. H2 Green Steel, in Boden, Sweden, are erecting a new primary iron ore plant powered by hydrogen, which eliminates the need for coke and hence eliminates greenhouse gas emissions for the primary generation of iron. This is highly reliant upon the large hydroelectric schemes nearby to make this viable. In a DRI plant in Germany, the switch to using hydrogen instead of natural gas in the iron ore reduction process is being prepared [11]. But also, the Blast Furnace route itself can become more efficient. Some manufacturers have launched promising pilot projects, that demonstrate the use of biomass, to replace fossil coal in the Blast Furnaces in an industrial scale. The biomass consists of waste wood and waste plastic. The EU Horizon 2020 funded project, 'Torero', also deals with carbon capture and usage. Hence, carbon monoxide from the Blast Furnace's exhaust fumes can be captured directly in the plant and microbially fermented to bioethanol, that can be used in gasoline or chemical industry. This allows material and energy loops to be closed to a large degree. This project allows the creation of a value chain of waste wood, which has currently no attractive applications [12].

During the steel making process, several co-products are generated. The BF/BOF route generates around 400 kg of solid co-products, whereas the EAF route produces only 200 kg. The main solid co-products are slag (90%), dust and sludge. These materials are considered as by-products, not as waste since they have an economical value and are used in other industries. Slag, for instance, is a welcomed resource in road construction and in cement industry, where it is used as roadstone or clinker replacement. The efficient use of steel co-products, in e.g. cement, road construction, metallurgical use, fertiliser and other areas, leads to an overall material efficiency in the steel industry of 97.5%. Furthermore, the use of slag in cement has an environmental value since it can reduce the embodied carbon of concrete up to 59%. Besides solid co-products, process gases from coke ovens and BFs and BOFs can be exploited. They are generally used to produce steam and to fuel reheating furnaces after they are cleaned. Process gases are also used as reducing agents in the BF. The exceeding heat of reheating furnaces, for instance, can be used for heat supply of entire districts. Obviously, using co-products from steel industry contributes to circular economy [10].

4.3 Concrete

The most relevant CM strategies for concrete in construction are presented in Table 4.3.

Concrete acts as both a composite material and a structural element, depending on the lifecycle stage. Its individual components, like cement and aggregates, can also be viewed as distinct products or integral parts of the concrete itself. In terms of Circular Economy strategies, two levels are identified [13].

Material-scale. The diverse material scales involved in concrete (angstroms to meters) and its chemically distinct components—aggregates and binders—restrict

Table 4.3 CM strategies for concrete

Concrete	
1. **Reduction of material use** On material and product scale	4. **Recycling** Downcycling–Crushing concrete
2. **Increasing longevity** DfA	5. **Resource efficiency in manufacturing** Biofuels, Supplementary cementitious materials
3. **Reuse and remanufacturing** DfD	

the feasibility of complete recycling. Consequently, it is typically reprocessed as components in new concrete or other products, limiting the ability to recapture its original material state. Concrete has remarkable versatility due to its ability to incorporate a wide range of materials such as aggregates, extending its functionality and performance. Few examples are the inclusion of fibre-reinforced polymers, rubber [14] or mixed plastic waste [15]. Although incorporating downcycled materials offers potential benefits both for the life cycle of the material and the specific properties of concrete, questions remain regarding their impact on future reuse or recycling options. However, the effectiveness of these materials in fulfilling their engineering function within the infrastructure is evident.

Product-scale. Where structural elements and whole buildings are considered, the remarkable tensile strength advantage of reinforced concrete over its unreinforced counterpart (which in design is assumed to be zero) becomes evident. This superior characteristic allows for its application in demanding structural components like beams and columns, solidifying its value and desirability for reuse compared to its unreinforced counterpart. Despite its superior strength and value for reuse, reinforced concrete constitutes a minority within the global concrete landscape. Estimations suggest that only 25% of globally produced cement ends up in reinforced concrete, highlighting the potential for expanding its utilization for more sustainable construction practices [16]. While reinforced concrete provides superior functionality, the incorporation of steel reinforcement creates new vulnerabilities that can impact its longevity. Specifically, exposure to atmospheric CO_2 and chlorides from de-icing salts or seawater can trigger corrosion of the steel, potentially compromising the structural integrity of the concrete. Concrete's interaction with the environment triggers degradation mechanisms that reduce its load-bearing capacity and lifespan, significantly impacting its performance and ultimately leading to costly repairs or replacements. These detrimental effects depend on the specific concrete mix and its exposure environment. Notably, the economic burden of steel corrosion in reinforced concrete is substantial, representing roughly 4% of GDP in industrialised nations [17]. The inherent differences in value and physical longevity between reinforced and unreinforced concrete significantly impact the effectiveness of various reuse and recycling strategies. This necessitates a nuanced approach considering these distinct characteristics to optimise resource recovery and minimise waste.

Circular Economy approaches for concrete encompass various strategies targets: minimising resource consumption through material reduction, designing for durability and resilience, extending lifespan through proper maintenance and repair, maximising value through reuse, and ultimately recovering resources via remanufacturing and recycling.

Reduction of material use in concrete construction starts with minimising material used in the design stage. This multi-pronged approach focuses on: (1) Structural optimisation—product scale (reducing the overall volume of concrete needed in structures while maintaining safety and functionality), (2) Material optimisation—material scale (lowering the amount of cement per cubic metre of concrete through innovative mix alternative materials), (3) Clinker optimisation—material scale (using alternative sources or minimising the clinker content within the cement itself, aiming at a smaller environmental footprint).

Increasing longevity represents another design-stage strategy within the Circular Economy for concrete. While the immediate reduction in the in-use concrete volume might be modest, the long-term benefits are substantial. Extending the lifespan of structures translates to reduced material flows and waste generation over time, consequently minimising environmental impact. Design for Adaptability (DfA) promotes a product-scale approach that prioritises designing products with inherent flexibility, enabling them to adjust to evolving needs and circumstances [18]. The principles of DfA extend beyond products and can also be effectively applied to infrastructure projects [19]. In-service strategies like maintenance, repair, and refurbishment play an important role in slowing resource flows, by extending the technical lifetime of products and components. However, these efforts must constantly evolve to 'keep up' with upstream innovations in the concrete lifecycle, such as the development of low-carbon novel concretes that require specific protective measures.

Reuse and remanufacturing constitute complementary end-of-use strategies that focus on slowing resource flows by extracting and re-integrating functional components from decommissioned concrete products into new applications, thereby minimising reliance on virgin materials. Reuse is defined as the act using again a component or product in its original or a similar function, potentially requiring preparatory steps such as inspection, cleaning, or repair [20]. In the context of concrete structures, a discrete concrete structural component can be considered a product offering. Refurbishment entails a meticulously documented process of disassembling a product offering into its constituent parts. These parts are then meticulously inspected, cleaned, repaired or replaced as necessary, and subsequently reassembled into the original product offering, while delivering an equivalent or enhanced warranty pertaining to the product's functionality [21]. Within the construction industry, a structure can be viewed as a complete product, comprised of numerous component parts, encompassing (but not restricted to) structural elements. Remanufacturing and refurbishment, while sharing similarities, represent distinct approaches to extending the functional lifespan of structures. Refurbishment focuses on replacing individual, end-of-life components within an existing structure to prolong its overall operational life. In contrast, remanufacturing involves the disassembly of a structure at its end-of-life, with the utilisation of still-functional components to construct a new structure entirely. Both methodologies align with the principles of Design for Disassembly (DfD). Within this framework, disassembly signifies the strategic removal of structural components with the intended purpose of their subsequent utilization in different structures.

Recycling constitutes an end-of-use strategy aimed at closing resource loops. This strategy entails the reprocessing of materials for integration into the creation of new products, thereby circumventing both waste generation and the extraction of virgin resources. In the context of concrete, recycling ranks as the second most prevalent Circular Economy strategy utilised. The typical recycling process for demolished concrete structures entails the fragmentation of the material at its end-of-use stage. This coarse aggregate is subsequently employed as a substitute for natural aggregate in the creation of new concrete. This method falls under the classification of downcycling, indicating that the recycled aggregate exhibits diminished value and functionality relative to the original concrete. Not all downcycling is equal. "Recycled concrete aggregate" boasts higher quality and finds application in structural concrete, while the more prevalent "recycled aggregate" exhibits lower quality and is typically confined to road sub-base construction [22].

Resource efficiency in manufacturing is key pillar in reducing the environmental impact in the cement industry: (1) the focus on improving the energy efficiency of cement plants primarily emphasizes optimising the thermal performance of their kilns; (2) substituting/decreasing the use of conventional fuels (coal and/or petcoke) in cement kilns with biofuels and other alternative fuels, (3) optimising the clinker-to-cement ratio through the strategic replacement of clinker with alternative materials or supplementary cementitious materials (SCMs), respectively reducing the clinker content of cement; (4) carbon capture, utilisation, and storage [23].

Currently, most cementitious binders in production already incorporate a small quantity of SCMs. In fact, the estimated global clinker factor was 0.77, indicating that out of the total 4200 million tonnes of cement produced in 2015, at least 800 million tonnes of SCMs were utilised [24]. Integrating alternative materials and lowering the clinker-to-cement ratio in cement production yields reductions in both emissions and energy consumption. Exploring the utilisation of waste products from various industries as alternative raw materials in construction presents an intriguing eco-friendly option and is widely used in the cement industry. Materials such as ground blast furnace slag (GBFS) from pig-iron/steel production process, coal fly ash (FA) from coal fired industries, natural pozzolanas (silica fume, rice husk ash) have proven to be effective in substantially reducing CO_2 emissions per tonne of cementitious materials. While GBFS and FA are the most widely used Supplementary Cementitious Materials (SCMs), their availability is projected to be limited. Currently, these materials account for only 17% of the global supply compared to current cement production. This supply is expected to decline to a mere 7% by 2050, driven by increased steel recycling and a shift away from coal usage. The restricted availability of established supplemental cementitious materials, such as slag and fly ash, in conjunction with the emerging potential for enhanced clinker substitution facilitated by calcined clay and limestone blends, is transforming the cement production landscape. A ternary blend (limestone-calcined clay cement, LC3) offers higher levels of substitution due to the synergistic effects among clays, limestone, and clinker. Clay, a widely abundant resource globally, serves as the primary raw material for LC3 production, alongside clinker. Clays with a substantial presence of kaolinite, a critical factor in determining clay quality for cement applications, have demonstrated exceptional pozzolanic properties when subjected to calcination within the temperature range of 700 to 850 °C [25]. Additionally, to address the increasing demand for cement and consequently concrete, considering the constraints on the availability of high-quality SCMs, research is now directed toward exploring alternative possible wastes as SCMs from the other industries such as red mud, incinerated sewage sludge ash, municipal solid waste (MSW) ash, wood biomass ash, construction and demolition waste powder and others. Currently most of these wastes are landfilled due to lacking technical solutions, symbiotic value chains, and coverage by the EU regulations. One of the critical aspects of using new waste materials in the cement production are standardisation and compatibility with the cement production process related specifically on maintaining consistent cement quality and performance. Establishing standards and guidelines will help to ensure the safe, reliable, and environmentally responsible incorporation of waste-derived materials into the cement manufacturing process. One of good example of activating value chain and foster industry-urban symbiosis is AshCycle project focused on use underutilised incinerated ashes as secondary raw materials in the construction and wastewater treatment sectors trough developing of technical guidance, requirements and specifications.

An alternative to traditional cement is the use of alkali-activated materials (AAM). Alkali-activated materials (AAMs) constitute a category of binding agents produced via the chemical interaction between an alkali metal activator and a solid silicate precursor [26]. The solid precursor can consist of materials rich in calcium silicate or aluminosilicate, including natural pozzolan, bottom ash, fly ash, or metallurgical slag. Activators are soluble substances that provide alkali metal cations, elevate the mixture's pH, and expedite the dissolution of the solid precursor. Despite significant potential, the global commercial adoption of these materials remains negligible compared to established alternatives [16]. Researchers are currently directing their attention toward innovative alternatives as precursor materials, including ferronickel slag, electric arc furnace slag, red mud, and calcined clay.

4.4 Timber

The most relevant CM strategies for timber in construction are presented in Table 4.4.

Although timber constructions offer significant potential to promote sustainable building practices, achieving a fully closed material cycle with negligible emissions remains a challenge. Although the inherent characteristics of timber enable partial carbon sequestration during growth and facilitate recycling, various aspects of the process, such as forestry practices, transportation, and processing, require further optimisation to fully realise the material's sustainability potential. As approximately half the dry weight of timber is composed of carbon and one kilogram of carbon is

Table 4.4 CM strategies for timber

Timber	
1. **Reduction of material use** Optimise building structures	3. **Recycling** To a small amount
2. **Reuse and remanufacturing**	

equivalent to 3.6 kg of CO_2, each kilogram of dry timber stores roughly 1.8 kg of CO_2. Despite its carbon storage potential, timber is a finite resource, and significant amounts of processed wood currently end up as fuel, releasing its stored carbon back into the atmosphere. Furthermore, at the end of its life cycle, through combustion or natural decay, timber releases its stored CO_2, limiting its positive long-term impact on climate change. To increase the volume of timber and wood-engineered construction, strategies should focus on maximising material efficiency and raw material utilisation through: (1) optimising structural design for material efficiency, (2) integrating secondary wood streams into construction components, and (3) establishing a circular economy framework that promotes the extended service life of timber products [27].

Despite the potential for circularity, timber *recycling* and closed-loop material use remain marginal practices. Most of the timber is still used for energy production, effectively eliminating it from the construction cycle and negating its long-term carbon storage potential. Several European research projects investigated specific aspects of wood recycling such as "WoodCircus!–Underpinning the vital role of the forest-based sector in the Circular Bioeconomy", or "CaReWood"–Cascading Recovered Wood providing the wood satisfies the requirement of being free of contamination [28]. In the latter case, the research focused on true timber recycling, using used timber from demolition projects instead of simply "downcycling" it. This is particularly relevant given the significant amount of high-quality construction timber discarded during demolition. Across Europe, the construction sector generates 70.5 million tonnes of waste timber annually, yet only one-third undergoes recycling processes [29].

The circular economy draws inspiration from nature's cyclical processes, emphasising resource optimisation and the continued circulation of materials within closed loops. Often described as a holistic approach, it embraces the "reduce, reuse, recycle" mantra. By prioritising reuse and reintegration of materials into new products, the circular economy strives towards eliminating waste as a concept, recognising its inherent resource inefficiency. Polymers and other fossil-based materials demand a transition from linear to circular economic models. Preventing their disposal in landfills or conversion into fossil fuels during energy recovery is crucial. The rise of industrialisation coincides with a dramatic increase in CO_2 emissions, demonstrably contributing to global warming [30].

Reuse and Remanufacturing: throughout its lifecycle, timber acts as a natural carbon sink. During photosynthesis, trees capture atmospheric CO_2 and store it within their cellular components, primarily cellulose, hemicellulose, and lignin. Upon harvesting and subsequent combustion, stored carbon is released back into the atmosphere, completing the cycle [31]. Direct combustion for energy accounts for roughly half of the globally harvested wood, resulting in the immediate release of its stored carbon back into the atmosphere as CO_2 [32]. Diversifying the energy mix with renewable sources such as solar could reduce the reliance on fuelwood, thus reducing carbon emissions. However, the immediate reduction of the use of fuelwood in developing countries remains a complex challenge due to its critical role in providing energy access. The other half of global timber harvest enters the industrial sector, where it is processed into valuable engineered wood products widely used in building applications. Contemporary timber construction primarily utilizes adhesive-bonded elements like glue-laminated timber (glulam) and cross-laminated timber (CLT), with minimal use of untreated solid timber. Strand-based products, such as Oriented Strand Board (OSB) and Parallel Strand Lumber (PSL), offer additional options for ceiling elements and solid wall, albeit to a lesser extent. One example among currently available products is the "Magnum Board," a solid element crafted from glued OSB panels, manufactured by Swiss Krono [33].

Instead of dismantling and recycling timber components, the most sustainable approach prioritises the reuse of entire buildings or their components whenever possible. The optimal waste management strategy in timber construction revolves around maximising reuse, starting with the entire building and progressing to individual components only when necessary. At the material level, shredding and reassembling timber particles into new products instead of direct thermal conversion should be preferred.

Hassan et al. identified wood chips, sawdust and bark as primary sawmill side streams, comprising 38.3% of log input, with wood particles and sawdust constituting the most significant volume. In particular, processing hardwood logs, often less straight, is expected to further increase this percentage. Although wood particles have diverse applications in energy (pellets), construction (concrete additives, particleboard), and agriculture (fertilisers), most of the waste wood still goes directly to energy production [34]. While regulations like the Renewable Energy Act (EEG 2017) and RE2020 promote resource efficiency through "cascading use", current practices like those in the particleboard industry often result in downcycling, ultimately diminishing material value and hindering true circularity. Downcycling is the current norm, but no technology exists to break down particleboards into their constituent materials because of the use of thermoset adhesives, whose irreversible curing process effectively "locks" the materials together, preventing efficient separation into their original components. Current "cascading use" systems remain ineffective, failing to meaningfully increase timber's market share against competitors. Only a true recycling process, epitomised by the cradle-to-cradle approach, can achieve a truly wasteless, circular economy.

Regarding the environmental footprint, the cradle-to-gate concept measures a product's environmental impact from raw material extraction to factory output, excluding use and end-of-life stages where producer responsibility ceases. Looking beyond production to the full product lifecycle, from cradle-to-cradle, requires the development of innovative material design approaches. These approaches must integrate recycling considerations from the outset, alongside primary material development, to achieve true circularity.

4.5 Additive Manufacturing

Additive manufacturing (AM) is a CM strategy that can be applied on different construction materials; hence, it is treated separately. Table 4.5 presents the key characteristics of additive manufacturing as a CM strategy.

Although additive manufacturing promises to be a pivotal pillar of Industry 4.0, driving the circular economy and reducing carbon through minimal material waste, its adoption in construction remains below its potential compared to other industries [35]. Utilising data from CAD software or 3D scanners, additive manufacturing builds objects iteratively, one layer at a time. It is also known as 3D printing. AM minimises energy consumption and waste by using only the precise amount of material needed for a design, eliminating the need for subtractive processes and scrap material. This process can be used to create new products from recycled materials, reducing waste and saving resources, and offering substantial environmental benefits for the construction sector [36–38].

As outlined by Gibson, Rosen and Stucker, the foundational steps of additive manufacturing comprise [39]:

- 3D model generation via either computer-aided design (CAD) software or 3D scanning;
- conversion of the model into an executable format specific to the intended 3D printer, typically involving slicing into 2D sections;
- object construction by the AM machine (3D printer) through sequential deposition of material layers based on the pre-generated slices;
- removal and potential post-processing of the printed object.

The main 3D printing methods used in construction are:

Extrusion: This approach creates objects by adding material in sequential layers, using one or more nozzles depending on the specific technology (e.g., fused deposition modelling uses a single nozzle, while multi-jet modelling employs multiple) mounted on a robotic arm, gantry system, or crane. The material can be concrete, cement, wax, foam or polymer. This is the most common and versatile method, as it can be used in almost any environment, including construction sites, and for various applications [40]. As technical challenges, the balance between printability and buildability becomes a crucial aspect during printing, since instability during manufacturing can induce zones of weakness in the extruded material [35].

Table 4.5 Key characteristics of additive manufacturing as CM strategy

Circular manufacturing	
1. **Main 3D printing methods** Extrusion, Power Bonding, Additive Welding	3. **Potential reduction of material waste, energy consumption and transport costs**
2. **Materials** Concrete/cement, polymer, metal a.o	4. **Barriers to overcome** Costs, Size and Dimension limitations a.o

Powder Bonding: This method creates an object by selectively bonding together layers of powdered material using a binder, a laser, or a chemical reaction. The material can be polymer, metal or sand. This method can produce complex and detailed shapes but requires a controlled environment and post-processing [40].

Additive Welding: This method creates an object by depositing droplets of molten metal or wire using an electric arc or a laser. The material is usually steel or aluminium. This method can produce strong, durable structures, but it requires high temperatures and skilled operators [40].

Due to their inherent fresh and hardened properties, the vast number of readily available raw materials and the flexibility in mix design, cement-based materials offer unmatched adaptability, making them the most studied option for widespread use in additive construction. Printable cement-based materials typically blend common construction materials (sand, soil, clay, crushed stone, recycled aggregates, etc.) with binders (cement, polymers, fly ash) and workability agents/additives, but there are no standard protocols for assessing printable cement-based mixes, leading to challenges in formulation and performance optimisation [41]. Additive manufacturing (AM) could unlock substantial incentives for polymer recycling and reuse within a circular economy framework. By enabling the creation of new products from used or recycled materials, AM offers a closed-loop approach that minimises waste and maximises resource efficiency. Pellets, as an example of polymer reuse, can be used as a raw material in additive manufacturing. Pellets are small cylindrical pieces of plastic that can be melted down and used to create 3D printed parts [42].

Polymers offer an attractive option for AM in construction due to their combination of affordability and lightweight properties, enabling the cost-effective and potentially faster construction of lighter structures, while allowing storage in a controllable, deposit-ready state, unlike that of cement-based raw materials. AM of polymers has attracted significant interest across various sectors. However, widespread implementation as functional, load-bearing components remains limited. While research explores various polymeric materials such as elastomer, photosensitive resin, acrylonitrile–butadiene–styrene (ABS), nylon, and wax, the resulting AM products often function primarily as conceptual prototypes due to limitations in strength and overall performance compared to traditional manufacturing methods [41].

Thus far, there have been no demonstrations of the production of building components using solely lignocellulosic resources or wood-based products, without the inclusion of any mineral or plastic binders. In their study, Lamm et al. provide a comprehensive analysis of the present state of 3D printing using wood and lignocellulosic materials (such as lignin, wood particles, nanocellulose, and cork). The authors delve into the examination of filament-based printing technologies and granulate-based extrusion processes, particularly in the context of large-scale printing [43].

In wood-based FDM/FFF printing, there is a trade-off between wood content and printability/strength. Increasing the wood content beyond 30% becomes difficult to manage successfully with current technology. Rosenthal et al. achieved an impressive 89% wood content in small-scale specimens using liquid deposition modelling.

Their key innovation was a paste-like methylcellulose suspension with ground beech sawdust [43]. Launched in 2020, the TU Dresden's "Addwood–3D printing of furniture " project demonstrated the potential of timber-based 3D printing using a layered particle-resin approach (this technique-built elements by layering sprayed timber particles and adding resin, achieving qualities similar to particleboards). However, existing patents reveal that a fully bio-based solution for the construction industry remains elusive.

Recent publications indicate an absence of discourse surrounding metallic structures in the context of additive manufacturing applications for construction [35]. An all-encompassing adoption of additive manufacturing techniques for large-scale structure printing can be realized once the current size and resolution limitations are overcome. Below are some practical examples of the use of AM parts in construction: steel structures for pedestrian bridge construction—which are 3D printed; new 3D printed steel structural elements and connectors [45–48]; 3D printed multi-binding geopolymer composites—which are a type of cementitious material that can be reinforced with nano additives to improve mechanical properties; 3D printed concrete houses using robotic concrete printing; among others.

Despite a diverse array of AM processes available for architectural and construction applications, many remain restricted to creating objects from single, homogeneous materials, hindering the exploration of more complex and versatile structures [36]. Though in its early stages, multi-material AM in architecture and construction shows promise, necessitating discussions about its potential advantages and drawbacks to accelerate its development. A 2022 study by Pasco et al. [35] suggests that by 2025, AM could significantly improve manufacturing sustainability. Qualitative assessments predict a 5% reduction in key sustainability criteria such as production costs, energy consumption, and CO_2 emissions.

Additive manufacturing can support the circular economy in several ways, such as described in [46, 48–51]:

- reduce material waste by using only the amount of material needed to create an object and reusing or recycling excess material;
- reducing energy consumption by using less energy-intensive processes and optimising the design and performance of objects;
- reducing transport costs and emissions by producing objects closer to the point of use or demand and enabling distributed and decentralised production networks;
- extending the useful life of products by allowing repair, refurbishment, remanufacturing or customisation using additive manufacturing techniques;
- create new business opportunities and value propositions by offering on-demand, customised or innovative products and services using additive manufacturing capabilities.

Since 2015, the ISO/ASTM 52900 international standard has brought clarity and consistency to the terminology used in the AM and ASTM community. This standardisation helps to distinguish AM from traditional techniques such as casting, machining, rolling, forging, and extrusion. However, a radical change in licencing structures, patents, trademarks, and copyrights is also expected. Sustainability policies that focus on technology, work, and regulation also need to be created [35].

To truly realise the environmental benefits of AM in construction, a comprehensive life-cycle assessment (LCA) approach is essential. This involves meticulous analysis of the entire lifecycle of the structure, from manufacturing to end-of-life, alongside the AM process itself. This holistic perspective is crucial for paving the way towards a circular economy within AM construction [52–56]. According to MTC, the following are some of the challenges that AM faces in a sustainability context:

- develop a greater understanding of the AM lifecycle and collect its data;
- identify how Design for the Environment (DfE) approaches can be adapted to Design for AM (DfAM);
- maximize resource recovery through efficient material recycling;
- enhanced safeguards for intellectual property (IP) and better control over regulated products;
- investigate the potential challenges and unforeseen expenses inherent to MA, among others [50].

Also, important barriers need to be overcome in the construction sector, such as:

- additive manufacturing machines are expensive;
- metal additive manufacturing has its benefits in cost when you need 1 to 100 prototypes.
- customising parts is very costly;
- parts have size and dimension limitations;
- using them to create large batch sizes takes more time than traditional manufacturing;
- many additively manufactured objects require some post-processing to clean up and smooth edges, among other things;
- ensuring the final part has good properties. From a materials science perspective, this is probably the greatest challenge in additive manufacturing [57].

In recent years, numerous initiatives have emerged in the development of materials and processes, in addition to designing strategies and applications specifically optimised for additive manufacturing. Large-format 3D printing is gaining traction in construction, with new suppliers emerging and established companies developing innovative solutions. Panjonk et al. highlight the increasing involvement of established construction companies in 3D printing, indicating a promising future for this technology in real-world applications [58].

The achievement of sustainable AM construction practices requires a rigorous and well-defined framework that addresses all key aspects. Continuous and consistent material delivery through optimised mixer and pump settings is paramount for uninterrupted printing and robust interlayer adhesion. This necessitates the precise selection of compatible material types and their specific formulations, including the appropriate incorporation of additives and compatibilizers (materials that allow two largely incompatible materials to mix together to form a new blend or alloy) for optimised interaction. To advance AM in construction, one need to focus on developing standardised performance criteria, material properties, methods to ensure strong layer adhesion and robust structural design approaches. The deployment of additive manufacturing (AM) as a leading technology within the circular economy (CE) model presents potential benefits including, but not limited to, shortened localized value chains and production costs, enhanced resource efficiency and environmental sustainability through the use of recycled materials, and reduced transportation-related emissions [41].

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Chapter 5
Recovery and Reuse of Salvaged Products and Building Materials from Existing Structures

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Abstract The recovery and reuse of salvaged products and building materials from existing structures is an essential practice in sustainable construction and environmental conservation. This process, often referred to as building deconstruction or architectural salvage, involves carefully dismantling buildings to preserve reusable materials. It offers numerous benefits, including significant environmental impact reduction, economic advantages, and historical preservation. Environmentally, it reduces the amount of construction and demolition debris in landfills, conserves natural resources by reusing existing materials, and reduces the carbon footprint by decreasing the need for new materials, thus reducing emissions from manufacturing and transportation. Recovery and reuse involve several steps. It begins with assessment and planning, where a detailed site assessment is performed to identify salvageable materials. A deconstruction plan is then developed that details the steps

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and methods to safely dismantle the structure. During the deconstruction phase, the building is carefully dismantled, starting from the top down, using manual labour and specialised tools to preserve the materials in good condition. These materials are then separated into categories such as steel, timber, concrete, bricks, etc. Next, the salvaged materials undergo cleaning and processing, making them ready for reuse. Proper storage and distribution are crucial to preserve the integrity of materials. However, practice faces challenges such as labour intensity, risks of contamination from hazardous materials such as asbestos and lead paint, fluctuating market demand, and ensuring the quality and safety of reused materials, which may require certification and compliance with building codes. The present chapter starts with aspects of pre-demolition/deconstruction audit that involves the collection of information about the materials and elements that will be recovered and continues with the evaluation of reusability of materials, mainly with steel, timber and concrete, structural components, entire primary and secondary structure.

Keywords Recovery · Reuse · Upcycling · Salvaged products · Building materials · Existing structures · Pre-demolition/deconstruction audit

5.1 Introduction

Salvaging and reusing materials from existing structures is a cornerstone of the use of circular materials in construction, minimising waste and conserving resources. Instead of demolishing buildings and sending the debris to landfills, salvaging materials by disassembly allows for their reuse in new construction projects, reducing waste and conserving resources.

Crowther [1] highlights the principles of disassembly as an alternative to demolition. These include the following:

- offer unimpeded access to all building elements slated for disassembly;
- enable disassembly at any scale, from individual materials to entire structures;
- arrange components based on a hierarchy of access that correlates with their respective life expectancies;
- facilitate simultaneous disassembly of multiple elements instead of linear sequences;
- clear label of components and document their assembly/disassembly procedures;
- separate building structure, envelope, and internal walls using distinct systems;
- standardise and limit the number of material types, components, connections, and systems while ensuring compatibility with existing standards;
- embrace open construction systems that accommodate various structural alternatives;
- minimise the number of components and connections for straightforward disassembly;
- prioritise mechanical connections over chemical ones for easier separation;

- favour readily available tools and practices for widespread adoption;
- design component sizes compatible with intended disassembly methods;
- utilise lightweight materials to simplify handling;
- prevent component deformation caused by repeated assembly/disassembly.

Here are some key aspects related to the recovery and reuse of salvaged building materials:

1. Salvage Operations: Salvage operations involve carefully deconstructing or dismantling existing buildings to recover reusable materials. This process requires skilled labour, the right tools and techniques to ensure the safe removal and preservation of salvaged items;
2. Materials Identification and Sorting: During the salvage process, the materials are identified, categorised and sorted to determine their reusability and potential applications. This includes assessing the condition, quality and compatibility of salvaged materials for future reuse;
3. Preservation and Storage: Salvaged materials may require proper preservation and storage to maintain their quality and usability. This may involve cleaning, repairing, treating, or storing materials under the appropriate conditions to prevent deterioration or damage;
4. Material Assessment and Testing: Salvaged materials should be evaluated and tested to ensure that they meet safety and quality standards for reuse. This includes evaluating their structural integrity, durability, and performance characteristics to determine their suitability for future applications;
5. Inventory and Cataloguing: Establishing an inventory and cataloguing system for salvaged materials helps streamline the reuse process. It enables architects, builders, and designers to easily access information about available salvaged materials, facilitating their integration into new construction projects;
6. Design Considerations: Incorporating salvaged materials into new designs requires careful consideration of their characteristics, limitations, and aesthetic appeal. Designers and architects need to explore innovative ways to integrate these materials while ensuring structural integrity and meeting regulatory requirements;
7. Local Networks and Partnerships: Building networks and partnerships among salvage yards, contractors, architects, and other stakeholders can improve the reuse of salvaged materials. Collaboration allows for the exchange of information, expertise, and the creation of marketplaces for salvaged materials;
8. Education and Awareness: Increasing awareness among industry professionals and the general public about the benefits and opportunities associated with salvaging and reusing building materials is crucial. The implementation of educational programs, workshops, and public awareness campaigns aimed at various stakeholders can significantly contribute to the promotion of disassembly design principles and the creation of a robust market for salvaged materials.

The recovery, de-characterisation and reuse of salvaged building materials offer multiple benefits, including waste reduction, resource conservation, cost savings, preservation of architectural heritage and environmental impact reduction. By incorporating salvaged materials into new construction projects, the construction industry can significantly contribute to circular material usage and sustainable building practices, even reduce costs due to the significant rising costs of some raw materials. The following subchapters deal mainly with steel, timber and concrete.

5.2 Pre-demolition/Deconstruction Audit

Selection of demolition methods depends on the construction materials and site conditions and is subject to regulatory requirements. Top-down demolition method is commonly used for multi-storey buildings meaning that demolition starts from the top floor level. Temporary propping and shoring are usually needed to ensure stability of the structure. Excavators are generally used to demolish the structure; structural steel members sheared, or flame cut into short lengths for ease of handling, transportation, and recycling; and concrete demolished for down-cycling or landfill.

Pre-deconstruction audit involves the collection of information about the materials and elements that will be recovered, the waste streams, and recommendations for further handling and reuse. Recommended waste audit includes field survey, documentation research, condition evaluation, and management recommendations [2, 3]. Guidance for the deconstruction process using the top-down method is available, offering recommendations from project planning to deconstruction stages, along with compliance legislation [4].

A *Pre-demolition audit–overall guidance document* has been prepared as an extension to the Waste Audit Guideline released by the European Commission in 2017 [5]. The pre-demolition audit guidance package has been prepared within the project "*Best practices for Pre-demolition Audits ensuring high quality RAw materials–PARADE*" funded by EIT RawMaterials. The Guideline helps maximize the recovery and reuse of valuable materials and components from buildings and infrastructure, prioritizing sustainability while upholding the safety standards outlined in the EU Construction and Demolition Waste Management Protocol [2].

A document offering guidelines on conducting a reclamation audit was developed through a collaborative effort within the project Interreg NWE 739: Facilitating the Circulation of Reclaimed Building Elements (FCRBE), October 2018–January 2022–*A guide for identifying the reuse potential of construction products* [6]. This manual guides you through the process of conducting these audits. It's designed for building professionals, and anyone involved in (de)construction, including architects, engineers, contractors, and owners.

According to Building and Construction Authority [7], the Pre-demolition Audit is a continuous process, spanning across three key phases: (a) pre-demolition planning, (b) active demolition, and (c) post-demolition assessment. This multi-stage approach ensures the optimal recovery of demolished materials for beneficial reuse and recycling, while always prioritizing safety practices and measures.

Steel. The practice of deconstruction with the intension of reclaiming and reusing structural components is not yet commonplace due to a lack of demand for salvaged materials and the associated time and labour costs. Many existing buildings present challenges for deconstruction and material reuse due to their original design. The findings of the PROGRESS project [8] indicate that deconstruction of existing single-storey steel-framed building is relatively straight-forward when following a reversed construction sequence. Deconstruction begins with the removal of non-structural elements and equipment, followed by the methodical disassembly of flashing elements, cladding, and secondary structures before tackling the primary structure. This deconstruction is recommended to be carried out on a bay-to-bay basis rather than by the entire building layer. Optical Emission Spectroscopy analysis can easily and quickly analyse chemical composition of steel which can serve as a non-destructive method to sort steel from waste stream. In general, steel is the perfect material to reuse, as the integrity of a steel element after deconstruction can be easily tested, compared to other construction materials. Steel is predestined for deconstruction after service life as there is a wide variety of mechanical connections.

At the European level, a technical specification for reuse of structural steel is under development, which is complementary to the provisions in EN 1090-2 [9] for the execution of steel structures. It specifies requirements for both reusability assessment and quality assessment. A testing protocol is proposed for determining the following properties: yield and tensile strength, elongation, tolerances on dimensions and shape, heat treatment delivery condition, and weldability [10, 11]. Non-destructive or destructive techniques may be used depending on the provenance of steel and availability of original inspection documents.

Precast Concrete. The widespread use of pre-cast elements throughout Europe creates a readily available pool of materials for large-scale reuse, making this approach particularly attractive. Evaluating the potential for concrete reuse demands a two-step process: delving into historical records like design drawings and calculations, followed by on-site inspections involving visual and non-destructive assessments. Complete original manufacturing drawings and certificates, if available, can provide invaluable information to assess concrete reuse potential, further validated through suitable testing. Information availability, historical exposure level, and intended new application will determine the 'pre-classification' categories for concrete elements, which will guide further evaluation.

The European research project *ReCreate–Reusing precast concrete for a circular economy* [12], aims to address the challenge of damaging demolitions. This European research project explores methods for deconstructing precast concrete elements for their safe reuse in new buildings, with the objective of transforming waste into resources and creating a profitable circular economy model for construction. This project explores innovative approaches to deconstructing precast concrete, even for structures built without disassembly in mind, aiming to improve both the technical feasibility and economic attractiveness of this sustainable approach. Deliverable D2.1 of the projects discussed in detail the process of information collection as a BIM-aided pre-deconstruction audit process [13]. A central goal of the pre-deconstruction audit is to create a comprehensive inventory of recoverable materials and components within the donor building, maximising potential for reuse and minimising waste. Buildings incorporate a variety of precast concrete elements: structural members (columns, beams, load-bearing and non-load-bearing walls, and shear walls provide structural support and stability to buildings), enclosure elements (facades, incorporating sandwich elements contribute to thermal performance and architectural expression), circulation elements (stairs, stair landings, and balconies facilitate movement and access within and around buildings), etc. In theory, these precast elements can be repurposed for the same intended use. During the pre-deconstruction phase, it was essential to gather data on the physical dimensions, shape, and potential damage of all elements. If the information was already accessible from archives, it was essential to verify its accuracy.

PEIKKO White Paper [14] reviewed a set of connections between precast concrete structures to determine their capacity to allow the dismount and reuse of the structures. Existing solutions must agree with the current norms recognising reuse, and their potential must be proven in practice. The benefits of reuse are also assessed from an economic and environmental point of view by presenting a study case for pre-cast concrete frame load bearing structures. However, the document highlights the need for new standards dealing with the topic, which would also help to verify the condition of old concrete structures for reuse.

Timber. After centuries of dominance by other materials, Europe witnessed a renaissance of timber construction in the late twentieth century, fuelled by the rise of light timber frame systems. Now, in the twenty-first century, innovative advancements are taking this sustainable building method to new heights, transforming the industry. Mass timber, such as CLT (cross-laminated timber), shattered the limitations of timber construction, paving the way for high-rise timber buildings in some countries. Although predominantly used in residential projects, timber is increasingly being used for office buildings, schools and hotels, transforming the construction landscape. The rise of off-site construction could be seen as an even more game-changing development, as it amplifies the benefits of timber, leading to even greater accuracy, material efficiency, speed, and waste reduction. Although modern construction methods gain traction across Europe, regional differences emerge in prefabrication, materials, and design styles. This requires adaptable Design for Deconstruction and Reuse (DfDR) guidelines that can effectively address the specificities of each partner country.

The InFutUReWood project [15] tackled the challenge of reusing wood from existing buildings, specifically focussing on its viability as a structural material. The following transformative recommendations stem from their work:

- For new buildings, local or building authorities could mandate the inclusion of deconstruction plans, prepared by designers, as part of the building permit application process. These plans would facilitate future disassembly and reuse of building materials.
- Minor tweaks to the design of timber buildings can significantly enhance the potential for deconstruction and material reuse. Deconstruction plans, when linked to data on material origin and environmental footprint, become powerful

tools to promote circularity in construction. This allows for targeted material reuse, informed selection of replacements, and minimised environmental impact throughout the lifecycle of a building. Mandatory deconstruction plans with material passports and recycling information should be integrated into the building permit process for new buildings, facilitating future disassembly and material reuse. Current financial incentives that favour biomass energy for building would create a major barrier to its reuse over multiple life cycles. To encourage such reuse, a shift towards tax advantages and subsidies specifically supporting timber reuse is crucial.
- Financial incentives should encourage "cascading use" of timber, prioritising renovation and reuse over virgin materials in new construction. Robust assessment methods are important to demonstrate the full impact of cascading, demonstrating its contribution to sustainability (environmental, social and economic), as well as circularity within the construction sector.
- Without harmonised standards and adaptable assessment documents, the construction industry faces limitations in advancing sustainable building practices. This impacts not only manufacturers and architects, but ultimately hinders progress towards meeting society's growing expectations for environmentally responsible construction. Stakeholders involved in the revision of the Construction Products Regulation should prioritise finding solutions to address this challenge.
- Instead of viewing upfront costs as mere expenditures, integrated policy frameworks are crucial for both the construction and recycling sectors to recognise them as investments in a global resource deposit, promoting long-term resource value and sustainability.

While the EU's Construction Products Regulation review tackles reuse, traceability of materials after first use, and standards, specific solutions are needed for timber due to its distinct natural properties compared to non-living materials. For low-risk circular economy products and applications, exploring alternative approaches like streamlined processes or targeted support programs can unlock their potential, even if broader solutions remain elusive.

Although building safety is paramount, it is equally important to consider its interdependencies and vulnerabilities within the larger urban ecosystem. Effective building safety strategies must be systemic, addressing how structures interact and impact each other. Buildings, major climate culprits, now face growing threats from the climate crisis itself, putting communities and livelihoods at risk. Storms, floods, and landscape-scale fires are just some of the increasing dangers.

Although certain outputs can be currently implemented, further research is required in all aspects of timber utilisation. Specifically, cross-laminated timber has been recognised as a construction material with significant potential for future reuse. Additionally, it can be manufactured using reclaimed timber. Collecting the necessary data for wood characterisation and product certification is a huge undertaking. Hence, project consortia working in this field should collaborate and share data to accumulate a substantial body of knowledge over time. The scope of wood quality and property research, as they are so variable, necessitates data sharing beyond individual projects, and therefore the involvement of multiple projects in sharing their data is crucial. In addition to data sharing, it is essential to compile a Guide to Good Practices that encompasses various circular design solutions. This guide should incorporate research projects and industry solutions and be tailored to meet the regulations of different countries. The transfer of knowledge to society and the education of building professionals are crucial aspects. Transitioning from the current state can pose numerous challenges and obstacles, including new building regulations and the need to adapt to harmonised standards.

One of the most effective waste reduction strategies is to prolong and diversify the use of the same resource through cascading. Risse [16] defines cascading as a resource strategy in which units serve various material applications sequentially, culminating in their final use (in the case of timber) for energy generation through incineration. As Risse explains "It follows a holistic perspective on the material's value chain and can include various reuse and recycling processes as well as end-of-life treatments". Cascading can reduce pollution, resource depletion, and energy consumption associated with manufacturing, while simultaneously extending carbon storage in products and delaying emissions for years, making it a valuable tool for environmental sustainability and climate change mitigation [17]. Cascading can reduce pollution, resource depletion, and energy consumption associated with manufacturing, while simultaneously extending carbon storage in products and delaying emissions for years, making it a valuable tool for environmental sustainability and climate change mitigation (e.g. Irle et al. [18]; Lesar et al. [19]; He et al. [20]). The success of high-value recycling for recovered wood hinges on overcoming the hurdles presented by its inherent heterogeneity and lower quality, which currently restrict yields [21].

Cascading wood effectively demands not only novel technologies but also a transformation in demolition and waste treatment practices to maximise material quality [22–27]. Ideally, product and building design should prioritise material preservation and straightforward and efficient recycling. Most of the wood from demolished buildings is incinerated for energy, primarily to heat power plants, with only a negligible amount diverted to landfills. This highlights the growing interest in timber buildings, which offer a more sustainable alternative.

Despite relying on wood waste for energy, many countries are missing a key opportunity: a massive amount of high-value wood products and assemblies, like structural components, end up incinerated instead of being cascaded for further use. Embracing design for reuse and recycling in wood construction could unlock a treasure trove of opportunities: timber structures could be readily reused, paving the way for practical implementation of wood cascading across the industry.

5.3 Evaluation of Reusability: Materials/Structural Components/Entire Primary and Secondary Structure

The reports of many studies consistently highlight innovative design concepts for deconstruction and reuse, which have the potential to be applied in contemporary buildings. The reports highlight that both the feasibility and the potential for reuse increase with the size of the reclaimed components. Larger elements save time, reduce greenhouse gas emissions, and minimise waste generation. By prioritising adaptability in volumetric and planar units, it not only reduces waste but also unlocks valuable opportunities for repurposing them in different contexts or modifying them within buildings as component lifespans differ. This results in long-term cost savings and improved sustainability. There are examples that demonstrate various design strategies for Design for Deconstruction and Reuse (DfDR) in buildings. Each example is accompanied by its specific design approach to facilitate the reuse and deconstruction process. In the given examples, the buildings are designed to be in one place for a specific period of time. They are constructed with the intention of being easily deconstructed and reassembled in another location without the need for component replacement. Buildings designed for disassembly and reuse often exhibit key features such as modular component systems, easily reversible connections, adaptable floor plans, and circular procurement strategies. Although it is clear that structural timber reuse is feasible, it has not yet been widely adopted as a common approach. The primary obstacles to the use of reclaimed structural components are primarily the absence of demand for salvaged materials, as well as restrictive building regulations and the absence of established design standards. The practices employed during the demolition phase also hold significant importance and should be taken into consideration during the design of buildings to prevent damage to the components.

Entire Structures. Relocating entire buildings in order to reuse a maximum of the components and structure is considered in PROGRESS project [8, 10, 11]. The SEGRO warehouse building in Slough, UK, for instance, built in 2000 was relocated in 2015 on the same business park, to make it possible to construct a new road bridge. The primary steel structure was relatively easy to recover with an intumescent coating removed and repainted on site. Reclaim of secondary steelwork was more challenging due to the large number of elements and their relative fragility. The precast concrete floor planks were easy to remove as there were no rebars between them but grouts; some of the planks were damaged during the deconstruction process and required repair. New composite steel cladding was installed due to the costs of reclaiming the bricks from the original cladding and the difficulty in reinstallation.

Other case studies from the PROGRESS [8] project include the Agrocolumna warehouse built in 2004 and initially located in Craiova and relocated to Copăceni, Romania in 2012 (see Fig. 5.1), and a warehouse building situated within the western harbour of Helsinki underwent a nearby relocation utilising crane technology, eliminating the need for disassembly etc.

Fig. 5.1 Deconstruction and relocation of a warehouse and office building [8]

A similar approach is followed by Capelle et al. [28]. Within their BAMB-Project, circular solutions for the building sector were analysed with the help of several pilot projects. Find hereafter a non-exhaustive list: BRIC–An educational transformable wooden building in Belgium, new building, disassembled and assembled twice, used as an office building in 2018, a shop in 2019 and an acoustic laboratory in 2020; GTB LAB–A novel building module constructed in the Netherlands that combines a steel frame with exchangeable components, enabling flexibility and transformation, which has already undergone its first functional change; REMs An indoor interactive and modular exhibition space on circular building materials, in Brussels, London, Watford, Amsterdam, Eindhoven, Westerlo, new construction, assembled, transformed, and relocated six times.

The 2015 Finnish project ReUSE, explored by Hradil [29], investigated the potential for reusing various building materials, including timber (with a particular focus on mass timber elements). Hradil observes that a substantial variety of load-bearing building elements possess reusability potential, either through recovery from construction and demolition waste or direct reuse from existing structures. He proposed a size- and complexity-based classification system, dividing projects into five distinct categories: (1) building (2) structures, (3) structural elements, (4) basic structural elements, (5) building blocks. Hradil leverages the summarized building element definition to establish a criteria-driven approach for categorizing and evaluating individual elements. Hradil [29] identified these key features of mass timber building components as:

A: sports halls, modular houses, towers, bridges;
B: roof trusses, glulam frames;
C: sandwich panels, ceiling joists, curved glulam beams;
D: wood-based panels, straight solid or glulam beams;
E: boards.

Structural components: Steel. It is not always reasonable to relocate entire buildings. However, single building components such as roofing, cladding, floors or load bearing structures can be recovered and reused. Flat steel construction products for

Fig. 5.2 Flat steel construction products

the building envelope cover inter alia steel metal sheeting, PIR sandwich panels and mineral wool sandwich panels (see Fig. 5.2).

The steel metal sheeting products are 100% recyclable with 16.74% average of recycled content. With choosing special steel from selected producers, options with e.g. a minimum of 75% of recycled content and thus significant CO_2 savings can be chosen. Recycling of the foam of PIR sandwich panels is technically feasible into raw materials to produce again PIR foam sandwich panels. For mineral wool sandwich panels, steel and mineral wool are separable and both are recyclable. Mineral wool can contain between 30 and 50% of recycled content. Also, mineral wool production waste is mainly recycled (up to 90%). The industry is currently looking into an enhancement of circular economy on each step of the products life of steel construction products by:

1. Recycle production waste in particular for PIR sandwich panels as well as waste on site;
2. Use of environmentally friendly surface coatings;
3. Concepts to promote separation into mono-materials;
4. Innovative deconstruction concepts.

Further carbon equivalent savings can be achieved by value engineering with optimised design and related steel thicknesses. Innovative deconstruction concepts promote the reuse of steel construction elements. The construction as such as planned with mechanical fastening techniques. The fastening elements are to be placed from one-side only to facilitate easy deconstruction layer by layer. Riveted connections can be opened by drilling. Setting pins can be loosened by hammering. Bore holes remain in the elements.

Sealing tapes and other sealing products at element edges or intersections may not be removed residue-free. Impacted edges of used panels can be refitted respectively needs to be cut-off from the product being reused. Loss of material can be recycled. It is to be noted that standard element sizes may not remain. It is to be noted that producers do not have a business model in place accounting for reuse of construction elements, mainly due to the challenge of warranty respectively product responsibility. The assessment for fitness-of-purpose of the product to be reused is to be agreed between the party selling product, the designer as well as the purchaser as no legal framework does exist for this case.

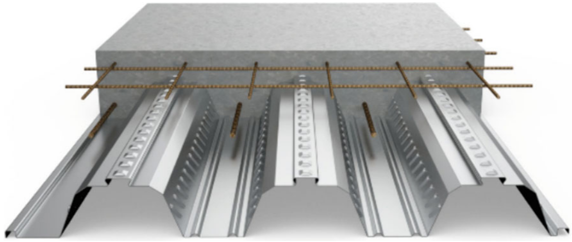

Fig. 5.3 Composite concrete floor

Reclaiming and reusing concrete floors as components are not easy tasks. In current practices, concrete floors are crushed for recycling or landfilling. Precast floor slabs may be easier to reclaim and reuse from existing buildings, compared to cast in-situ applications. Hollow core slabs are prefabricated concrete slabs pre-stressed for strength, commonly used in residential construction for fast and efficient floor systems. In one pilot project in Oslo, hollow core concrete slabs were carefully removed from a demolished multi-storey building to be reused in a new building [30]. Norwegian standard NS 3682 issued in 2022 [31] has provided guidance on reuse of hollow core slabs, from dismantling to assessment.

Composite concrete floors (see Fig. 5.3) comprise reinforced concrete and profiled steel deckling as formwork during concreting and as reinforcement in a final stage. They are commonly designed with composite beams with steel connectors, such as welded shear studs, in steel framed buildings usually non-residential multi-storey buildings. Reclaiming steel sections from such applications is possible, with concrete crushed and studs cut. One easy and elegant way to make this type of composite solution fully deconstructable (floor slabs detachable from composite beams) is to use demountable connectors such as bolts, however, the design of such solution is not covered by Eurocodes.

Using high-strength structural bolts as shear connectors is acceptable in Australian/New Zealand standard AS/NZS 2327 [32]. Within the EU-funded project REDUCE, a total of twenty different demountable shear connection systems have been identified with selected solutions tested, and a design guide on demountable composite construction has been published [33, 34]. Reuse scenario of composite beams with composite floors and demountable connectors has been tested in the UK by Lam et al. [35]; cast in-situ composite floors was cut along the troughs of steel decking after first use, detached, reassembled, and tested to failure, to create a reuse phase. Demountable composite construction has the merits of resource efficiency in first use due to improved strength and stiffness and thus reduced material consumption, and time, labour, carbon savings during assembly and disassembly in first use and subsequent uses of components or structure.

A steel-timber composite flooring system as described by Romero et al. [36] has been developed recently; using demountable shear connectors between timber floor and steel beam to form composite action. Timber panels can be detached from the beams and potentially reused with the same or new beams or repurposed as non-structural elements.

Stockists in the UK have a growing business on reclaimed steel sections thanks to the newly developed steel reuse protocols and the increasing demand on low carbon steel. Before, finding reclaimed steel sections in good quality was not easy and a systematic assessment method was lacking. Completed in 2002, the BedZED project in London used reclaimed steel as frames amounts to 95% of the structural steel [37]. In retrofitting projects, steel is usually the right and light weight material to use for load bearing; the Holbein Gardens project in London, for instance, used reclaimed steel for extension of the frame [38].

A demonstration project in Luxembourg demonstrates opportunities on how to reuse steel load bearing structures. The Project Petite Maison contributes to the concept of design for deconstruction, reuse, and circularity. The project has three phases named: construction phase, use phase (and open for public visits), and deconstruction phase. The load-bearing structure is steel framed with the demountable composite solutions and adaptable steel connections developed within the REDUCE project [39]. The elements adhere to a standardized 1.35-m grid system, prevalent in European construction. Noted that, using a higher grade of steel from S355 to S460 saves approximately 24% of material consumption thus reduced embodied carbon. The developed systems are designed as modular, demountable, standardised, and potentially reusable. Each building element has been linked with a QR code and virtual platform containing material passport data such as technical properties and manufacturers to facilitate tracking and future reuse.

Steel foundations consist of bearing piles and sheet piles and can be found mainly as deep foundation elements in structures as bridges, industrial facilities, housing, underground car parks or quay walls (see examples in Fig. 5.4). The purpose of the foundation can be temporary or permanent, which results in a service-life ranging from some months up to 100 years. Two main modes of action for steel foundations are identified:

1. Vertical load bearing elements,
2. Retaining walls with limited vertical bearing capacity.

Fig. 5.4 Steel as a reclaimable foundation element

The vertical load bearing is assured by steel bearing piles that are generally combined with a shallow concrete foundation. Retaining walls, constructed with sheet piles take horizontal loads, but also have a certain bearing capacity, which allows an efficient use of material. Steel sheet piles are modular, prefabricated elements. For either case, steel elements can be reclaimed after the service life of the structure. Three options are identified for reuse of steel foundations:

1. Reuse steel foundation on the same site (in-situ reuse);
2. Reuse steel foundation on the same site (ex-situ reuse);
3. Reuse steel elements on another site (off-site ex-situ reuse).

Reuse steel foundation on the same site (in-situ): It is possible to reuse vertical bearing piles. As described by Sangiuliano et al. [40], the Ministry of Transportation of Ontario in Canada, is assessing existing bridge abutments that need to be rehabilitated/replaced. The aim is to reuse the existing steel foundations. The authors describe the assessment procedure to check if an existing, 50-year-old, steel foundation, could be maintained and used to support a new superstructure for another 75 years. The procedure considers corrosion as well as geotechnical and structural assessment. The positive result leads to substantial savings in cost, construction time and natural resources.

Reuse steel foundation (ex-situ): Sheet piles can be used for temporary applications and then reused on the same site for further construction stages or on another jobsite. They can be reused up to ten times [41]. The multiple reuses allow the efficient use of a steel element. Being reused multiple times, the steel element is kept on a high level of circularity over several lifecycles. Manufacturers as well as contractors offer rental services and buy-back schemes for sheet piles. Vertical bearing piles are generally used in permanent applications. After reclamation they would be used on another site.

After deconstruction of the superstructure, the use of vibratory hammers, typically used for pile installation, facilitates the efficient extraction of sheet and bearing piles. For steel used in infrastructure, other than quay walls, very limited corrosion is to be expected as the elements often emerge in the soil [42]. Steel foundations are ideal for reuse, due to their integrity and ease of reclamation and storage. Reusing steel foundations significantly reduces the use of raw material, waste, and energy. Today, the reuse of steel foundations, in the form of sheet piles, is common. Around 25% of sheet piles in Europe are reused at least once.

Reuse of steel is technically viable: steel is inherently reusable and durable; and steel construction is easily reversible to facilitate reclamation of materials and components. Reuse of steel is already common practice in shoring, excavation, and the railway industry. Case studies indicate that salvaged steel can be repurposed as structural elements: over 40% of structural steel used in the Brent Cross Town substation project (see Fig. 5.5) was salvaged from surplus oil pipelines [43].

Steel can also easily serve as an intermediary to improve the reuse potential of other materials such as concrete, brick, and timber through connections [44].

Structural components: Concrete. In practice, the elements most commonly used in concrete constructions can be reused. These are:

Fig. 5.5 Brent Cross Town primary substation [43]

- Columns: serving as vertical supports for a structure, columns transfer the compressive forces and bending moments from upper floors, through foundations, to the ground. Square, rectangular, and circular are the most common cross-sectional shapes for these vital structural members;
- Beams: characterised by their rectangular cross-section, beams serve to transfer primarily transversal loads to supporting elements. Their reinforcements enable them to effectively resist both shearing forces (frames) and bending moments (longitudinal steel bars);
- Walls: these vertical elements, carry vertical loads and, due to their inherent strength, also resist horizontal forces generated by wind and earthquakes;
- Floors: characterised by their horizontal orientation and primarily subjected to bending moments, floors are categorised according to the direction of their spans (unidirectional or bidirectional) and construction style (solid, ribbed, or mixed);
- Façade panels: relatively thin, flat elements of uniform thickness, employed primarily to fill the spatial gaps between structural columns. Primarily serving aesthetic and environmental purposes, these non-structural components do not contribute directly to the building's load-bearing capacity.

Küpfer et al. [45] presented an original collection of 77 concrete component reuse cases in new construction projects in Europe and the United States, spanning projects built between 1967 and 2022. Employing a chronological approach, the authors identified seven distinct trends categorised across three main time intervals: (a) the early, pioneering period (1967–1998), (b) the intermediate, development period (1999–2010), and (c) the recent, diversification period (2011–2022).

Within the study, the authors established a three-tier value recovery framework for concrete component reuse, based on the disparity between the structural demands of the components in the new design and their original roles in the donor structure, i.e.:

(a) equivalent reuse of components when the reuse is for the same purpose,

The residential quarter before refurbishment

The residential quarter after refurbishment

Fig. 5.6 Residential quarter before and after refurbishment [47]

(b) downcycling reuse when the reuse of concrete components in new applications are subjected to a less diverse or less intense spectrum of loads or stresses compared to their original design specifications, and
(c) upcycling reuse, when the reuse of concrete components in the receiver structure is required, is subjected to more intense spectrum of loads or stresses compared to their original design specifications.

Asam [46, 47] presented the latest developments in the area of reuse of building parts from disassembled concrete prefabricated parts from housing construction in eastern Germany. He presented four pilot projects implemented between 2005–2007 in the Berlin area. The slab and wall components were supplied by donor buildings in an area of 35 km around Berlin (see Fig. 5.6).

In 2015, Huuhka et al. [48] conducted a study to evaluate the reusability of concrete panels prevalent in the Finnish mass housing stock. The research focused on assessing the dimensional compatibility of these panels with the requirements of contemporary architectural design paradigms. Analysing multi-story housing built between 1968 and 1985, the study discovered that a single, average-sized apartment building could provide enough materials to construct up to nine detached houses.

In his study, Glias [49] investigated the feasibility of reusing existing structural concrete elements. His findings confirmed the technical practicality of this approach while highlighting its potential for cost reduction and environmental benefits compared to the use of new construction materials. In addition to its other applications, this strategy presents a potentially valuable solution for vacant office buildings. These encouraging findings warrant further research to fully explore the full potential for reuse and to realise a pilot project that utilises reused elements in the foreseeable future.

Several noteworthy examples, including the Kummatti housing estate rehabilitation project in Raahe, Finland (2008–2010), have provided concrete evidence of the environmental, economic, and construction time advantages associated with the reuse of concrete elements; a small-scale initiative involving the reuse of wall panels resulted in a noteworthy 36% reduction in construction costs [48]. The design of new housing in Mehrow, near Berlin, exemplifies another successful implementation of circular construction principles. Precast concrete elements from unwanted buildings were repurposed for the project, resulting in a 30% cost reduction, highlighting the potential of resource conservation in the construction industry [50].

In 2001, a research project titled "Recycling Prefabricated Building Components for Future Generations" was initiated by the Federal Ministry of Transport, Building, and Housing in Germany. This initiative aimed to assess the feasibility and potential of dismantling and reutilising prefabricated concrete elements in the construction of new houses. The project yielded significant findings regarding the viability of reusing building elements. The use of hand procedures with light machinery proved to be more cost-effective compared to heavy-duty equipment. Furthermore, measurements ensured the quality of the dismantled elements and the reused components were demonstrably 50% less expensive than their new concrete counterparts. In particular, total building costs were observed to be 26% lower when using reused elements [49].

Salama [51] conducted a comprehensive analysis of contemporary issues concerning concrete technologies and their influence on building assembly and disassembly processes. Recognising the environmental implications, he delves into the potential of design-for-disassembly (DfD) principles and explores theories for future advancements. Ultimately, his work aims to guide the construction design of concrete buildings towards a more environmentally responsible future. The study concluded that the implementation of the design for disassembly (DfD) criteria in precast concrete systems and elements presents a feasible and effective solution to transition their linear life cycle to a circular model.

Drawing upon insights from pilot projects conducted in Finland, Sweden, Germany, and the Netherlands, the ReCreate project [13] is currently in progress. This research initiative investigates the feasibility of transitioning from a traditional build-and-demolish approach to a model where elements from dismantled structures are repurposed to construct new buildings. As the project is still under development, further details and results are not yet available.

Structural components: Timber. "Building elements of higher category can be often separated into several elements of lower category. Even though the higher category elements have typically higher value than their parts together, the separation would make sense, because it may be more difficult to find a suitable application of higher category elements. The re-using complexity depends on many factors" [29]:

(a) the substantial weight of certain elements may employ difficult handling,
(b) architects may deem design modifications necessary,
(c) cleaning/separation or disassembly/reassembly processes may be required,
(d) revised or new structural designs are needed,
(e) adaptation to alternative applications should be evaluated,
(f) quality/geometry assessments are needed, particularly for smaller pieces lacking documentation.

Hradil's research [29] underscores the critical role of time in the entire construction process, encompassing design, construction, deconstruction, and reuse. This study highlights that time directly translates into both labour costs and environmental impact, positioning it as a decisive factor in the move towards circular construction models within the building industry chain. The implementation of a comprehensive DfDR strategy demonstrably contributes to time optimisation within the construction process. This approach facilitates expedited decision-making, enhances the efficiency of element categorisation based on size and complexity, streamlines disassembly procedures, promotes the timely identification of optimal reuse opportunities, and expedites the reconstruction phase, resulting in significant time savings across the entire project lifecycle.

The implementation of a successful design for deconstruction and reuse (DfDR) strategy is contingent on a nuanced understanding of several key factors, primarily the 'scale' of the element under consideration. This scale encompasses both the size of the individual element and the size of the intended reuse unit. For example, the complexity of deconstructing and reusing structures changes based on the design. Choosing to reuse entire volumes presents different hurdles than focussing on individual planar components. Similarly, the deconstruction of stud-and-chipboard units versus CLT elements involves tackling distinct challenges. Deconstructing a stick-frame building to reuse separate studs involves distinct issues compared to other systems. These challenges include meticulously separating the studs without damaging neighbouring elements, managing the sheer number of smaller components, and ensuring their viability for reuse. The implementation of design for deconstruction and reuse (DfDR) strategies requires careful consideration of a multitude of interrelated factors. These include the scale and type of the building that is deconstruction, the intended objectives of the reuse process, the perceived quality and potential resale value of the salvaged elements (whether planar, modular or individual), the inherent ease of disassembly associated with different materials and joint types, the feasibility and cost of transportation, and the associated labour costs. By comprehensively evaluating these factors, stakeholders can make informed decisions regarding the most appropriate DfDR approach for each specific project, maximising the potential for resource conservation and promoting the reuse of valuable building materials beyond commonly used options such as slates and bricks.

The implementation of design for deconstruction and reuse (DfDR) strategies in the context of timber construction requires a flexible and adaptable approach. This requires moving beyond a one-size-fits-all model and tailoring the DfDR principles to the specific characteristics of the elements under consideration. A three-tier framework can be used to guide this adaptation, which includes Level 1 (linear elements, such as studs, joists and trusses), Level 2 (planar units, such as walls, floors, and roofs), and Level 3 (volumes, such as rooms or entire buildings).

Level 3 deals with buildings as complete volumes in DfDR for timber. Such structures can be deconstructed and reused either on the larger scale of entire units or broken down into smaller components such as walls and floors, allowing for adaptable reuse based on project needs. Level 2 delves into timber structures composed of planar elements such as walls, floors, and roofs. Here, the emphasis lies on exploring various DfDR strategies to disassemble and reuse these individual components with maximum effectiveness. Level 1 within the DfDR framework for timber constructions applies familiar principles found in traditional light-frame stick building practices. However, post and beam systems introduce additional considerations due to the frequent use of engineered timber elements. These elements often possess unique shapes and configurations, such as portal frames commonly used in sports halls, industrial buildings, and commercial structures. The aim of retrieving larger components during deconstruction presents several compelling advantages. Each additional dismantling step requires increased time, labour, and equipment, leading to higher costs and associated greenhouse gas emissions.

Examples:

Level 1: A building that can be reused: Brummen Town Hall [52]

Opened in 2013, the town hall stands as a testament to sustainable design, earning a Dutch Award for Sustainable Architecture. Its architectural concept bridges generations, meticulously preserving its historic foundation (dating back to 1890) while seamlessly integrating a contemporary, modular space beneath a captivating glass roof. Approximately 90% of the materials utilised in the recently constructed modular addition exhibit the remarkable capability of being dismantled and subsequently reused. Furthermore, the adoption of a modular design strategy not only facilitated a significant reduction in the overall construction timeframe but also contributed to the environmentally responsible approach employed in the building expansion. The existing structure incorporates a foundation dating back to 1890, serving as the historical cornerstone of the building. This foundational element will remain preserved and unaltered even after the dismantling of the recently constructed circular extension (Fig. 5.7). Equipped with the first materials passport, the town hall transforms into a transparent "depot" revealing the history and future potential of every element, some already earmarked for a new purpose. Collaborating with suppliers from the beginning streamlined the sourcing of recycled and recyclable materials, contributing to the high degree of circularity of the building. The initial decision to utilise thicker wooden beams, rather than adhering to a "less is more" mentality, prompted a pivotal realisation within the project team. This experience illuminated the inherent differences between key performance indicators (KPIs) employed within a linear economic model, focused on minimising material usage, and those essential for success within a circular economy framework, which prioritises durability, reusability, and the potential for future use cycles. This shift in perspective underscores the crucial role of re-evaluating traditional metrics and establishing new, circularity-aligned KPIs to facilitate responsible resource management and achieve long-term sustainability goals within the construction industry. Implementing the concept of a novel materials passport faced hurdles in customer persuasion and supplier data accessibility, reflecting the challenges inherent in pioneering sustainable practices.

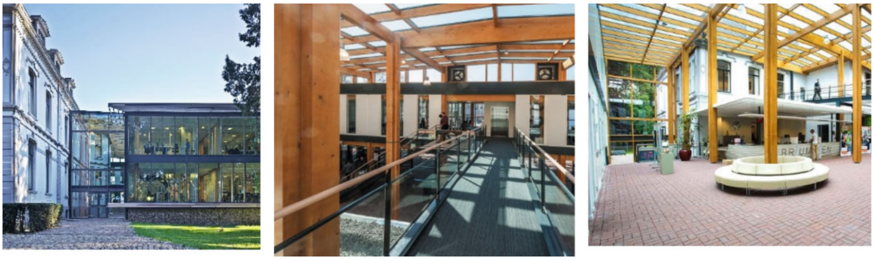

Fig. 5.7 Brummen Town Hall (*photo source* https://www.rau.eu/portfolio/gemeentehuis-brummen/)

Level 1 and 2: Fielden Fowles Architecture Studio [53]

This demountable studio, crafted from sustainable Douglas fir timber and clad with rugged corrugated bitumen sheets, minimises cuts, waste, and optimises resource use through a carefully chosen 2440 mm internal datum and 1830 mm structural grid, utilising full and three-quarter plywood sheets to perfection. The internal walls employ 610 mm plywood boards, corresponding precisely to a quarter of a standard plywood sheet. The structural framework utilises paired beams and columns measuring 300 $\times$ 600 mm, all supported by a modular grid system defined by 1800 mm (for primary beams), 600 mm (for purlins), and staggered 2400 mm (for noggins) spacings. This strategic alignment seamlessly integrates with the plywood butt joints, minimising material waste and facilitating efficient disassembly. Additionally, the inclusion of steel T-sections for window frames further exemplifies the focus on both structural integrity and adaptability, highlighting the design's commitment to sustainability and future-proof functionality (see Fig. 5.8). Although initially set for a specific lease period, this structure is designed to be dismantled and reassembled elsewhere, offering long-term possibilities beyond its current location.

Level 2: Temporary Market Hall, Östermalm, Stockholm [54]

Fig. 5.8 Fielden Fowles architecture studio (*photo source* https://www.woodawards.com/portfolio/feilden-fowles-studio-2/)

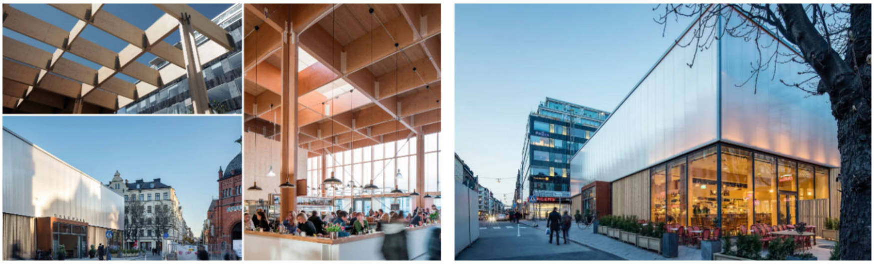

Fig. 5.9 Temporary Market Hall, Östermalm, Stockholm (*photo source* https://hicarquitectura.com/2017/03/tengbom-ostermalms-temporary-market-hall/)

During the refurbishment of the existing market hall, in 2017, a temporary solution was implemented to shelter the traders. The façade utilizes untreated cedar cladding on plywood at the lower level, while the clear-storey incorporates modular polycarbonate sheeting for ample natural light. Internally, the structure remains exposed, showcasing a visually striking latticework of glulam beams supported by columns constructed from cross-laminated timber (CLT) (see Fig. 5.9).

This building uses a modular mounting system, which facilitates efficient erection and dismantling for potential reuse at alternative locations. The sustainable choice of timber construction results in a lightweight structure that minimises the need for heavy foundations. The roof structure is comprised of sturdy 1.2-m LVL beams supported by glulam columns, offering a robust and weatherproof solution.

5.4 Ease of Recycling

Significant greenhouse gas emissions associated with the production of building materials, notably cement, steel, aluminium, glass, and insulation materials, contribute substantially to the embodied carbon footprint of buildings, highlighting the need for sustainable construction practices that minimise this environmental impact.

Steel. If steel elements are not reclaimed for reuse, a recycling strategy is generally followed for steel elements from construction. Recognised as the most recycled material globally, steel exhibits remarkable circularity within the construction industry. This assertion is supported by the European Steel Association's 2012 survey, which analysed steel recovery rates from building demolition sites, revealing a significant percentage of material being salvaged and diverted from waste streams. The average recycling rate for steel across all products was found to be 92%. Taking into account all steel products, also those products that are not used in construction, a recycling rate of 85% is realised.

Since steel scrap has a financial value, it is generally not landfilled. For post-consumer scrap, the recycling loop starts in the end-of-life of a steel element. The lifetime of a steel product in construction or infrastructure can vary from 50 to100 years. If it's not intended to reuse the steel elements, they are reclaimed to enter the recycling loop. Big metal recycler collect scrap and process it, to sell it again to the steel industry where it's used as input for new steel production. The processing mainly consists of shredding, or shearing of the steel elements, to sort them and remove plastics or non-ferrous materials. Large beams are cut with a high-temperature torch cutter, to assure an easy handling.

Steel recyclers are constantly upgrading their (mechanical) sorting systems to assure reliable and homogenous scrap qualities. Steel scrap comes not only from demolitions sites, but also from ferrous consumer goods (e.g. washing machines, vehicles etc.). It is from highest importance that the sorted steel scrap is not containing high amounts of copper, which could contaminate the required chemistry for steel grades in the new production. Steel is 100% recyclable and can be infinitely recycled without loss of properties. This means that no 'downcycling' occurs, even when steel is recycled repeatedly. It is a truly circular material. Every steel plant is a recycling plant, as steel scrap is used in the production. Besides, by-products from the production like slag or dust are used in many other industries, which leads to an overall efficiency of 97.5% in the steel industry. Slag is widely used in the concrete industry, where it's defined as secondary cementitious material (SCM) and allows to create low carbon concrete. The use of SCM is for the moment the only way to decarbonise the cement mixture on an industrial scale.

Concrete. The manufacture of cement, characterized by its energy-intensive chemical processes, contributes significantly to greenhouse gas emissions, depletes natural resources like sand, and negatively impacts ecosystems. Cement, the critical binding agent in concrete, stands out as the material requiring the highest energy input during production, contributing significantly to the overall environmental impact of the concrete industry [55]. Its manufacturing process currently accounts for a 3% of global energy consumption [56].

Concrete recycling is the process of reusing crushed and recycled concrete materials in various construction projects. It is an environmentally sustainable practice that helps reduce the demand for new concrete production and minimises waste disposal in landfills. However, recycling concrete is an energy-intensive process.

Recycled concrete has established itself as a valuable source of aggregate, demonstrating successful applications in various contexts, including granular subbases, soil–cement, and even new concrete production. Notably, these repurposed materials are classified into two distinct categories:

1. Recycled Aggregate (RA), and
2. Recycled Concrete Aggregate (RCA).

Below it will be shown some benefits of concrete recycling and the various methods used in the recycling process.

One of the primary advantages of concrete recycling is the conservation of natural resources. The use of crushed concrete as aggregate offers a significant environmental advantage by reducing the need for the extraction and processing of virgin raw materials such as gravel, sand, and cement. This approach contributes to resource conservation, reduces the environmental footprint associated with mining activities, and even alleviates the demand for energy-intensive cement production.

The implementation of concrete recycling practices presents another environmental benefit, such as reducing the amount of waste deposited in landfills. Concrete waste can take up significant space in landfills and its disposal can be costly. By recycling concrete, the volume of waste sent to landfills is reduced, contributing to a more sustainable waste management system.

The concrete recycling process involves several steps. The first step is the collection and transportation of concrete waste to a recycling facility. Once at the facility, the concrete is crushed into smaller pieces using heavy machinery. The crushed concrete is then screened to remove any contaminants or debris.

After the initial processing, the crushed concrete is further processed to create recycled aggregate. Recycled aggregate can be used in various construction applications, such as road base, drainage systems, and as a substitute for natural aggregate in new concrete production. The quality of recycled aggregate is tested to ensure it meets the required specifications and standards.

In addition to recycling concrete as aggregate, it is also possible to recycle the cementitious materials present in concrete. This process, known as cementitious material recycling, involves separating cement paste from the aggregate through mechanical or chemical methods. The recovered cementitious materials can then be used in the production of new cement or other construction materials.

In conclusion, concrete recycling is an essential practice that promotes sustainability in the construction industry. By reusing crushed concrete as aggregate or recycling cementitious materials, natural resources can be conserved, reduce waste in landfills, and minimise the environmental impact of concrete production.

5.5 From Recycling to Upcycling

Steel. Construction industry is using more and more high-strength steel (up to S700) to assure lightweight, durable, environmentally friendly, and efficient steel structures. Steel scrap is used as input in every steel production route. In the Blast Furnace route currently up to 20%, and in the Electric Arc Furnace route up to 100% is used. Decades ago, the used steel grades were less efficient (up to S275), however exactly these steel elements are now entering the recycling loop and are used for new production. To achieve high-strength steel grades, alloying elements may be added to this steel scrap.

Steel stands out as a unique material because of its closed-loop recycling potential. Unlike most materials, which experience some level of degradation during recycling, steel retains its strength and quality indefinitely, allowing it to be perpetually reused. In particular, the recycling process can even enhance its strength and value (it can be "upcycled") in certain applications, further highlighting its sustainability credentials within the circular economy. As a result of a high demand for high-strength steel, steel scrap is achieving higher quality, and this phenomenon will continue to develop.

Timber. Upcycling of timber is a creative and environmentally friendly approach to repurposing discarded or old wood materials into new and useful products, rather than sending them to landfills or incineration. The practice of reusing timber contributes significantly to environmental sustainability by reducing waste generation, conserving natural resources, and minimizing the carbon footprint associated with the production of new wood products.

Other promising avenues for the use of recycled secondary wood in prefabrication, modular construction, and methods for the design of demountable wood products have been identified. The utilization of large cross-laminated timber (CLT) panels often presents challenges due to their size. Fortunately, deconstruction techniques allow panels to be disassembled and cut to desired lengths, facilitating their repurposing in various construction applications. Although a small amount of waste is unavoidable, the implementation of efficient deconstruction processes and the exploration of creative reuse strategies can significantly reduce its impact. To fully maximise the environmental and economic benefits of sustainable construction practices, it is essential to provide readily available guidance on both materials' disassembly methods at the end of their initial life cycle and potential reuse applications in subsequent projects. To encourage a closed-loop economy, manufacturers or main suppliers could offer take-back programs for end-of-life products, enabling their reclamation and reintroduction into the market. The certification of upcycled secondary timber presents several unique challenges. First, the visual quality of the material often varies significantly compared to cross-laminated timber (CLT) produced from virgin wood, making the adherence to established aesthetic standards difficult. Secondly, the inherent flammability of wood requires the implementation of robust fire safety measures to meet the certification requirements.

5.6 Efficient Waste and Circular Resource Management

Steel. Only a small part of steel elements from construction industry is not recycled or reused. In average it's about 4%, that are mainly generated by rebars or light structural steel. For heavy structural sections a survey shows a 100% reuse and recycling rate, hence no landfill is generated [57]. Compared to other construction materials, steel in construction generates no or only small amounts of waste. The production phase of steel is also minimizing waste, as by-products are used in several other industry sectors.

Steel and metal recycler treat steel scrap from different sources. As consumer goods can contain as well non-ferrous elements, these are separated from the ferrous elements and fed to their own recycling chain (e.g. copper, plastics).

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Part II
Design Strategies and Tools for Circular Buildings

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Designing circular buildings involves incorporating principles of sustainable design, construction, and materials to minimise waste and maximize efficiency, considering various principles and strategies such as circularity, adaptability, disassembly, and adaptive reuse. These approaches focus on creating sustainable buildings and products that can be more easily maintained, repurposed, or recycled to reduce waste and environmental impact. They embrace the idea of creating structures with longevity and flexibility in mind.

Circular principles aim to create a sustainable and regenerative system in which resources are reused, recycled, and restored. Key principles include:

- *Design Out Waste*: Products and materials must be designed to minimize waste and pollution.
- *Keep Products and Materials in Use*: Extend the lifecycle of materials through reuse, repair, refurbishment, and recycling.
- *Regenerate Natural Systems*: Ensure that human activities have a positive impact on natural ecosystems.

The lifecycle of a building can be divided into several phases, each offering opportunities to apply circular principles:

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- *Concept and Design Phase* where on the one hand *Circular Design Strategies* will incorporate flexibility, modularity, and disassembly in the design, while on the other hand, selecting materials that are sustainable, recyclable, and have low environmental impact. Moreover, *Life Cycle Assessment (LCA)* will evaluate environmental impacts from the outset to inform design choices;
- *Construction Phase*, where *Efficient Resource Use* will optimise construction processes to reduce material waste and energy consumption, while *Sustainable Materials*, able to be reused, recycled, upcycled, and locally sourced materials will minimise environmental footprint;
- *Operation and Maintenance Phase. Energy Efficiency* is implementing energysaving technologies and renewable energy sources, while Maintenance and Upgrades will extend the building life and adaptability;
- *End-of-Life Phase.* Plans for building deconstruction rather than demolition to enable material recovery and reuse are important circular principles, while *Recycling and Upcycling* will ensure that materials can be recycled or upcycled into new products, closing the loop.

To effectively implement circular principles throughout the building lifecycle, several design strategies can be used. This part of the book is focussing on the following strategies, i.e.:

1. *Modularity and Prefabrication*: Using modular components and prefabricated elements in construction to increase efficiency, reduce waste, and allow for easier disassembly or reconfiguration.
2. *Design for Circularity*: This involves designing products and buildings in a way that keeps materials in use for as long as possible and eliminates waste. The goal is to create a closed-loop system in which materials can be recycled or reused continuously.
3. *Design for Adaptability*: Designing structures that can easily be adapted to different uses or changing needs over time, promoting longevity and reducing the need for demolition or reconstruction.
4. *Design for Disassembly*: Creating products and buildings that can be easily taken apart for maintenance, repair, or recycling purposes, promoting resource efficiency and reducing waste.
5. *Reversible Buildings and Products*: Structures and products designed with the ability to be reversed or returned to their original state, promoting flexibility and sustainable usage.
6. *Transformable Buildings*: Buildings that can physically change shape or configuration to adapt to different requirements, optimising space utilization and functionality.
7. *Adaptive Reuse of Existing Buildings*: This involves repurposing and modifying existing structures to meet new needs, preserving historical value and reducing the environmental impact of new construction.

Incorporating the principles of circularity, adaptability, and disassembly into the design of buildings and products can significantly enhance their sustainability and lifecycle efficiency. Strategies such as reversible buildings, transformable designs, adaptive reuse, and modularity not only reduce environmental impact but also provide economic and social benefits, leading to a more sustainable future in construction and product design.

Chapter 6
Design Frameworks for Circular Buildings: Circular Principles, Building Lifecycle Phases and Design Strategies

Marianna Marchesi and Vanessa Tavares

Abstract This chapter explored the current theory and practices on circular building design to provide an overview of what a circular building is and how a circular building has been implemented by design through a literature review. Until now, the circular economy in the built environment has mainly been implemented through technological innovation focusing on materials, products, business models and industrial systems. Design for a circular economy in the built environment has progressively expanded from single products and components to building and urban systems. The enlargement of the design scope has entailed a shift from insular to system innovation. Besides a technocentric approach focused on circulating resources through economic and technical innovation, a holistic vision has emerged in the literature that sees circularity as a transformation which integrates technological, social, organizational and institutional considerations of circularity to promote systemic changes in large urban social-technical systems. This study initially investigated the current understanding of the circular building concept, and then analysed design frameworks applied to develop circular buildings by reviewing the literature. Finally, it defined propositions for evaluating the current level of implementation of circular buildings This exploration provided an overview of the current body of knowledge on the circular building concept, a classification of existing design frameworks and strategies for implementing the circular building concept and the identification of relevant propositions to test through case study research to assess the level of implementation of circular buildings.

Keywords Circular building · Design framework · Circular building design · Design for a circular economy · Built environment

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6.1 Introduction

This chapter aims to contribute to the knowledge of practitioners on circular building design by providing an understanding of what a circular building is and how a circular building has been implemented by design through the analysis of existing literature and design frameworks created to support the development of circular buildings.

Until now, a circular economy has mainly been implemented in the built environment through technological innovation focusing on materials, products, business models and industrial systems. Design for a circular economy (CE) in the built environment has progressively expanded from single products and components to building and urban systems. The enlargement of the design scope has entailed a shift from insular to system innovation. Moreover, while it has mainly focused on the technical aspects of circularity, it has also recognized the crucial role of users, communities, and more in general of stakeholders and dynamics in socio-technical systems like the built environment. Besides a technocentric approach focused on circulating resources through economic and technical innovation, a holistic vision has emerged in the literature that sees circularity as a transformation that integrates technological, social, organizational and institutional considerations of circularity [1–3]. While design for a CE shows a growing interest towards a more holistic approach to circularity, literature in design for sustainability acknowledges that systemic changes in large urban systems like the built environment can only be achieved by complementing technical innovation with social innovation and focusing on broader changes in socioeconomic systems [4]. Sustainability-oriented innovations have shown a progressive evolution from technically focused solutions to socio-technical focused innovations to address sustainability as a socio-technical challenge and promote systemic changes [1].

This study explored the current theory and practices on circular building design to understand current practices and identify propositions for evaluating the current level of implementation of circular buildings. Initially, the study explored the current definitions of the circular building concept and design frameworks to implement it by reviewing the definitions of circular building in the literature and existing design frameworks for circular buildings. This exploration provided an overview of the current body of knowledge, a classification of existing design frameworks and strategies for implementing the circular building concept and the identification of relevant propositions to test in future through case study research to assess the level of implementation of circular buildings.

The questions addressed throughout the chapter are the following:

1. What is a circular building?
2. How to implement a circular building?

To reply to the research questions, we formulated the following objectives:

1. Define what a circular building is in terms of building and process definitions and in relation to building layers and building life cycle through a literature review.

2. Define how a circular building has been implemented by design through mapping and classifying existing frameworks of design strategies in the literature.
3. Compare definitions, life-cycle models and design frameworks to identify propositions to apply for evaluating the current level of implementation of circular buildings.

6.2 Materials and Methods

The study consists of practice-oriented research [5] aiming at contributing to practitioners' knowledge of circular building design by exploring the circular building definitions, mapping existing building life cycle models and design frameworks developed to support the implementation of circular buildings and identifying suitable design frameworks for assessing the current level of implementation of circular buildings in future research.

The study was conducted in 3 stages:

(1) Exploration of theory and practice: gathering information on the circular building concepts, building lifecycle models and existing frameworks of design strategies for circular building design from various sources.
(2) Classification of design frameworks: structuring design frameworks in categories according to design principles, building life cycle stages and building life cycles.
(3) Comparison of concepts, life cycle models and design frameworks for circular building design: comparing information to identify suitable propositions for assessing the level of implementation of circular buildings.

Exploration of theory and practice: An exploration of theory and practice on circular building design was performed to review the most recent definitions, life cycle models and design frameworks for circular building design. Information was creatively combined from different practical and theoretical sources to formulate propositions—concepts and specifications of relations between concepts. This information came from sources related to circular building design, i.e., insights from experts, practitioners, stakeholders, existing research, and the researcher's experiences. Information was selected using Google Scholar to obtain the most comprehensive perspective on circular building definitions. In addition to academic work defining CE concepts, the study explored a growing body of grey literature outlining the steps necessary to embed CE strategies within building design through Google search. This includes work from organizations of varying geographic coverage, including the global, international, national and city levels. The selection of information was performed according to the following selection criteria: (1) publications from 2015 to 2023; and (2) keyword(s) used in various combinations: "circular building design", "design for the circular economy", "design for circularity", "design for building life cycle", with the terms: "framework", "models", and "design strategies". In this study, by a design approach or methodology, we mean an overall framework for doing design.

By design methods, we mean sequences of activities to be followed to improve particular stages of the design process (task clarification, conceptual design, detail design, etc.), and specific tasks within these stages (e.g., generation, evaluation,) etc.). We defined design framework as a “design guideline that provides a set of rules, principles and strategies that are useful to follow in attaining some design objectives or performing specific tasks within stages of the process” [6]. Examples of design frameworks include the conceptual design principles suggested by French (1985), and the many Design for-X sets of guidelines, such as Design-for-Manufacturing, or Design-for-Environment guidelines. By design tools, we mean hardware and software for supporting design based on some design approach, method or set of guidelines. The design tool supports the effective and efficient use of the approach, method or guideline [6]. The exploration collected a growing body of literature mainly produced outside of traditional publishing and distribution channels to provide support embedding CE strategies within the building design process. This includes work from organizations at the global level (Arup; Ellen Mac Arthur Foundation), international level (Circle Economy, Dutch Green Building Council, Metabolic, and SGS Search; European Commission), national level (UK Green Building Council), and city level (Greater London Authority).

Classification of design frameworks: This phase of the research describes the current body of knowledge and the identification and classification of design frameworks and strategies. Based on the exploration, a set of design frameworks and strategies were identified, analysed and classified according to the most often-used hierarchical structures to arrange design strategies for the CE [7] as reported below:

- Classification of design strategies based on circular principles/objectives.
- Classification of design strategies based on the building life cycle phases.
- Classification of design strategies based on life cycles.

Comparison of definitions, models and design frameworks: This research phase compared the identified definitions, lifecycle models and design frameworks. The criteria adopted for the framework comparison were (1) framework structure [7]; (2) purpose; (3) stage supported [8]; (4) level of implementation supported [8]; and (5) impact areas [9]. The comparisons were discussed to define consolidated concepts and models, identify gaps and trends in design frameworks for future research development on circular building design and lead to the identification of relevant design frameworks for assessing circular buildings through case study research in the future.

6.3 Circular Building Definitions

A review of definitions of the circular building and the circular building process was performed. Four definitions of the circular building as a process and three definitions of the circular building as the resulting object were identified and reported in Table 6.1.

Table 6.1 Circular building—process and object definitions

Term	Definition
Applying circular economy principles to buildings *(process)*	"Buildings can be designed to have a positive, enduring legacy by making them more adaptable and by ensuring that valuable materials and components can be reclaimed and reused at end-of-life. Ensuring that buildings can be disassembled provides the opportunity for them to be redeployed in new places or for new uses and allows components to be salvaged and reused or remanufactured. This, in turn, reduces dependence on raw materials for construction while salvaging and remanufacturing creates local employment. Declaring and understanding the ingredients that make-up materials and components will help to ensure that biological materials can be safely returned to the biosphere and technical materials can be reclaimed for reuse within the industry. There is also the added benefit that using pure materials with the contaminants designed out helps provide better environments where people can live and work" [10]
Application of the circular economy at the building level *(process)*	"In a circular economy, buildings will be designed for a whole lifecycle and not simply an end use. Policy and incentives will encourage clients to issue full lifecycle contracts from design to operation and disassembly as well as push their ambitions in achieving holistic lifecycle certification and awards. Components and structures will often be leased rather than purchased. Performance-based contracts will see tenants and landowners pay for a service such as lighting rather than individual fittings or materials. Circularity will be embedded in all parts of an ecosystem. This will ensure that individual assets are flexible, interchangeable, and highly customizable [11]. Design decisions such as optimizing disassembly and reuse from the beginning of the program have implications for the operation, renewal and repurposing of the building and its components. In the circular model, a building's construction will be integrated with the resource and reuse cycles of other industries. In operation, the building will use renewable sources and, where possible, locally available used material streams. This will make it more resilient, and it will provide lower risks to investors. Buildings will also be used flexibly 24/7 with high levels of occupation during the day and night" [11]
Circular building *(process and object)*	"Circular building (verb) is the dynamic total of associated processes, materials and stakeholders that accommodate circular flows of building materials and products at optimal rates and utilities" [12] "A circular building (noun) is the manifestation of this in a temporary configuration" [12]
Circular building *(object)*	"An architecture characterized by reversible connections, allowing buildings and components to be taken apart in a way that allows for future reuse or lengthens the building life by being flexible and adaptable" [13]

(continued)

Table 6.1 (continued)

Term	Definition
Circular economy in buildings *(process)*	"A strategic programming of a building to easily change its configuration for longevity and potentially be susceptible to the loop of reduction, reuse and recycling for resource efficiency" [14]
Circular building *(object)*	"A circular building" is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demountable and reusable at the end of their (extended) lifespan, and biological elements can also be brought back into the biological cycle" [9, 15]

6.4 Circular Building Lifecycle Phases

According to the ISO standard, a Life Cycle Assessment (LCA) follows 4 stages:

(1) Goal and scope definition when the problem to be analysed is defined including stating the intended application of the study, the reason for carrying it and to whom the results may be communicated (defined in ISO 14040).
(2) Inventory analysis (ISO 14041) when all inputs and outputs flows are listed and accounted for (flow model), data are collected for all activities within the product systems (processes and transports), and the resources used, and pollutant emissions are calculated in the systems in relation to the functional unit.
(3) Impact assessment (ISO 14042) when impacts are linked to flows, and the inventory results are transformed into more relevant environmental information.
(4) Interactive stage of interpretation (ISO 14043) when results are analysed and discussed, feeding the previous three stages in a retroactive process.

When focusing specifically on buildings, EN 15,978 defined 5 different life cycle phases (Fig. 6.1):

- A1–A3 is defined as the "Product stage" with A1—raw material extraction, A2—transport to plant, and A3—manufacturing.
- A4–A5 is defined as the "Construction process stage" including A4—transport to site, and A5—construction and installation process.
- B1–B7 is defined as the "Use stage" with B1—use, B2—maintenance, B3—repair, B4—refurbishment, B5—replacement, B6—operational energy use, and B7—operational water use.
- C1–C4 is defined as the "End-of-life stage", including C1 de-construction and demolition, C2—transport to waste management facilities, C3—waste processing, and C4—disposal.

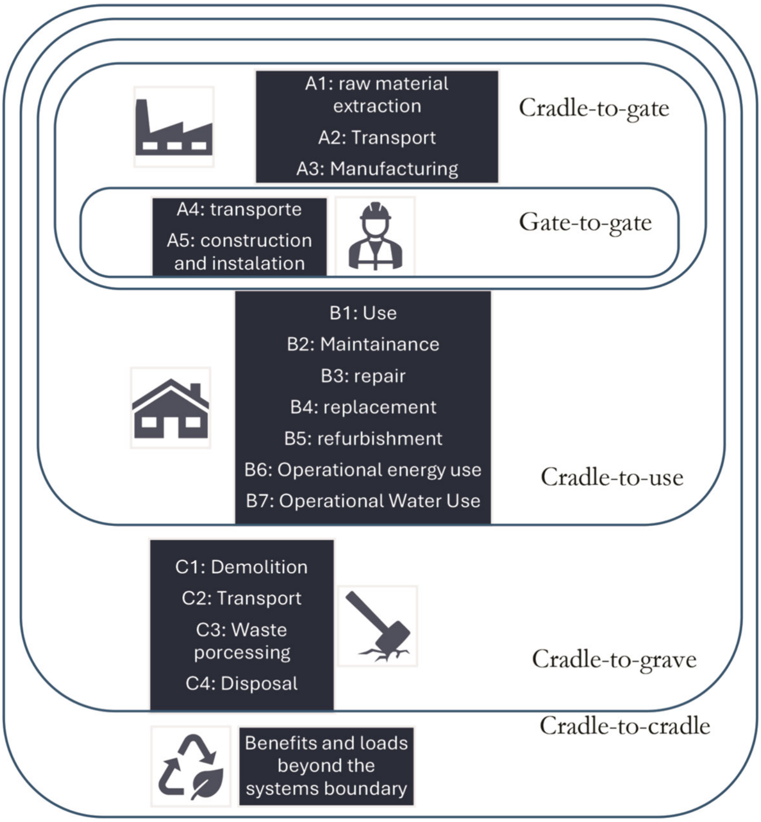

Fig. 6.1 Life cycle stages according to ISO

- D is defined as "Supplementary information beyond life cycle" which includes benefits and loans beyond the building life cycle attained through reuse, recovery, and recycling actions.

Depending on the goal and scope of the analysis, different scopes can be used in an LCA: (1) a "cradle-to-gate" focus on the product stage (A1-A3); (2) a "cradle-to-site" includes construction and assembly (A1-A5); (3) a "cradle-to-use include use stage (B1-B7); (4) a "cradle-to-grave" assesses the whole LC including the end-of-life stage; (5) a "cradle-to-cradle" includes benefits and loads beyond the system boundary (D).

Environmental product declarations (EPD) of building products have been emitted focusing on product stage (A1–A3). However, in June 2019, the EN15804 was revised, giving place to a new version of the standard (EN15804 + A2), and accepted by the European Committee for Standardization (CEN). End-of-life scenarios (C1–C4) and the benefits and loads beyond the system boundaries (D) now must be considered.

The life cycle of a circular building has been defined by [15] according to [9, 11] into 5 stages. It differs from the EN 15,978 standard since it includes the design stage, but it does not consider a stage beyond the building life cycle. The five stages are described in Table 6.2 reported below.

Table 6.2 Building life cycle phases and circular principles [9, 11, 15]

Lifecycle stage and substages	Circular economy principles
Production phase	"The sourcing of virgin materials to produce building materials is reduced to a minimum and substituted with secondary raw materials—such as reused materials or components, recycled materials and bio/renewable materials –, with priority given to local sourcing. Production includes material extraction and domestic material consumption of construction materials" [9]
Extraction and processing of raw materials	
Transport to factory	
Energy, waste, and water use in the factory	
Design phase	The design of buildings is conceived within a long-term perspective, which considers both modularity and adaptability criteria as well as energy-efficient principles that minimize externalities. Operation and performance are embedded in the design and its processes, while open-source architectural design techniques allow designers, architects and engineers to distribute design ideas and build on each other's work
Design of building	
Construction phase	"The process of construction accommodates more flexibility, enabling easy remodelling of buildings during renovation and easier disassembly at the end-of-life stage." [9]. Off-site manufacturing and prefabrication help eliminate waste from construction sites. Transportation of construction materials prioritizes distance over price. Novel techniques, such as 3D printing, allow the production of construction materials, components or even entire buildings at high accuracy and flexibility in design, time efficiency, lower cost and material waste production; with the use of resins and substrates made from renewable or reusable materials
Transport to location	
Building installation	
Use phase	The life of the building is prolonged using internal circular resource cycles, such as waste capture and filtering, or net-energy production. "Users of circular buildings lease components and services instead of owning them" [9]. "Through regular maintenance, optimal resource operation in buildings is ensured, while the premature destruction of building components is prevented through repair or small renovations" [15]. Flexible use and sharing of buildings optimize use and occupancy rates
Use	
Maintenance	
Repair	
Repair	
Replacement	
Renovation	
Operational energy consumption	

(continued)

Table 6.2 (continued)

Lifecycle stage and substages	Circular economy principles
End-of-life phase Reconstruction/demolition Transport Waste processing Disposal Reuse, recover, and recycling	"The demolition of buildings is minimized and mostly limited to old and inefficient building stock" [9]. New design approaches allow easy access to building services and include demountable and reconfigurable systems. Systems or models, such as Building Information Modelling (BIM) supported by Digital Product Passports (DPPs), help to expand, contract or redesign buildings as well as to reconstruct and deconstruct them. "Cloud-based BIM models offer an opportunity to collaborate remotely and with more stakeholders" [15]. The lifetime extension of construction materials, products, components and even whole buildings is achieved through reuse, repurposing, refurbishment, recovery and recycling. These approaches maximize the value of elements in use, thereby minimizing the demand for virgin raw materials

A 9-stage lifecycle framework for circular buildings has been proposed by Brincat et al. [8]. The study mapped out the different stages of the building lifecycle including key actors and relevant circular strategies. The framework is reported below in Table 6.3.

Table 6.3 Building life cycle phases and circular approaches [8]

Lifecycle stages	Circular strategies
Concept	During this stage, it is possible to lay out the first steps of a project. It is where initial ideas are outlined regarding the building design, the durability of the project, the resilience of the materials to be used, the different use scenarios in mind and the suitability of the different solutions, parts and construction products. "All these initial concepts/ideas will be further set down in the design phase" [8]
Procurement	"This stage is relevant for the acquisition of goods and services prior to the construction phase" [8]. It is where the project's environmental impact can be assessed. The main actors involved in this phase are able to specify sustainable building approaches that should be used in tenders/proposals
Design	In this stage, the ideas of the concept stage are made more concrete. Plans, schematics and details regarding the construction project are developed. This stage is relevant for implementing CE principles in the design requirements and strategies and for considering aspects such as the use of recycled materials, the future reuse potential and recyclability capacity of both the building and the materials to be used, as well as the building's/infrastructure's transformation capacity
Manufacture	In this stage, the manufacturing of goods takes place. This stage is relevant as it is possible to ensure the product's durability and the products' recycling and recovery potential. It is also a relevant stage to reduce the use of hazardous substances that hamper the reuse/recyclability and thus curb the products' use in buildings due to these reuse/recyclability challenges

(continued)

Table 6.3 (continued)

Lifecycle stages	Circular strategies
Demolition of existing assets	This stage consists of the dismantling of existing assets (e.g., buildings/infrastructure or parts thereof), which occurs through pre-planned and controlled methods. In this stage, the reduction of waste and a high-quality waste management plan is relevant to separate materials resulting from the demolition into batches with an appropriate place of destination/treatment. During this stage, it is also possible to do a preliminary on-site sorting of all waste, where hazardous and non-hazardous waste is separated accordingly
Construction	This stage consists of the assembly and erection of the structure(s) designed previously. Construction techniques are relevant as these may promote the durability of buildings and the resilience of the materials, and also promote the adaptability of buildings/infrastructure. Appropriate construction techniques also contribute to easy and clean building deconstruction in the future
Handover, use, asset management	During this stage, the formal finalization of the project takes place. The end-users of the project begin to use the building/infrastructure. Asset management maximizes usability due to the collection of critical asset performance data in real-time, which leads to understanding the asset's complete life cycle. Asset management is relevant because it adopts life cycle thinking in realizing full value from the assets and allows for decision-making in terms of e.g., greener investment in production systems; investments/practices to increase energy and material efficiency; using, maintaining and remanufacturing production systems which can be reused and recycled at the end of their first life, etc
Refurbishment, adaptive reuse, renovation, maintenance, and repair	In this phase, remodelling, renovation, adaptation or improvement of the building/infrastructure is enabled. Moreover, existing buildings/infrastructure can be extended in their lifespan and the intensity of building use can be increased. Overall, this stage reduced the demand for new construction, which consumes more materials than renovating, repairing, maintaining and refurbishing existing buildings
End of life and deconstruction of future assets	During this stage, the selective dismantling of building/infrastructure components occurs for the purposes of reusing, repurposing, recycling and managing waste. "Deconstruction represents value for the CE goals since extracting high-value materials for resale or reuse is possible "[8]. These materials include steel, wood, aluminium, furnishings and finishes, which all can be reused and/or repurposed for future use. Within each stage, the stakeholders identified—such as government/regulators/local authorities and those within the financing and planning/design stages—have key roles to play in the uptake of circular approaches. In addition to this, stakeholders are also relevant for data creation which facilitates the measurement of circularity

In this analysis, we included the RIBA Work Plan [16] even if it is not a representative framework for circular building design since it does not include the end-of-life stage. We considered it because the process was adopted in a few frameworks to embed CE principles in the design and construction stages of buildings. The RIBA Work Plan provides the project team with a road map for promoting consistency from one stage to the next, and guidance to clients. It is composed of 8 stages [16]: (1) strategic definition, (2) preparation and briefing, (3) concept design, (4) spatial coordination, (5) technical design, (6) manufacturing and construction, (7) handover, and (8) use.

6.5 Building Layers and Lifetime

The concept of building in 'layers' was first proposed by Frank Duffy in the 1970s and developed by Stuart Brand in the 1990s. It is based on the idea that buildings are dynamic systems that interact with a set of evolving needs; consequently, they require the ability to accommodate change—i.e., space, function, and componentry—over time [17]. This statement implied the definition of building layers as a set of building component systems organized based on functions and life spans [17]. Brand's model is composed of six layers and each layer holds specific functions and has an expected service life as explained below [18]:

- Site is the building location.
- Skin is the façade and building exterior (20–35 yrs.).
- Structure is the building's loadbearing system including the foundation and loadbearing elements (30–300 yrs.).
- Services are pipes, wires, energy and heating systems (15–30 yrs.).
- Space plan is the internal fit-out including walls and floors (10–30 yrs.).
- Stuff is the rest of the internal fit-out including the furniture, lighting, and ICT (5–20 yrs.).
- System is an additional layer that has been recently included with the intent to apply this approach beyond the scope of a building, for example in the context of a district or city [11].

According to this approach, buildings are made of separate and interlinking layers, each with a different lifespan. If each layer is conceived to be easily separated and removed, the possibility to reuse, remanufacture and recycle is facilitated. When buildings are devised in separate layers, with different lifespans, each element can be repaired, replaced, moved or adapted at different times without affecting other layers or the whole system. This increases the flexibility of use and longevity over time obviating the need to construct entirely new buildings and assets and avoiding large-scale wastage of assets while reducing unnecessary obsolescence, resource use and other environmental impacts. Design for deconstruction, design for ease of maintenance, design for flexibility, and design for adaptability are all circular design approaches that are supported by the approach of building in layers.

Defining a product life span is also crucial in order to perform an LCA, to know the reference flow of the system under analysis, and to account for impacts according to the predefined functional unit. In a building that is a complex system composed of different products and with a long-expected lifetime (normally over 50 years), we need to define the specific lifetime of each component. To address this issue, various sources have determined the expected lifetime of each of the building components by defining layers such as structural frame, building envelope, finishing, and opening.

6.6 Design Frameworks Based on Circular Principles

Research showed an initial effort to apply CE principles to building design and provide design frameworks arranged according to circular principles/objectives.

The first design framework was the ReSOLVE framework formulated by the Ellen MacArthur Foundation and McKinsey [19] and then adapted to the built environment by ARUP [11, 18]. The ReSOLVE framework (Table 6.4) outlines six strategies to apply to products and buildings as well as neighbourhoods, cities, regions, or even entire economies through layers to identify circular economy opportunities.

In 2016, David Cheshire formulated a framework for supporting the design of circular buildings (Table 6.5) [10]. He identified 3 objectives—(1) design principles; (2) waste as a resource; and (3) circular business models—and circular strategies in each objective to apply to circular building design. This framework defines a hierarchy for design strategies which maximizes the use of existing materials, with the idea being to retain existing buildings. Diminishing returns are gained by moving through the hierarchy outwards: working through refurbishment and re-use through to the least preferable option of recycling materials produced by the building or demolition process. The hierarchy is supported by some key design principles: (1) building in layers—ensuring that different parts of the building are accessible and can

Table 6.4 ReSOLVE framework [11, 18, 19]

Strategy		Building layers						
		System	Site	Structure	Skin	Services	Space	Stuff
Regenerate	Regenerating and restoring natural capital							
Share	Maximizing asset utilization							
Optimize	Optimizing system performance							
Loop	Keeping products and materials in cycles, prioritizing inner loops							
Virtualize	Displacing resource use with virtual use							
Exchange	Selecting resources and technology wisely							

Table 6.5 Applying circular economy principles to building design [10]

Objective	Strategy
Design principles	Building in layers
	Designing-out waste
	Design for adaptability
	Design for disassembly
	Selecting materials
Waste as a resource	Retain
	Refit
	Refurbish
	Reclaim/reuse
	Remanufacture
	Recycle/compost
Circular business models	Performance-based models
	Take back models

be maintained and replaced; (2) designing out waste; (3) designing for adaptability; (4) designing for disassembly and (5) selecting materials—for example, those that can be re-used and recycled.

A more holistic framework for designing and constructing circular buildings was developed by Kubbinga et al. in 2018 [9]. Starting with a definition of a circular building, followed by desired impact areas, they defined building design strategies and sub-strategies in more detail to create the desired impacts. This framework (Table 6.6) provides strategies to foster the circularity of materials, energy and water while promoting biodiversity, human culture and society, health and well-being and multiple forms of value. A crucial area to consider is the inclusion of measurements of building circularity through project-level indicators that are both practically quantifiable with available data. This framework was designed to integrate existing validation and certification systems for a sustainable built environment such as BREEAM.

In 2019, Surgenor et al. developed a framework (Table 6.7) to assist construction clients wishing to specify circular principles in the project brief. It considers a range of circular economy principles and design strategies [13]. Surgenor et al. [13] included benefits and gave suggestions on what to ask for in the brief. They also featured considerations for potential challenges and suggested responses.

This analysis also includes a design framework proposed by the Great London Authority (GLA) in 2020. They looked at how to embed CE principles into built environment practices at the local scale and adopt less resource-hungry approaches to the delivery of buildings and infrastructure. GLA implemented a policy to ensure buildings consider CE principles which includes setting out waste reduction objectives. A CE statement is mandated as part of the planning application for all major schemes within the Greater London area to implement CE considerations and inform design decisions at early project stages [20]. It consists of a framework of design strategies and measures to help London transition to a CE (Table 6.8).

Table 6.6 Framework for circular buildings [9]

Impact area	Principle	Strategy	Indicators (unit)
Materials cycle	Optimize material use	Accountability and substantiation of the building volume	Feasibility study
		Design for flexibility	Building flexibility rate
		Design for resilience	Thermal comfort, Function's location, Extra protection measures for vulnerable building parts
		Design reassembly	De/re-mountable connections, Accessible connections
		Checks and balances on environmental impact (prerequisite)	Life Cycle Assessment
	Reutilize	Maximize the number of reused materials	Material Circularity, Indicator score, Local supply of reusable/ second-hand materials
		Maximize the number of reused components	Renewable components, Local supply of reusable components
		Maximize the number of reused elements	Use of recycled products, Renewable elements, and Local supply of reusable elements
		Future use	Circular business models for return and reuse, Future re-utilization/recycling, Performance-based models, Feasibility study
	Circular materials	Maximize the number of renewable materials	Recyclable materials used Biobased materials used
		Minimize use of scarce/ critical materials	No critical materials, Documentation of critical materials
		Minimize the use of scarce/ critical materials	Environmental impact of the used materials, % of used responsible origin materials
	Knowledge development and sharing	Availability of information (element, component, material)	Building material passport, Demolition specifications/ disassembly guidelines
Energy cycle	Minimize energy consumption	Building design contains and uses a minimal amount of energy	Amount of energy used, Energy consumption during both construction and use, Information sharing systems, Amount of embodied energy

(continued)

Table 6.6 (continued)

Impact area	Principle	Strategy	Indicators (unit)
	Optimize energy demand	Energy matching (space and time)	Energy storage and/or management Systems
	Sustainable and local energy	Minimize environmental impact on the energy source	Energy sources with a minimal environmental impact
	Sustainable and local energy	Availability of information (energy) for building stakeholders	In and out energy data measured, In and out energy data publicly available
		Possibility of optimization during the use phase	Performance-based contract models
Water cycle	Minimize water consumption	Building design contains and uses a minimal amount of water	Water-saving or water-free facilities, information-sharing systems
	Water cascading	Greywater system	Grey water system
		Rainwater collection system	Rainwater collection system
		Resource/nutrient recovery	Possibility of recovering resources and nutrients
	Knowledge development and sharing	Availability of information (water) for building stakeholders	Water management system
Biodiversity and ecology	Avoid the loss of biodiversity	Minimal loss of biodiversity through embodied and use-phase impacts	See BREEAM
	Integration of ecosystem services	Ecosystem elements	See BREEAM
	Integration of ecosystem services	Strengthening local biodiversity by building design	See BREEAM
	Knowledge development and sharing	Long-term biodiversity preservation	See BREEAM
		Availability/accessibility of biodiversity information	See BREEAM
Human culture and society	Integration of ecosystem services	Minimal social shortfall and loss of cultures through embodied and use-phase impacts	Not available
	Facilitate shared amenities and services	Functional shared spaces and amenities	Not available

(continued)

Table 6.6 (continued)

Impact area	Principle	Strategy	Indicators (unit)
	Knowledge development and sharing	Availability/accessibility of social information	Not available
Health and wellbeing	Avoid toxic materials and pollution	Building design embodies no or minimal toxicity	No C2C Banned List of Chemical Materials, no or minimal VOC emissions
		Prevent pollution during the construction, use phase and deconstruction	Not available
	Ensure sufficient quality of life by providing an optimal indoor environment	Ensure air quality and thermal comfort	See BREEAM
		Ensure light and visual comfort	See BREEAM
		Ensure optimal acoustics	See BREEAM
	Knowledge development and sharing	Availability/accessibility of information	Not available
Multiple forms of values	Ensure long-term aesthetics	Long-lasting aesthetic value of the building	Not available
	Knowledge development and sharing	Availability/accessibility of information	Not available

Table 6.7 Circular economy guidance for construction [13]

Principle	Strategy
Maximize reuse (including refurbishing and repurposing)	Reuse the existing asset
	Recover materials and products on-site or from another site
	Share materials or products for onward reuse
Design buildings for optimization	Design for longevity
	Design for flexibility
	Design for adaptability
	Design for assembly, disassembly and recoverability
Use standardization	Designing and constructing buildings that apply standardized elements or modular designs for materials and products that enable a reduction in construction waste and easier reuse in next life

(continued)

Table 6.7 (continued)

Principle	Strategy
Products as a service	Establish and promote a payment structure through which customers have unlimited access to resources but only pay for what is actually used, or for the result linked to their use
Minimize impact and waste	Use low-impact new materials
	Use recycled content or secondary material
	Design out waste
	Reduce construction impacts

Table 6.8 Circular economy statement [20]

Principle	Strategy/ indicator (unit)	Building layers						
		Site	Structure	Skin/ skell	Services	Space	Stuff	Construction stuff
Conserve resources, increase efficiency and source sustainably	Minimize the quantities of materials used (*material quantity in Kg*)							
	Minimize the quantities of other resources used (energy, water, land) (*quantity*)							
	Specify and source materials and other resources responsibly and sustainably (*recycled content in % by value; reused content in % by value*)							

(continued)

Table 6.8 (continued)

Principle	Strategy/ indicator (unit)	Building layers						
		Site	Structure	Skin/ skell	Services	Space	Stuff	Construction stuff
Design to eliminate waste (and for ease of maintenance)	Design for longevity, adaptability or flexibility and reusability or recoverability (*assumed number of replacements; repair and replacement quantities in Kg; estimated reusable materials in Kg/m3; estimated recyclable materials in kg/m3; strip-out waste arising in T; construction waste arising in T*)							
	Design out construction, demolition, excavation and municipal waste arising (*t/m2 Gross Internal Area*)							
Manage waste sustainably and at the highest value	Manage demolition waste (*% reused or recycled onsite/offsite*)							
	Manage excavation waste (*% reused or recycled onsite/offsite*)							

(continued)

Table 6.8 (continued)

Principle	Strategy/ indicator (unit)	Building layers						
		Site	Structure	Skin/ skell	Services	Space	Stuff	Construction stuff
	Manage construction waste (*% reused or recycled onsite/offsite; % not reused or recycled*)							
	Manage municipal waste (and industrial waste, if applicable) (*t/ annum; % reused on or off-site; % recycled or composted, on or off-site; % not reused or recycled*)							

In 2020, Densley Tingley Mihkelson, Gillott and Cheshire [21, 22] developed a CE design framework (Table 6.9) comprising four overarching circularity principles (Design for Adaptability; Design for Deconstruction; Circular Material Selection; and Resource Efficiency) and contributing design strategies. In line with Cheshire's [10] built environment hierarchy, this CE design framework was constructed, highlighting the order in which these principles should be considered to maximize circularity. Within the adopted principles, a set of 45 specific design strategies or actions for which compliance may be evidenced were defined. This framework provides design decisions and actions that may be taken to implement proposed objectives. Strategies are assessed by a three-level criteria rating system, developed in place of a credit weighing, to measure projects. This framework was used to develop a CE digital tool called Regenerate for the assessment of the technical implementation of circular building design in new and existing buildings.

All the analysed frameworks in this category focus on providing a set of strategies to implement defined principles/objectives and achieve the expected features and performances of a circular building, but they do not provide support in terms of the implementation process. Most of them support material circularity; only one of them includes additional resources like water and energy. Indicators are rarely reported: only one framework includes them aiming at supporting the assessment of circular buildings.

Table 6.9 Regenerate [22]

Principle	Strategy/indicator (unit)	Building layers				
		Site	Structure	Skin/ skell	Services	Space
Design for adaptability	Floor loading enables change of use					
	Structural grid allows different configurations					
	Column and foundation capacity allow future vertical expansion					
	Fire rating of frame and escape strategy suitable for different uses					
	Floor-to-ceiling height enables new services for changing climate or change of use					
	Environmental design strategies (e.g. ventilation, daylighting and acoustics) suitable for alternative uses					
	Accessible services for easy upgrade					
	Accessible services for easy upgrade					
	Interior design allows reconfiguration					
Design for deconstruction	Deconstruction plan					
	Material inventory—with core properties and materials designed for reuse highlighted					
	Mechanical not chemical connections					
	Easily accessible connections					
	Durable connections and components					
	Minimize different types of connections					
	Composites designed to be separated into component materials for future recycling					

(continued)

Table 6.9 (continued)

Principle	Strategy/indicator (unit)	Building layers				
		Site	Structure	Skin/ skell	Services	Space
Circular material selection	Reused materials					
	Leased materials					
	Part of buy-back schemes					
	Designed for upgrade/ remanufacture					
	No toxic/hazardous materials/coatings					
	Biological materials non-contaminated for return to nature					
	Technical materials easily separated					
Optimize	Design for material optimisation					
	Design for energy optimization (in-use)					
	Design for efficiency of use (space and time intensity)					
	Design for zero waste in construction					

6.7 Design Frameworks Based on Building Lifecycle Phases

The literature on circular building design revealed a progression of the approach from design strategies arranged according to circular principles/objectives to design strategies organized according to the building lifecycle stages. This progression shows a focus shift from the object (the circular building) to the process (the circular building process). This category of design frameworks arranges strategies according to stages of the building lifecycle and provides tasks to be performed during the process by the design team or through stakeholder collaboration. To implement circular buildings, circular economy strategies need to be applied along the building life cycle. Adopting circular design strategies throughout the entire life cycle of a building, from strategies for using renewable and secondary raw materials during the production stage and promoting building disassembly capability during the design stage, to strategies for extending the building's life through renovation during the use stage and reusing of materials and components at buildings' end-of-life, contributes to realizing circular buildings. For circular design strategies to be effective, new innovative business models and enabling policies are required to be complementarily implemented. Akhimien et al. [14] developed a basic framework based on a 4-stage

Table 6.10 Building life cycle stages and circular economy strategies [14]

Building life cycle stages (EN 15,978:2001)	Principles	Description
Product Manufacture	Building for disassembly	Building design consideration for easy building deconstruction. Use of prefabricated modules in the context of assembly and disassembly, design for adaptability, design for deconstruction, standardization
	Design for recycling	Building design program from inception for recyclability, reuse recycling of building components and reduction of construction waste
	Building materiality	Building materials analysis and selection as major considerations for a circular economy. Material selection and recyclability
Construction	Building construction	Building construction methods that can help. Construction facilitates the application of a circular economy
Operation	Building operation	Building in use and modalities for operation. Operation in line with circular economy principles
	Building optimization	Optimization of building parts for durability and longevity. Repair activities, upgrades, component exchange, etc. to improve building durability and performance, etc
End of life	Building end-of-life	Building end-of-life programs and loop systems. Interventions to either restore, reuse, or recycle building components

building lifecycle process (Table 6.10). While it provides a general overview of the implementation process, the set of strategies is very limited to be able to guide the process implementation.

Meanwhile, Arup and the Ellen Macarthur Foundation released the Circular Buildings Toolkit focused on supporting the design process to implement circular buildings [23]. This framework (Table 6.11) arranges design strategies to support the design team in the implementation of the circular building from the design to the construction stages. It also provides a set of objectives and related targets in terms of resource circularity that the design process should point to implement through tasks. It translated the principles of the CE into a prioritized set of strategies and actions relevant to real estate projects. This framework is based on relevant international best practices and policies (such as EU Taxonomy and EU Level(s)). The strategies are also aligned with CE recommendations from the World Green Building Council as well as National Green Building Councils. The design framework is embedded into a workflow, which leads the project team and key stakeholders from design brief to handover based on the RIBA Plan of Work [16]. The following stages from the building's use to its recovery are not included. CE principles are embedded in the design process from the initial concept stage involving investors and developers to

Table 6.11 Circular buildings toolkit [23]

Circular objective phase	Strategy action	Indicator
Build nothing	**1. Refuse new construction**	Reused floor area (% of total GFA)
Strategic definition	1.1 Reuse, renovate or repurpose an existing asset	
Build for long-term value	**2. Increase building utilization**	Total building utilization [h/sqm]
Preparation and briefing	2.1 Increase the multi-use potential of building spaces	
Spatial coordination—concept technical design	2.2 Create the general physical conditions to enable multi-use implementation	
Spatial coordination—concept technical design	2.3 Design for increased utilization of regularly "empty" spaces	
Technical design	2.4 Design local building performance units so that they can work at various space configurations and requirements	
Technical design	2.5 Make use of versatile/flexible/movable internal walls for the space layout to support multi-use	
	3. Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/yr.]
Concept architectural design	3.1 Design for future climate adaptability/resilience	
Technical design	3.2 Prioritize standardized, modular elements over bespoke/tailor-made solutions, and avoid complex building geometries	
Concept architectural design	3.3 Investigate Product-as-a-Service schemes for components expected to have a short or medium service life in the project	
Structural engineering	3.4 Maximize the durability of the building structure through careful selection, protection and maintenance of components	
Facades engineering	3.5 Ensure the individual service life of envelope systems, components, products and materials aligns with the minimum service life of the building	

(continued)

Table 6.11 (continued)

Circular objective phase	Strategy action	Indicator
Spatial coordination—concept technical design	3.6 Make use of Whole Life-Cycle Cost assessment (WLCC) as a design assessment tool	
Technical design	3.7 Issue a Building Materials Passport document for the project	
	4. Design for adaptability	EU Level(s) Adaptability Rating
Spatial coordination—concept technical design	4.1. Increase convertibility: choose architectural massing, a structural grid and a foundation layout compatible with all likely future uses	
Spatial coordination—concept technical design	4.2. Increase convertibility: Allow for changes in building use by designing the building envelope to allow for more than one use, or to allow modifications in window size and spacing	
Spatial coordination—concept technical design	4.3. Increase convertibility: Make passive provision accounting for possible changes to MEP systems and provide a plant replacement strategy that avoids waste	
Technical design	4.4. Develop and issue an Adaptability Manual document	
	5. Design for disassembly	EU Level(s) Disassembly Potential Rating
Technical design	5.1 Develop reversible connections between the building super-structure elements	
Technical design	5.2 Allow access to reversible connections between the structure and building services	
Technical design	5.3 Develop and issue a Disassembly Manual Document for the building	
Build efficiently	**6. Refuse unnecessary components**	Material use intensity per functional unit [kg/unit/yr]

(continued)

Table 6.11 (continued)

Circular objective phase	Strategy action	Indicator
Strategic definition	6.1 Refuse redundancy in spaces and overestimate headcounts	
Concept architectural design	6.2 Eliminate/reduce the need for on-site parking space	
Spatial coordination—concept technical design	6.3 Prioritize passive and simple servicing strategies over overly complex ones	
Technical design	6.4 Refuse finishes where possible	
	7. Increase material efficiency	Material use intensity by area [kg/sqm /yr]
Concept architectural design	7.1 Avoid material-intensive deep underground and high-rise construction	
Spatial coordination—concept technical design	7.2 Reduce the material use intensity in the building structure via material-efficient structural forms and techniques, such as hybrid and/or composite solutions	
Spatial coordination—concept technical design	7.3 Reduce dimensions of the building structure components through the selection of high-strength materials	
Technical design	7.4 Use advanced engineering practices to improve the material efficiency of structural and envelope components	
Manufacturing and construction	7.5 Reduce material waste at production and construction through off-site prefabrication of the building structure and envelope components	
Build with the right materials	**8. Reduce the use of virgin materials**	EMF's Material Circularity Indicator (MCI)
Spatial coordination—concept technical design	8.1 Maximize the use of reclaimed components for all building layers	
Manufacturing and construction	8.2 Use concrete with high secondary content	
Concept architectural design	8.3 Use engineered timber (or other biobased materials) in building structures	

(continued)

Table 6.11 (continued)

Circular objective phase	Strategy action	Indicator
Technical design	8.4 Use bio-based rapidly renewable materials for the interior design concept	
Technical design	8.5 Reduce the use of critical raw materials	
	9. Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [$kgCO^2eq/m^2/year$]
Technical design	9.1 Track the embodied carbon footprint during design and set an ambitious overall embodied carbon target for the project	
Technical design	9.2 Track the embodied carbon footprint of the building structure and set a target that is below the regionally recommended thresholds	
Technical design	9.3 Track the embodied carbon footprint of the building envelope and set a target which is below the regionally recommended thresholds	
Technical design	9.4 Track the embodied carbon footprint of building systems and set a target that is below the regionally recommended thresholds	
Technical design	9.5 Track the embodied carbon footprint of building fit-out components and set a target that is below the regionally recommended thresholds	
Concept architectural design	9.6 Design for digital information management and provide sufficient information for LCA	
	10. Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]
Technical design	10.1 Track all environmental impacts during design through detailed LCA, not just carbon, and set an ambitious target for the overall project (all layers, including realistic functional and service lives of components)	

(continued)

Table 6.11 (continued)

Circular objective phase	Strategy action	Indicator
Technical design	10.2 Ensure that building materials and products are not on the 'Living Building Challenge (LBC) Red List'	
Manufacturing and construction	10.3 Use on-site electric equipment to reduce the use of fossil fuel-driven machines on site, in turn, reduce the impact of nitrogen, smog and particulate matter emissions in the area	
Technical design	10.4 Avoid the use of hazardous/pollutant materials in the services inside the building	
Technical design	10.5 Avoid the use of hazardous/pollutant materials in the space	
Manufacturing and construction	10.6 Manage hazards of legacy materials in existing buildings	

define the project objectives. The framework is mainly focused on material circularity while other resources like energy and water are not included.

A few years later, Liebetanz and Wilde [24] released the Circular Economy System Enablers Framework which defines CE strategies across the building lifecycle to be performed by identified system enablers to implement circular buildings. This framework is based on the theoretical premises that solutions for a CE are the result of the interplay among four main building blocks across all the stages of the building lifecycle: (1) circular design, (2) circular business models, (3) reverse cycle, and (4) enablers [19, 26]. The four building blocks are the requirements on a systemic level for the circular economy to emerge. The circular design is one of them. Acharya et al. [18] show that implementing a circular economy in the built environment industry requires not only designing buildings in line with circular principles but also an understanding of the whole building life cycle and the construction value chain, which involves high levels of collaboration and information exchange. To do this, new business models are needed that reimagine the currently fragmented value chain and facilitate more circular behaviours. To ensure success, however, the enabling conditions also need to be introduced while potential and existing barriers to implementing circularity in the built environment need to be removed. New tools and incentives are required that enable investors to receive a financial return on decisions that affect not only the selling and leasing of properties and spaces but also their end-of-use and repurposing. Table 6.12 includes examples in the building sector for each building block [18, 25].

Table 6.12 Building blocks for a circular economy in buildings [18, 25]

Circular design	Circular business models	Reverse cycle	Enablers and favorable system conditions
Material selection	Flexible spaces	Take back scheme	Collaboration
Design for reuse, repair, remanufacturing and recycling	Adaptable assets	Materials passports	Access to financing
Modularization/ standardization	Relocatable buildings	Extraction technologies	Leading by example and driving scale
Production process efficiently	Residual value		
	Performance procurement		

Based on these premises, the Circular Economy System Enablers Framework [24] (Table 6.13) identifies 6 stages in the building lifecycle and maps 8 action-orientated enablers that help deliver CE strategic objectives through strategies across the building lifecycle. The "Circular economy design principles" is one of the enablers that aims at implementing "an architecture characterized by reversible connections, allowing buildings and components to be taken apart in a way that allows for future reuse or lengthens the building's life by being flexible and adaptable" [24] through strategies applied in the extraction and manufacture, design, construction, in-use and end-of-life.

A different approach was applied by Brincat et al. [8] to develop the Framework of Circularity Strategies and Indicators across the Building Lifecycle reported in Table 6.14. They evaluated levels of uptake of circular strategies by consulting key stakeholders across the construction value chain to assess activities. Based on this study, they defined a list of 11 circular strategies currently implemented in the construction industry ecosystem at four levels of the built environment (product/material, building/infrastructure, organizational/process and city/region/national levels). Then they mapped these strategies across all the stages of the building lifecycle, including design, construction, use or end-of-life phases. Each stage allows for the possibility of applying identified circularity approaches differently. Indicators for assessment are included at each stage of all levels to measure the uptake of circular approaches.

This framework introduces two innovative aspects in this category: 4 levels of interventions systemically linked and arranged in stages as well as related indicators for the assessment of the strategies. While it aims to support the need to work systemically at different levels of the built environment to implement circular buildings, it does not provide guidelines on the implementation of tasks for stakeholders across the building lifecycle to work collaboratively.

Table 6.13 Circular economy system enablers framework [24]

Stage	Enabler	Strategy
Investments	Green contracts and leasing	Ensure aspirations for circularity are shared by all stakeholders
	Tax and legislation	Stimulate green innovation
	Tax and legislation	Incentivize reuse to stimulate the market
	Green financing	Financing to match circularity ambitions set out in the client brief
	Green financing	Financing to support innovative circular business
	Green financing	Cheaper debt financing for assets that adopt circularity, net zero carbon pathways, and green credentials
	Education	Benefits of green contracts and leases
	Education	Increase investor understanding of how CE fits into ESG portfolios and lower risk associated with climate change
Extraction and manufacture	Collaboration and early engagement	Allows contractor to work with supply chain to secure materials needed (reused options can take longer than new)
	Secondary materials market	Procure secondary materials via secondary materials markets e.g. reuse hubs
	Circular economy design principles	Materials designed to be disassembled at the end of the first use to enable reuse
	Circular economy design principles	Takeback schemes to enable reuse or remanufacture
	Tax and legislation	Tax on virgin materials
	Metrics, benchmarks and indicators	Marking of materials for identification to help with maintenance/repair/disassembly e.g. by using material passports
	Education	Education on circular economy design principles
Design	Collaboration and early engagement	Allows design team, client, and contractor to work together to procure secondary materials and implement circular design principles
	Secondary materials market	Design to the availability of secondary materials
	Circular economy design principles	Implement circular economy design principles (see Circular economy guidance for construction [13]
	Green contracts and leases	develop alternatives to Cat A fit-out and work with future tenants if possible
	Tax and legislation	Mandate circular economy statements and Whole Life Carbon Assessments (WLCA) to inform design decisions
	Green financing	Utilizing circular design principles to help investors align to Environmental, Social, and corporate Governance (ESG) and new regulations

(continued)

Table 6.13 (continued)

Stage	Enabler	Strategy
	Metrics, benchmarks and indicators	Set targets for % of reused materials within a building as part of brief
	Education	Education on the use of circular economy design principles
	Education	Benefits of early engagement
	Education	Challenge perceptions of rescued and secondary materials being inferior to new
Construction	Collaboration and early engagement	Engagement with the whole team
	Secondary materials market	Contractors interact closely with the secondary materials market for procurement and giving back excess materials
	Circular economy design principles	Information communicated on the disassembly of products
	Green contracts and leases	Legally binding obligations in different lifecycle phases
	Tax and legislation	Establish conditions that minimize the construction of new buildings and incentivize refurbishments
	Metrics, benchmarks, and indicators	Detailed measure of onsite waste and monitoring its destination
	Metrics, benchmarks, and indicators	Monitoring of performance in use and waste
	Education	Training to minimize waste and better segregate products
	Education	Education on how to install materials so they can be uninstalled
	Education	Green procurement training and skills for using secondary materials
In-use	Collaboration and early engagement	Share best practice examples
	Secondary materials market	Materials are salvaged to be reused via reuse hubs or take-back schemes for future reuse
	Circular economy design principles	Deconstruction and extension of the lifespan of materials enabled by design allow materials reuse or manufacturers to take back products
	Green contracts and leases	Contract changes, so the building does not have to be returned to the original state between tenancies because of collaboration between new/old tenants on what can be reused
	Tax and legislation	Incentivize refurbishment over demolition by removing VAT on retrofit
	Tax and legislation	Legislation for pre-redevelopment audits

(continued)

Table 6.13 (continued)

Stage	Enabler	Strategy
	Metrics, benchmarks, and indicators	Detailed monitoring of materials
	Education	Educate demolition contractors on deconstruction to maintain the value and maximize reuse

Table 6.14 Framework of circularity strategies and indicators according to the building lifecycle [8]

Level	Stage	Strategy	Indicators (unit)
Product or material level	Manufacture, construction, end-of-life stages	Increasing direct reuse of products and materials	Reused product (Yes/No)
		Increasing reuse/recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
	Manufacture, end-of-life stages	Increasing direct reuse of products and materials	Remanufactured/reused content (% by mass which has been remanufactured or from a reused source)
		Increasing reuse/recycling of waste from demolition works	
		Lifetime extension e.g., through retaining and refurbishing	
	Manufacture, construction, end-of-life stages	Increasing recycled and secondary content of construction products and materials	Recycled/secondary content (% by mass of product that is from a recycled or secondary content)
		Increasing reuse/recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
	Manufacture, end-of-life stages	Designing for future disassembly and reuse	Design for disassembly and circularity (measured using an index/checklist)
		Increasing reuse/recycling of waste from demolition works	
	Construction stage	Reducing waste/wastage rates/ waste generation from construction activities	Wastage rate (amount of product/material delivered but not used measured as % by mass)
	Manufacture stage	Improving durability, lifespan, and repairability of construction works	Predicted service life (measured in years)
		Lifetime extension e.g., through retaining and refurbishing	

(continued)

Table 6.14 (continued)

Level	Stage	Strategy	Indicators (unit)
	Manufacture, construction, end-of-life stages	Increasing reuse/recycling of waste from construction works	Hazardous waste (% by mass)
		Increasing reuse/recycling of waste from demolition works	
		Reducing waste/wastage rates/ waste generation from construction activities	
	Manufacture, construction, end-of-life stages	Increasing recycled and secondary content of construction products and materials	Realistic end-of-life scenarios developed (measured as Yes/No)
		Increasing direct reuse of products and materials—Increasing reuse/ recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
	Manufacture, construction, end-of-life stages	Increasing recycled and secondary content of construction products and materials	Residual financial value per unit product/material at end-of-life (in Euros per functional unit)
		Increasing direct reuse of products and materials	
		Increasing reuse/recycling of waste from construction works	
	Design and construction, end-of-life stages	Product as service, new business models—Increasing recycled and secondary content of construction products and materials	Extended Producer Responsibility scheme (i.e. take-back scheme or product as service) (measured as Yes/ No)
		Increasing direct reuse of products and materials—Increasing reuse/ recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
Building or infrastructure level	Concept and design stages	Improving durability, lifespan, and repairability of construction works	Comparison of asset life cycle costs: costs of asset over life cycle. (e.g. euro/m2/ yr.)
		Product as service, new business models	
	Concept and design stages	Improving durability, lifespan, and repairability of construction works	Comparison of asset life cycle assessment: assessment of the whole life cycle of the asset (e.g. kgCO2 eq/m2/yr.)
		Increasing direct reuse of products and materials	
		Reducing waste/wastage rates/ waste generation from construction activities	
		Lifetime extension e.g. through retaining and refurbishing	
	Design stage	Improving material efficiency/ intensity/mass of materials used	Material intensity/ dematerialization: amount of material used (e.g. kg/m2/yr.)
		Improving durability, lifespan, and repairability of construction works	

(continued)

Table 6.14 (continued)

Level	Stage	Strategy	Indicators (unit)
	Concept, design stages	Increasing direct reuse of products and materials	Reused content: proportion of the asset that is designed with reused products / materials (% by mass)
		Increasing reuse/recycling of waste from demolition works	
		Increasing reuse/recycling of waste from construction works (for reuse of surplus products)	
	Design, manufacture, construction stages	Increasing recycled and secondary content of construction products and materials	Recycled content: proportion of the asset that is designed with recycled content (% by mass)
		Increasing reuse/recycling of waste from demolition works	
		Increasing reuse/recycling of waste from construction works (for reuse of surplus products)	
	Design stage	Designing for flexibility and adaptability	Measurement of the adaptability/flexibility of the asset in use (measured as a score)
		Lifetime extension e.g. through retaining and refurbishing	
	Design stage	Designing for future disassembly and reuse	Proportion of the asset that can be disassembled at end of life (% reuse potential by mass)
		Increasing reuse/recycling of waste from demolition works	
	Construction stage	Reducing waste/wastage rates/ waste generation from construction activities	Construction waste generated on and off-site (measured in tons/100 K Euros (pro-ject value)
	Construction stage	Reducing waste/wastage rates/ waste generation from construction activities	Hazardous waste generated during construction (measured in % by mass)
	Construction stage	Increasing reuse/recycling of waste from construction works	Construction waste reused, recycled, recovered, and landfilled (measured in % by mass)
	In-use, refurbishment stages	Improving durability, lifespan, and repairability of construction works	Construction-related waste generated through in-use/ refurbishment cycles (tons/ 100 K Euros (project value))
		Reducing waste/wastage rates/ waste generation from construction activities	
	In-use stage	Lifetime extension e.g. through retaining and refurbishing	Effective utilization of building (e.g. levels of occupancy) or asset; intensiveness of use (e.g. hours of utilization/m2)
	In-use, refurbishment, end-of-life stages	Lifetime extension e.g. through retaining and refurbishing	Proportion of building/asset retained (mass) for further use (e.g. % by mass of the asset retained for future reuse (adaptive reuse)
		Reducing waste/wastage rates/ waste generation from construction activities	

(continued)

Table 6.14 (continued)

Level	Stage	Strategy	Indicators (unit)
	End-of-life stage	Increasing reuse/recycling of waste from demolition works	Demolition waste generated from the deconstruction/ demolition (measured in tons)
		Reducing waste/wastage rates/ waste generation from construction activities	
	End-of-life stage	Increasing reuse/recycling of waste from demolition works	Hazardous waste generated from the deconstruction/ demolition (measured in % by mass)
	End-of-life stage	Increasing reuse/recycling of waste from demolition works	Demolition Waste reused, recycled, recovered, landfilled resulting from the deconstruction/demolition (measured in % by mass)
		Increasing direct reuse of products and material	
Organization or process level	In-use, refurbishment stages	Lifetime extension e.g. through retaining and refurbishing	Refurbishment/ Transformation rate of buildings/assets portfolio (% of buildings/infrastructure refurbished/year)
		Designing for flexibility and adaptability	
	Design, in-use stages	Improving durability, lifespan, repairability of construction works	Predicted service life of buildings/assets (measured in years)
		Lifetime extension e.g. through retaining and refurbishing	
	Manufacture, design, construction stages	Increasing recycled and secondary content of construction products and materials	Average proportion of a reused and recycled content in new assets/infrastructure (measured as % by mass)
		Increasing direct reuse of products and materials	
		Increasing reuse/recycling of waste from construction works	
	Manufacture stage	Increasing recycled and secondary content of construction products and materials	Reused, recycled and secondary content input (% by mass)
		Increasing direct reuse of products and materials	
		Increasing reuse/recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
	Construction, refurbishment, demolition stages	Reducing waste/wastage rates/ waste generation from construction activities	Non-hazardous waste arisings generated by construction, refurbishment and demolition (measured in tons /100 K Euros (overall project value)
		Lifetime extension e.g. through retaining and refurbishing	
	Construction, refurbishment, demolition stages	Reducing waste/wastage rates/ waste generation from construction activities	Amount of hazardous waste generated by construction, refurbishment, and demolition (Tons /100 K Euros (overall project value)
		Increasing reuse/recycling of waste from demolition works	
		Increasing reuse/recycling of waste from construction works	

(continued)

Table 6.14 (continued)

Level	Stage	Strategy	Indicators (unit)
	Construction, refurbishment, demolition stages	Increasing direct reuse of products and materials	Waste management routes generated from construction; refurbishment; and demolition (measured in % by mass/year for reuse, recycling, recovery or disposal)
		Increasing reuse/recycling of waste from construction works	
		Increasing reuse/recycling of waste from demolition works	
	All stages	All circularity approaches	number and proportion of buildings/assets in the portfolio which have requirements set for circular economy in their design, construction, refurbishment and end-of-life phases (measured by % of projects/ year)
	Refurbishment, demolition stages	Increasing direct reuse of products and materials	Number and proportion of buildings/assets that are to be demolished or refurbished that have requirements set for pre-demolition audits and subsequent implementation (measured by % of projects/ year)
		Increasing reuse/recycling of waste from demolition works	
Urban level (city/region/ national)	Construction, demolition; concept/ planning stages	Reducing waste/wastage rates/ waste generation from construction activities	Construction and demolition waste generated from construction, demolition, and refurbishment in a defined urban area (measured in tons/ capita)
		Lifetime extension e.g. through retaining and refurbishing	
	Construction, demolition; concept/ planning stages	Increasing reuse/recycling of waste from construction works	Recycling/recovery rate of construction and demolition waste: proportion of construction, refurbishment and demolition waste being recycled (or recovered) (measured in % by mass)
		Increasing reuse/recycling of waste from demolition works	
	Concept/ planning stage	Lifetime extension e.g. through retaining and refurbishing	Refurbishment and transformation rate relative to new construction: Amount of buildings/assets refurbished versus the number built new over a given timeframe (measured in % of projects/ year)
		Designing for flexibility and adaptability	
	Demolition; concept/ planning stages	Lifetime time extension e.g. through retaining and refurbishing	Demolition rate: number of buildings demolished over a given timeframe (measured as tons/capita)
		Reducing waste/wastage rates/ waste generation from construction activities	
	Demolition; concept/ planning stages	Lifetime extension e.g. through retaining and refurbishing	Average age at demolition (years)
		Reducing waste/wastage rates/ waste generation from construction activities	

6.8 Discussion

This chapter explored the definitions of a circular building in terms of object and process, building lifecycle models and design frameworks through a literature review.

By comparing the definitions of a circular building (Table 6.15), we observed that the definition focus is varied: two of them look at the circular building as a process, two of them at the circular building as a resulting object and three of them consider both aspects. All of them are centred around the circular flows of building materials and products implemented through strategies applied to building design, operation and end-of-life to keep resources at optimal rates and utilities.

While the circular flow of building materials is consistently considered in the definitions, a wider approach to resource circularity (water, energy, and materials) and biodiversity is not well-established. Moreover, while a focus on technical areas of impact is consistently observed in the definitions, social areas of impact are rarely considered. Only one definition applies a more holistic approach considering the circularity of multiple resources (materials, energy, and water) flows and biodiversity and including social aspects—i.e., human culture and society, health and well-being—and multiple forms of value [9, 15]. This is consistent with the literature on the evolution of the CE approach. Until now, the implementation of a CE has mainly adopted a technocentric approach focused on circulating resources through economic and technical innovation progressively expanding from single products/components to building and urban systems. However, while it has been mainly focused on the technical aspects of circularity, it has also recognized the crucial role of users and in general stakeholders and dynamics in socio-technical systems like buildings and the built environment. Based on this analysis, Zimmann et al.'s definition [11] may be the most representative and comprehensive of what a circular building is currently while

Table 6.15 Circular building definitions: (1) [10]; (2) [11]; (3) [9, 15]; (4) [13]; (5) [12]; (6) [14]

Criteria	(1)	(2)	(3)	(4)	(5)	(6)
Definition focus						
Circular building (object)	•	•	•	•	•	
Circular building (process)		•	•		•	•
Impact areas—technical						
Material cycle	•	•	•	•	•	•
Energy cycle			•			
Water cycle			•			
Biodiversity and ecology			•			
Impact areas—social						
Human culture and society			•			
Health and well-being			•			
Multiple forms of value			•			

Kubbinga et al.'s definition [9] later adopted by OECD [15] may offer a perspective for further implementation.

The analysis of the building life cycle in circular buildings showed a variety of building life-cycle models in terms of the number of phases and allocation in the process time frame (Table 6.16). By comparison, it emerged that the EN 15,978 (2011) model and Kubbinga et al.'s model [9] are both arranged in 5 stages, but they differ in the inclusion of a stage beyond the life cycle in the first model and the inclusion of a design stage in the second model after the production stage. The other 2 models [8, 16] introduced two additional stages before the design stage and moved the manufacturing stage close to the construction.

An integrated model of 6 stages that combines the first two models with the latest two is formulated to be adopted in the framework comparison. It is composed of the following stages: (1) the strategic stage (concept and procurement), (2) the design stage, (3) the manufacturing stage, (4) the demolition and construction stage, (5) the use and refurbishment stage, and (6) the end-of-life stage.

Then, the study investigated design frameworks developed to support the implementation of circular buildings to identify suitable propositions to assess the level of implementation of the circular building concept. The study identified 10 frameworks that embed CE strategies within building design to implement circular buildings and classified them into two categories:

(1) Frameworks of design strategies to achieve established circular principles.
(2) Frameworks of design strategies to be implemented throughout phases of the building life cycle.

The literature did not show any framework of design strategies based on life cycles according to the classification proposed by Franconi et al. [7]. Therefore, we conclude that this category has not yet been implemented in circular building design while it is observed in other design areas such as product design.

The analysed frameworks provide sets of design strategies summarized in key principles/objectives or building life cycle phases to ensure effective integration within the process. Table 6.17 compares the sets of strategies of 9 frameworks.

The Circular Economy System Enablers Framework [24] is not included since it is not comparable to the others. This comparison highlighted that currently available frameworks have sets of strategies that are not fully aligned. It also showed that 3 frameworks [8, 13, 23] are comparable in terms of the set of strategies. They show similar strategies even though Surgenor et al.'s framework is based on circular principles while Arup and Ellen Macarthur Foundation's framework [23] and Brincat et al.'s framework [8] are based on building lifecycle phases. Interestingly Brincat et al. defined their set of strategies, as well as critical indicators to assess them by consulting key stakeholders across the construction value chain.

Based on this comparison, we developed two visual charts (Figs. 6.2 and 6.3) to help identify trends and gaps and distinguish a set of frameworks to evaluate the level of implementation of circular buildings.

The first chart (Fig. 6.2) shows that the research on circular building design has moved from sets of strategies to achieve circular objectives/principles to sets of

Table 6.16 Building life cycle models: 1) EN 15,978:2011; 2) [9]; 3) [16]; 4) [8]

(1)	(2)	(3)	(4)
		Strategic definition	Concept
		Preparation and briefing	Procurement
Product stage	**Production stage**		
A1: raw material extraction and supply	raw material extraction and processing		
A2: transport to manufacturing plant	Transportation to factory		
A3: manufacturing and fabrication	Energy, waste, water use in factory		
	Design stage	**Concept design**	**Design**
	Design of building	Spatial coordination	–
	–	Technical design	–
		Manufacture and construction	**Manufacture**
			Demolition
Construction stage	**Construction stage**		**Construction**
A4: transport to the project site	Transport to location	–	–
A5: construction and installation process	Building installation	–	–
Use stage	**Use stage**	**Handover**	**Handover, use, asset, management**
B1: Use	Use	Use	–
B2: Maintenance	Maintenance	–	–
B3: Repair	Repair		**Refurbishment, adaptive reuse, renovation, maintenance, and repair**
B4: Replacement	Replacement		–
B5: Refurbishment	Renovation		–
B6: operational energy use	Operational energy consumption		–
B7: operational water use	–		–
End of life stage	**End of life stage**		**End of life and deconstruction of future assets**

(continued)

Table 6.16 (continued)

(1)	(2)	(3)	(4)
C1: deconstruction, demolition	Reconstruction/ demolition		–
C2: transport to disposal facilities	Transport		–
C3: waste processing for reuse, recovery and recycling	Waste processing		–
C4: disposal	Disposal		–
–	Reuse, recovery, recycling		–
Benefits and loads beyond the system boundary			
D1: reuse, recovery, recycling potential			

strategies to be implemented across the building life cycle. Initially, research focused on the definition of what a circular building is and how to implement it by design through circular objectives/principles and sets of related strategies. Then the focus moved to the building lifecycle and how to implement a circular building at different stages of the building lifecycle process through strategies or tasks to be performed during the process. The frameworks based on circular principles (see quadrants 1 and 2 of the chart) help define circular building features and performances as well as assess whether it is a design solution or an existing building. This category shows relevant frameworks to be applied in practice. In this category, the most recent frameworks provide sets of strategies as well as indicators to assess circular buildings mainly in technical areas of impact (specifically the materials cycle) and only one includes social areas. Only the Framework for Circular Buildings developed by Kubbinga et al. [9] considers holistically all the resources (materials, water, and energy) and values involved in the development, use and recovery of a building. Moreover, it included social areas of impact for evaluation and provides measurable criteria and indicators in both technical and social areas. The socio-technical approach adopted in this framework to assess circular buildings may be further developed and applied in future. The frameworks based on the building life cycle process (see quadrants 3 and 4 of the chart) help perform the process. This category guides the performance of the design process or the whole building life cycle process to implement circular buildings through tasks, targets and stakeholder collaboration. The Circular Buildings Toolkit [23] focuses on the design and construction stages while the other three frameworks in this category include the whole building lifecycle process. The Circular Buildings Toolkit provides a list of tasks to be performed in the strategic, design and construction stages to implement circular buildings. It also integrated main circular objectives to achieve through task implementation and related indicators for assessment. This

Table 6.17 Circular Framework/Strategy Comparison: 1. ReSOLVE Framework [11, 19]; 2. Applying circular economy principles to building design [10]; 3. Framework for circular buildings [9]; 4. Circular economy guidance for construction [13]; 5. Circular Economy Statement [20]; 6. Regenerate [21, 22]; 7. Building life cycle stages and Circular economy strategies [14]; 8. Circular Buildings Toolkit [23]; 9. Circularity Strategies and Indicators in the Construction Industry Ecosystem [8]. (*) it does not report 4 additional strategies—avoiding loss of biodiversity, integrating eco-system services, ensuring comfort, ensuring long-term aesthetics, and knowledge development—which are included in this framework and are missed in all the other frameworks

(1)	(2)	(3) *	(4)	(5)	(6)	(7)	(8)	(9)
	Reclaim/reuse	Reutilize	Reuse the existing asset				Refuse new construction	Increase reuse of products/ materials
Share		Facilitate shared amenities and services	Share materials or products				Increase building utilization	
Loop	Recycle/compost	Water cascading	Recover materials and products			Design for recycling		
	Refit/retain/ refurbish		Design for longevity	Design for longevity		Building operation	Design for longevity	Lifetime extension, improving durability, lifespan, repairability
	Building in layers		Design for flexibility					Design for flexibility and adaptability
Optimize	Design for adaptability		Design for adaptability	Design for adaptability	Design for adaptability		Design for adaptability	

(continued)

Table 6.17 (continued)

(1)	(2)	(3) *	(4)	(5)	(6)	(7)	(8)	(9)
	Design for disassembly/ remanufacture		Design for disassembly, recoverability	Design for, recoverability	Design for deconstruction	Building for disassembly	Design for disassembly	Design for future disassembly and reuse
	Take back models	Optimize material use/ energy demand	Use standardization	Minimize materials/ resources used	Optimize	Building optimization	Increase material efficiency/Refuse unnecessary components	Improve material efficiency/ intensity/mass of materials used
Regenerate	Selecting materials	Circular materials, sustainable local energy	Use recycled or secondary material	Source resources responsibly, sustainably	Circular material selection	Building materiality	Reduce virgin materials	Increase recycled or/and secondary content of construction products/ materials
Virtualize	Performance-based models		Products as a service					Product as service, new business model
		Minimize water/energy consumption	Use low-impact new materials				Reduce carbon-intensive materials	

(continued)

Table 6.17 (continued)

(1)	(2)	(3) *	(4)	(5)	(6)	(7)	(8)	(9)
Exchange	Design out of waste	Avoid toxic materials and pollution	Design out waste	Design out of waste		Building end-of-life	Design out hazardous polluting materials	Reduce waste generation from construction
			Reduce construction impacts	Manage demolition/ excavation/ construction/ waste		Building construct- ion		Increase reuse/ recycling of construction/ demolition waste

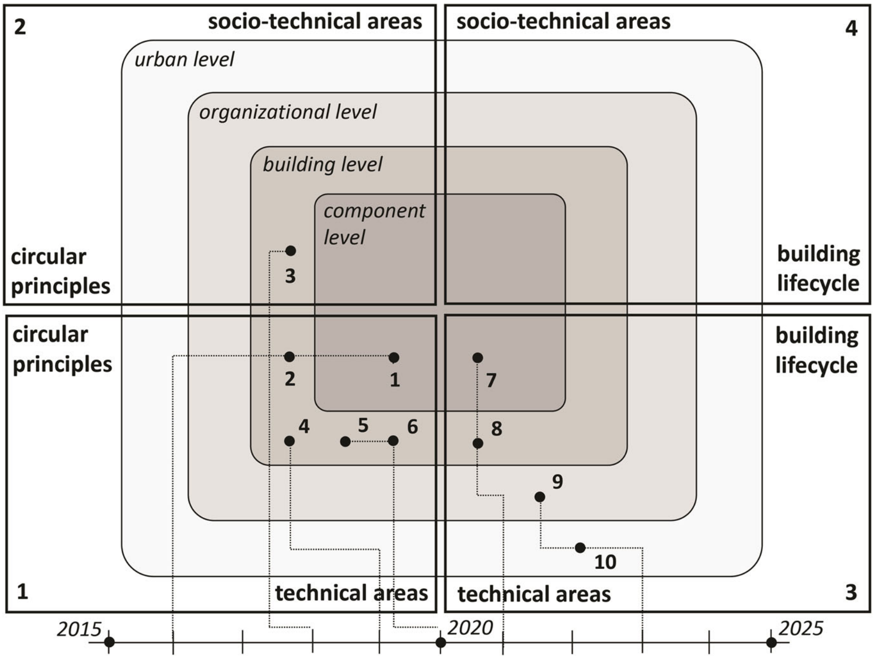

Fig. 6.2 Design framework map for circular building design

framework can support the design team in the collaborative process of implementing a circular building from the strategic to the construction stages. Similar to the other frameworks in this category, this one is implemented in the technical areas of impact while social areas are not included.

The second chart (Fig. 6.3) shows that most of the frameworks were developed to support the design and construction stages while recently they extended their aim to support the whole building lifecycle process. Frameworks based on circular principles showed through time the inclusion of indicators linked to strategies for assessment. Frameworks based on the building lifecycle process showed through time the identification of strategies and indicators for evaluation to promote collaboration among different stakeholders involved in the process. This progression displays an increasing awareness that a CE cannot be implemented in isolation. CE design principles need to be mutually connected to other critical enablers to shape successful circularity. Tailored actions for stakeholders at every level need to be performed collaboratively to advance the implementation of a circular built environment.

This study also showed gaps in research on circular building design. An integrated framework that combines circular principles with the lifecycle stages across the whole building process to support collaboration among stakeholders while providing indicators for assessment is missing. This framework may combine tasks to be performed by different stakeholders individually or collaboratively at each stage of the building lifecycle for supporting the implementation process with circular

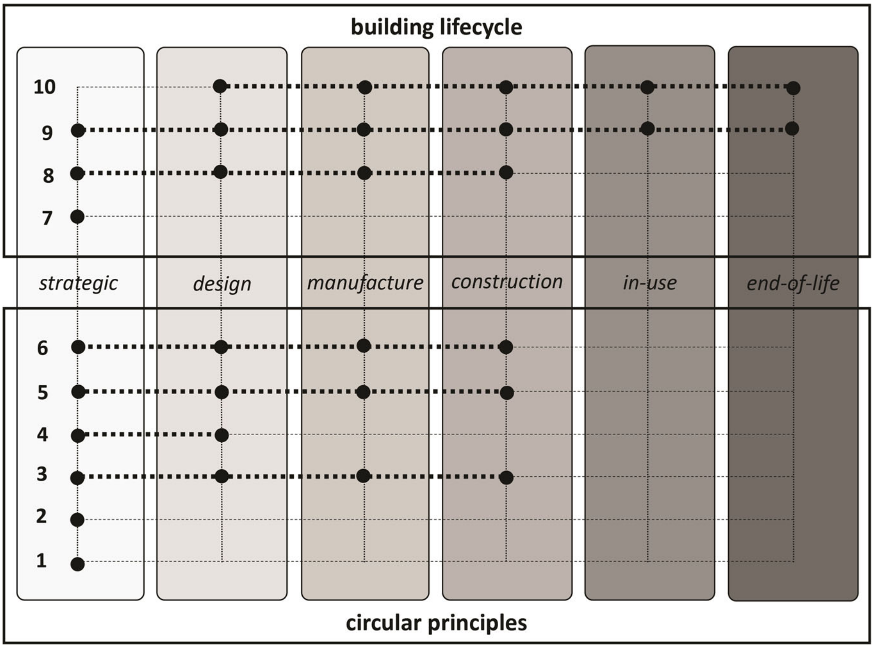

Fig. 6.3 Design frameworks for circular buildings and supported stages

principles and measures for supporting circular building assessment. Arup and Ellen Macarthur's Foundation framework [23] and Liebetanz and Wilde's framework [24] may be combined to develop this integrated framework while Brincat et al. [8] may help to include indicators for assessment. Moreover, frameworks that support the building life cycle process with wider consideration of impact in socio-technical areas are still missing. In the technical areas, most of the frameworks support the circularity of materials while other resources like water and energy are partially considered. Also, social aspects are currently limitedly explored. The interest in a more holistic approach to circular building design considering the circularity of multiple resource flows (materials, energy, water) and biodiversity, as well as social aspects (i.e., human culture and society, health and well-being, and multiple forms of value) is expected to grow in the next future.

6.9 Conclusions

This study aimed to provide an understanding of current knowledge on circular building design in terms of definitions, life cycle stages and design strategies by a literature review to identify appropriate propositions to assess the current level of implementation of circular buildings.

Through this exploration, it emerged that:

- The circular building definitions implemented in terms of building and process are mainly technocentric and focused on circulating resources (mainly materials) through economic and technical innovation. Definitions and design support implementation have progressively expanded from components to more complex systems at the building and urban levels. The enlargement of the design scope has also entailed a shift from insular to systemic.
- There are a variety of building life cycle models in terms of the number of phases and their allocation in the process time frame. An integrated model is proposed, and it is composed of 6 stages: (1) the strategic stage (concept and procurement), (2) the design stage, (3) the manufacturing stage, (4) the demolition and construction stage, (5) the use and refurbishment stage, and (6) the end-of-life stage.
- The design frameworks that embed CE strategies within building design to implement circular buildings can be classified into two categories based on circular principles and building life cycle phases. The category of design strategies based on life cycles observed in other design areas such as product design has not yet been implemented in circular building design.
- In circular building design, resources like energy, water and biodiversity are still partially considered compared to materials which is well-addressed. Moreover, social areas of impact like human culture and society, health and well-being and multiple forms of value are not yet consistently included. However, recent literature shows a growing interest in this direction.
- While the circular building concept and its design implementation have been mainly focused on the technical aspects of circularity, they have also shown recognition of the crucial importance of the role of users, communities, and more in general stakeholders and dynamics in socio-technical systems. Design frameworks focused on supporting collaboration among stakeholders across the building life cycle are emerging. This evolution reflects the growing awareness that systemic changes for environmental and social benefits in large urban socio-technical systems can be only achieved by collaboration combining technical and social innovations.
- This study allowed identifying frameworks to be used to evaluate the current level of implementation of circular buildings. The Circular Buildings Toolkit [23] may be used in the evaluation of the current level of implementation of circular buildings limited to the design and construction stages in combination with Brincat et al.'s framework [8] to integrate indicators for assessment.
- The design framework comparison allowed identifying gaps that may be addressed in future research development. An integrated framework that combines tasks to be performed by different stakeholders individually and collaboratively at each stage of the building lifecycle for supporting the implementation process with circular principles and measures for supporting circular building assessment is missing. Moreover, frameworks that support the building lifecycle process with consideration of impact in socio-technical areas are not yet available.

Based on the results from this study, the next steps will focus on selecting relevant case studies of circular buildings in their real-life context and assessing them through a comparative case study to understand the level of implementation of the circular building concept. Scores obtained from these cases will be analyzed qualitatively and quantitatively and results will be compared to define if the circular building is still a utopian concept or if it has been realized and in which measure it has been implemented.

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Chapter 7
Circular Material Usage Strategies—Principles

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Abstract The construction industry significantly contributes to global greenhouse gas emissions, raw material extraction, and waste production. Implementing circular economy (CE) principles in this sector could greatly reduce these impacts. However, adoption within the industry remains slow due to barriers such as limited knowledge and experience. This chapter aims to assess and help overcome these obstacles by providing a comprehensive analysis of circular material usage principles and strategies in construction. It also highlights opportunities and enablers of change, including innovations and emerging technologies in recycling, digitization, robotic systems, new materials, and processing techniques. Four case studies illustrate the application of circular theory through a Bio-Building, Urban Mining and Recycling (UMAR) Experimental Unit, Open-spaced apartment, and an "*Escuela Politécnica Superior*". The conclusions emphasize the need for strong regulatory frameworks, awareness initiatives, and international cooperation. Integrating technological advancements

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like AI, robotics, and blockchain is crucial for optimizing waste management. Additionally, education on circular practices is vital. By fostering global collaboration, standardizing circular construction approaches can lead to a more sustainable and resilient building industry.

Keywords Circular economy · Buildings · Circular materials · Strategies · Principles · Overview

One of the main waste flows in the European Union (EU) is construction and demolition waste (CDW), representing in 2018 around 36% of total waste generated [1]. Besides soils, concrete, bricks, gypsum, wood, glass, metals, plastic and solvents are the most often CDW found in the EU-27 countries [2], exhibiting not only a high resource value, but also a high potential for re-use and recycling [1]. Even with high financial penalties, illegal fly-tipping of CDW continues to take place (Fig. 7.1). In this context, the EU has made the management of CDW a priority [3] and the Waste Framework Directive (WFD) 2008/98/EC [4] imposed a mandatory recovery target (70% recovery rate of CDW in weight by 2020). Included in these recovery activities are "the preparation of non-hazardous CDW for re-use, recycling and other material recovery, including backfilling operations" [1].

This chapter presents an updated review of circular material usage principles and strategies within the construction sector. First, some basic concepts about circular economy and material usage are presented as an introductory framework. Next, the main principles for circular material usage at the design stage are described. After, the circular material usage strategies and principles in construction activities are presented, including: extending lifespan and end-of-life strategies, collaborative approaches and business models, technological innovations, main barriers and enablers of circular material usage. Finally, to conclude this subsection, some best

Fig. 7.1 Construction and demotion waste illegally discarded in the middle of a forest

practices related to the previous theoretical concepts about circular material usage in the building industry, are illustrated using some selected case studies.

7.1 Understanding Circular Economy and Material Usage Section

The circular economy (CE) is a model of production and consumption which focuses on retaining existing materials and products as long as possible and reducing waste [5]. Circularity aims to move away from the traditional linear model of 'take-make-dispose' where materials are extracted, manufactured into products, and ultimately disposed of. Instead, it focuses on creating a closed-loop system where materials are continuously reused, recycled, or regenerated to minimize the need for new resources and reduce the environmental impact. In the built environment, there is no clear and accepted definition of a CE [6]. However, a circular built environment can be a sustainable approach which caters to the growing needs of the sector without causing additional detrimental impacts on the environment.

The EU has agreed to reduce greenhouse gas emissions by 55% by 2030 (of 1990 levels) and to become carbon neutral by 2050 [7]. Although figures fluctuate year on year, the Circular Economy Action Plan [8] attributes 50% of extracted material and 35% of the EU's waste generation to construction. The sector accounts for 5–12% of total greenhouse gas emissions through material extraction, construction product manufacture, and building work. This includes cement, aluminium, steel, brick and glass production which account for approximately 9% of global energy related CO_2 emissions [9]. Confounding this issue, 10–15% of building material is wasted during construction and the majority of demolition waste is currently landfilled in the EU [10]. National construction and demolition waste (CDW) recycling rates vary greatly across Europe, from 10 to 90% [11]. A CE has the potential to reduce global CO_2 emissions from building materials by 38% by 2050 [12, 13].

According to the Ellen MacArthur Foundation [14] the three principles of a CE are: the elimination of waste and pollution, the use of circular products and materials and thirdly, the regeneration of nature. Within these principles, there are several subcategories and concepts which will be discussed below.

7.1.1 Eliminating Waste and Pollution

The first principle aims to move away from a linear system whereby raw materials are extracted, consumed and eventually thrown largely into landfills and incinerators. In circular design, raw materials use is minimized, and materials can be designed to remain in use for multiple cycles by following the R principles. There are many versions of the R principles for a CE which are based on the original 3;

Prioritised for a Circular Economy	Reduce	R1 Refuse	Don't use it, make a product redundant e.g. is the structure necessary, can you use something existing?
		R2 Rethink	Rethink use, can it be shared or serve multiple functions e.g. sharing of equipment between sites, adaptive use
		R3 Reduce	Use less of it e.g. efficient / optimised design, off-site manufacture
	Reuse	R4 Reuse	Reuse of product, e.g. reuse of windows elsewhere on the site
		R5 Repair	Repair or maintain, keeping original function e.g. weatherproofing
		R6 Refurbish	Refurbish, restore or update e.g. retrofit
		R7 Remanufacture	Use parts in a new product with same function e.g. remanufactured construction equipment
		R8 Repurpose	Use product or parts in new product with different function e.g. structural bricks to decorative internal
	Recycle	R9 Recycle	Process materials which can be same or lower quality, e.g. recycled aggregate
Low priority		R10 Recover	Energy recovery via burning e.g. Biomass from timber construction industry

Fig. 7.2 Circularity hierarchy of principles in the product chain with examples from construction. Based on a table by Potting et al. [19]

Reduce, Reuse, and Recycle. This can then be subdivided multiple times to make to up to 14 and even 22 Rs [15, 16]. Reike et al. [17] identified 38 "re-" words, as listed next by alphabetic order: "re-assembly, recapture, reconditioning, recollect, recover, recreate, rectify, recycle, redesign, redistribute, reduce, re-envision, refit, refurbish, refuse, remarket, remanufacture, renovate, repair, replacement, reprocess, reproduce, repurpose, resale, resell, re-service, restoration, resynthesize, rethink, retrieve, retrofit, retrograde, return, reuse, reutilize, revenue, reverse and revitalize". Ten of the most common include: Refuse/Reject, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. Figure 7.2 indicates the hierarchy of these, prioritized from 1 to 10 based on maximizing resource efficiency, minimizing waste generation, and highest value creation and retention. Recycling and recovery are ranked lowest because of the loss of complex state and the need for higher energy inputs [18].

7.1.2 Use of Circular Products and Materials

Circular Materials used within construction can be largely divided into two groups; low or zero-carbon materials such as wood and reused or recovered materials with minimal reprocessing or transport-related emissions [20]. The technical cycle and the biological cycle support circular material use and are illustrated in Fig. 7.3.

The technical cycle on the right involves materials such as metals, concrete, plastics, glass, or synthetic composites in building products. At the end of a structure's life, or construction products' life, these materials are recovered from the demolition or deconstruction process, sorted and processed before being reprocessed or reused in construction or other applications. The inner loops in the Fig. 7.3 butterfly

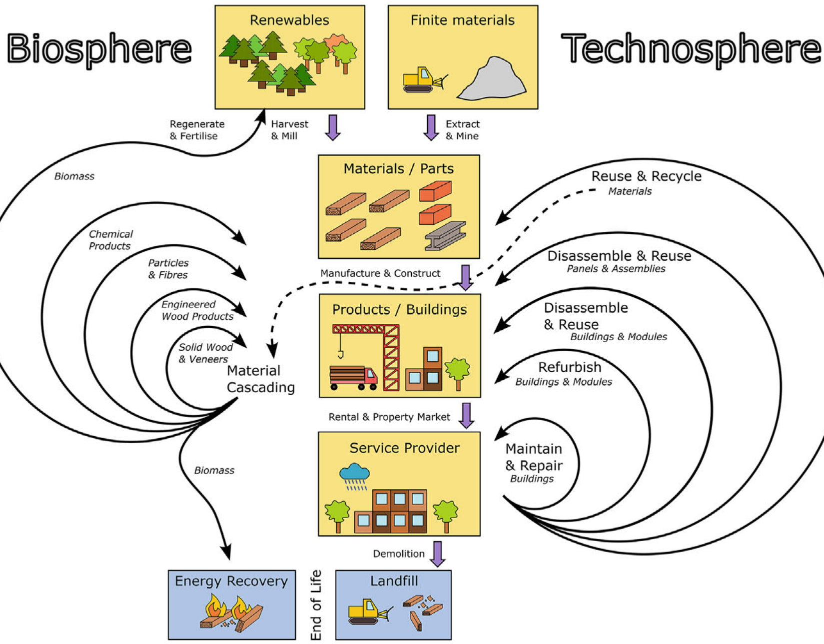

Fig. 7.3 Circular economy butterfly diagram interpreted for the construction industry by Ottenhaus [22]

diagram applied to the construction industry, retain most value in the material or product. This is based on the more general circular economy butterfly diagram [21], in which the innermost loop, 'Maintenance', prolongs the life of the material or product. This is followed by 'Reusing' and 'Redistributing' which keeps materials in their original form and displaces the need to manufacture new items or extract new materials. 'Refurbishing' and 'Remanufacturing' then include some processing and the outmost loop, 'Recycling', is a last resort when other options are not possible.

The biological cycle, or bio-loop, only includes materials that can be safely regenerated in the biosphere via composting or anaerobic digestion such as timber, bamboo or straw. Materials from the technical cycle can end up in the biological cycle, once they can no longer make a product. The inner loops of the left side of the butterfly diagram shows the 'cascading principle' which is the cascading use of renewable resources, with several reuse and recycling cycles [23]. For the construction industry, this is most applicable to timber, which could begin its first product life as solid timber beams and end its fifth life being incinerated for energy recovery [24]. Cascading ensures that biogenic carbon remains in the system for a longer period of time, resulting in lower environmental burdens and can support other industries such as farming via feedstock or soil fertilizer [25].

7.1.3 Regenerate Nature

Circular construction can contribute to the regeneration of nature by incorporating strategies that support ecological restoration, biodiversity enhancement, and sustainable land management practices. The aforementioned biological cycle contributes to biodiversity and ecosystem health by promoting the use of renewable materials that can be regrown and replenished. Maintaining materials in use also contributes to this principle as less land is required for sourcing virgin raw materials, which allows more land to be returned to nature.

While circular construction materials hold great potential for sustainable and resource-efficient building practices, there are several challenges that need to be addressed to facilitate widespread adoption. The details of the challenges faced can be specific to each stakeholder's role. However, they can be broadly grouped as economic, informational, institutional, political and technical challenges [26] with commonly encountered subcategories listed in Table 7.1.

A key challenge in the sector is the volume of existing buildings not designed for deconstruction, containing toxic materials, and lacking detailed documentation [28]. Reused materials require additional time and more qualified labour, and there is a lack of market mechanisms to aid recovery [6]. A system needs to be developed

Table 7.1 Challenge areas for a circular built environment compiled from review articles [6, 26, 27]

Challenge subcategories	Challenge
Economic	– Lack of grants/unclear financial case
	– Lack of financial aid, incentives or short-term benefits
	– Low value of circular materials
	– Cost of upfront investment
Informational	– Lack of research, education and information
	– Lack of awareness, interest and knowledge
	– Lack of best practice case studies and leadership
Institutional/structural	– Lack of strategic vision and collaborative platforms
	– Fragmented supply chains
	– Lack of market mechanisms for recovery
Political	– Lack of regulatory instruments/regulatory pressure
	– Lack of tax actions
	– Lack of circular vision
Technological	– Lack of integrated processes, tools, and practices
	– Lack of an information management system
	– Complexity of buildings
	– Technology and infrastructure readiness

which supports the use of circular materials which includes quality assurance, standardization, certification and classification, mechanisms for transport and storage and access to the market [26, 29].

Finances, or lack of financial case, were identified as a leading barrier for stakeholders [6, 10, 27]. For circular construction materials, this includes the high availability and low cost [27] of virgin raw material, the cost of deconstruction, the work involved in providing the material for reuse, the cost of recycled/reused materials, and the lack of reward or penalty [26].

Institutional or informational challenges include the lack of guidance and tools, and lack of knowledge [26]. Stakeholders throughout construction value chains in Europe are unfamiliar with how CE principles do or could operate in the built environment, with many unable to identify first steps in initiating the transition to a CE [10].

Addressing these challenges requires collaborative efforts from various stakeholders, including policymakers, industry professionals, researchers, and end users. Overcoming these barriers will pave the way for a more widespread adoption of circular construction materials, however there is a need initially to provide evidence, compile best practice examples and develop guidance.

7.2 Design Principles for Circular Material Usage

7.2.1 Designing for Circularity

There are several principles within the design stage to promote circularity in building constructions. These principles can be clustered into the following points [30, 31]:

- Design standardized products and materials, using regular and simple modular shapes to avoid waste.
- Design to decrease the need to extract and produce virgin materials.
- Design using recovered materials: by detecting unused materials from technical or natural flows and transforming them into circular materials which can be incorporated within the production of new materials and products, promoting the design of materials with high recycled content.
- Design durable materials so that they can prolong their use in the building and therefore increase lifetime and delay the end-of-use cycle.
- Design considering the setting procedure of the materials, so that the materials can be easily disassembled: Materials should be designed thinking that, when placed in a construction project, they should allow deconstruction and promote reuse and recycling. For example, using mechanical joints to avoid the use of binders and adhesives.

7.2.2 Material Selection and Management

The construction sector, in particular, plays a pivotal role in transitioning towards a less resource-intensive economy by maximizing the use and recovery of resources in building design and construction. Sustainable material sourcing and efficient recycling techniques are crucial for achieving a circular economy.

1. *Criteria for Selecting Circular Materials*

The EU emphasizes the significance of applying circular economy (CE) principles across all economic sectors, with a particular focus on water and energy conservation, waste prevention, material recycling, promotion of reuse and repair, and utilization of secondary raw materials [32].

CE in the construction sector aims to maximize the use and recovery of resources and buildings, reducing the environmental impact. Thus, it is of importance that designs aim to extend the useful life of buildings through rehabilitation, using recyclable materials; and the usage of new industrialized long-life materials based on recovered and valued resources. Additionally, adopting new industrialized long-life materials derived from recovered and valued resources can contribute to sustainable practices [33]. By implementing these recommendations, the construction sector can play a pivotal role in transitioning towards a less resource-intensive economy and fostering circularity. This approach aligns with the broader objectives of the CE, such as reducing waste generation, conserving resources, and promoting sustainable material use.

2. *Sustainable Material Sourcing*

Regarding the availability of raw materials, critical raw materials are of particular importance as their great economic importance for the European Union (EU); very sensitive to supply interruption; and being their extraction of a significant impact on the environment. Critical raw materials—e.g., lithium, are often present in electronic devices. The current low recycling rate of these materials means that significant economic opportunities are being lost. Thus, the fundamental directions that the circularity strategy must take at the European level are those that consider the need to incorporate these materials into reduction, reuse and recycling practices. To achieve autonomy with respect to these materials, the EU proposes diversified and undistorted access to global raw materials markets, while seeking to reduce external dependence on these materials as well as the environmental pressures associated with their import [32].

3. *Material Efficiency and Recycling Techniques*

The EU insists on the importance of incentives for the adoption of efficiency measures in the use of resources and for increasing recycling, eco-innovative performance, and investments in green products and services [32]. To move towards an economic model of material efficiency, economic priorities and lifestyles must be in line with reducing excessive economic material dependence by applying the principles of circularity—i.e., reduce and reuse before recycling [32]. Fundamental aspects of CE

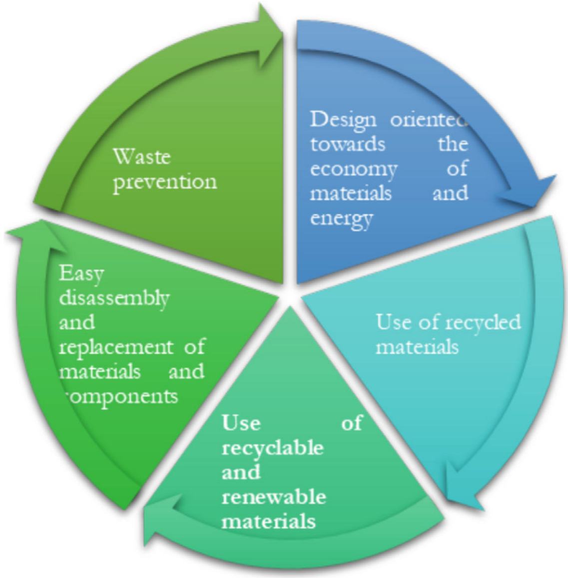

Fig. 7.4 Important recycle points (*Source* authors, based on S*ituación y evolución de la economía circular en* by Morató et al. [32])

related to recycling are: (i) design oriented towards economy of materials and energy, use of recyclable and renewable materials, and easy disassembly and replacement of materials and components; and, (ii) recycling and recovery of non-reusable materials [33].

Waste prevention continues to pose a major challenge in all Member States of the EU, including those with high recycling rates [32]. The use of recycled materials can contribute to partially covering the total demand for materials, thus reducing the extraction of raw materials. Creating efficient secondary materials markets enables higher value recycling cycles since most materials are recycled after disassembly. The principles are outlined in Fig. 7.4.

4. *Lifecycle Assessment and Material Management*

Production systems concerning efficient use of materials—given priority to activities allowing the development of CE principles from the beginning of the production process phases, and not only in its final dimensions; i.e., recycling and reconversion of waste—would serve as recommendations aimed at the change of economic models and the transition towards a less resource-intensive economy. Efficient use of materials in production systems is a critical aspect of the CE. It is essential to prioritize activities that promote CE principles from the beginning of the production process phases, rather than only focusing on recycling and reconversion of waste in its final dimensions.

This approach would serve as a recommendation aimed at changing economic models and transitioning towards a less resource-intensive economy. Innovative and effective methodologies to analyse the flow of materials and specific circularity indicators linked to the lifecycle are fundamental to addressing the transition to a circular model. These methodologies can help identify areas where material efficiency can be improved, and waste can be minimized [32]. They can also help to optimize resource allocation by identifying opportunities for reuse, recycling, or recovery of materials. By adopting such methodologies, companies can reduce their environmental footprint, enhance their competitiveness, and contribute to the development of a sustainable economy.

7.3 Circular Material Usage Strategies and Principles in Construction Activities

This sub-section is dedicated to reviewing the principles and strategies for circular material usage in the construction industry. First, some strategies for extending lifespan, as well for end-of-life products/materials are outlined. Next, some collaborative approaches and business models to foster a circular economy in the construction sector are described. Later, some technological innovations for circular material usage are assessed and exemplified. This is followed by a review of the main barriers and enablers of circular material usage in the building sector. Finally, some examples are presented of circular economy best practices within the construction sector regarding material usage, here identified as “case studies”.

7.3.1 Extending Product Lifespan and End-of-Life Strategies

Very often, the economy is filled with things that have been designed without asking: What happens to this at the end of its life? [34]. Therefore, it is very important to define at the design stage what will be the end-of-life strategies to promote CE of construction products and materials. The construction industry is making a gradual progressive transition to CE, as assessed and concluded by Charef et al. [35]. In fact, circular strategies are starting to be implemented by the building industry, as demonstrated by Nußholz et al. [36]. He analysed 65 novel real-world cases of new build, renovation, and demolition projects in Europe, regarding the circular solution applied, level of application in buildings, and decarbonization potential reported.

Several researchers developed and made use of disruptive technologies to foster the circular building industry. Setaki and Timmeren [37] outlined how disruptive, often digital, technologies can potentially enable a CE in the building industry, primarily within the two most wasteful phases of the building cycle, the construction and demolition phases. Moreover, regarding additive manufacturing, Tavares et al. [38] performed a state-of-the-art review regarding the evaluation of benefits and barriers of additive manufacturing for the circular economy, presenting also a framework proposal. Furthermore, artificial intelligence is being increasingly used to enhance the implementation of systemic circularity in the construction industry, as recently reviewed by Oluleye et al. [39].

As mentioned by Marsh et al. [40], the construction CE principles could be grouped as follows:

- Reduction of material use (through specification and design);
- Long-lasting design (increased durability);
- Maintenance, repair and refurbishing;
- Reuse and remanufacturing;
- Recycling.

One of the key principles for CE is to keep the products and materials in use, for as much time as possible [41], i.e., long-lasting design by increasing longevity [40]. The goal is to maximize the utilization time of products and materials, promoting reuse, refurbishment, remanufacturing, and recycling. By extending the life of products, their value is retained, and the need for extracting and processing new resources is reduced. Nevertheless, Kirchherr et al. [42] concluded: "*that the CE is most frequently depicted as a combination of reduce, reuse and recycle activities*". They also noticed that "recover" is also often added to the previously listed CE activities, accomplishing this way a 4Rs framework, instead of 3Rs.

Besides increasing the durability of materials and products, it is also important to foster their repairability. Furthermore, a remanufacturing process should be implemented, and the product should be upgraded to its highest value, whenever possible.

With so many existing possibilities and possible approaches to address CE in existing buildings, it is very relevant to estimate the recoverable value of in-situ building materials. Mollaei et al. [43] developed a new computational tool to "choose the optimal combination of reuse, recycling and disposal options for those materials", taking into account "cost, value, duration, environmental impacts, and building component precedence in demolition and deconstruction activities".

According to Marsh et al. [40], the CE principles/strategies could be structured into three main groups, depending on the lifecycle stage, as listed in Table 7.2. As seen before, it could be defined many other strategies and included in this table. One example is the product/material recover from an end-of-life building to be later reused, remanufactured or recycled. Another example could be the thermal energy recovery from a combustible material (e.g., plastic or rubber) during a burning process. Obviously, both previous examples are for the end-of-use lifecycle stage.

Table 7.2 CE principles/strategies structured as function of the life-cycle stage: adapted from Marsh et al. [40]

Lifecycle stage	CE principles/strategies
Design-stage	– Reduction of material through specification and design
	– Long-lasting design
In-service	– Maintenance
	– Repair
	– Refurbishing
End-of-use	– Reuse
	– Remanufacturing
	– Recycling

This sub-section will focus mainly on strategies to extend product lifespan and on the available end-of-life strategies to foster circular material usage in construction activities.

1. *Extending product lifespan*

- *Increasing Durability by Maintenance, Repair and Refurbishment*

Maintenance, repair and refurbishing are all in-service strategies for slowing resource flows, by extending the technical lifetime of products and components [40]. Maintenance corresponds to a universal upkeep, and correspondent damage prevention works to building components (such as applying protective coatings). Repair and refurbishment are the overhaul of limited damage to a component, or the replacement of a spoiled component wholesale with a new one [40].

Designers should think about how their product could fit into the technical or biological cycles after use, so that product could be made with that onward path in mind. This way, products destined for technical cycles would benefit from being easy to repair and maintain, easy to take apart, and made of modular components that can be replaced [44]. They should be durable enough to withstand the wear and tear of many users. Moreover, they should be made from materials that are easily recycled.

The most efficient solution would be to use self-healing materials to extend their lifetime and, at the limit, to make "immortal" products or components, as studied by Haines-Gadd et al. [45].

2. *End-of-life strategies*

- *Upgrading and Remanufacturing*

During the previously mentioned durability increasing processes, when the product can no longer be used, its components should be, whenever possible, remanufactured and upgraded [46].

Upgrading and remanufacturing are both product end-of-use strategies, intended to slow resource flows by continuing the use of still-functional components from end-of-use products in new products. Atta [46] delineated the involvement of digital technologies in supporting the implementation of circular service-based models built on remanufacturing in current construction practices.

Strategies for upgrading and remanufacturing of building components should be predicted at design stage. Van Stijn and Gruis [47] developed an integral design tool for circular buildings components (CBC), called "CBC-generator". This software it is a parameter based "three-tiered design tool, consisting of a technical, industrial and business model generator", where the designers could select and compare several design options.

- *Reuse, Reverse Logistics and Take-Back Programs*

These are also end-of-use strategies. In fact, the most effective way of retaining the highest value of products is to maintain and reuse them. Taking a window as an example: it is more valuable as a window than as a pile of components and materials (PVC or aluminum from the frame, glass, etc.). So, the first steps in the technical cycle are focused on keeping products whole to retain the maximum possible value. This could include business models based on sharing, so users get access to a product rather than owning it and more people get to use it over time (e.g., rent equipment during the construction stage). It could involve reuse through resale. It could mean cycles of maintenance, repair, and refurbishment.

Reverse logistics (RL) which could be defined as a set of activities which are conducted after the sale of a product to recapture value and end the product's lifecycle, is also important to foster CE in the construction sector [48]. It typically involves returning a product to the manufacturer or distributor or forwarding it on for servicing, refurbishment or recycling. In construction, RL "refers to the movement of products and materials from salvaged buildings to a new construction site" [48]. This way we are promoting material reuse, as well as deconstruction and disassembly.

More recently, Ding et al. [49] performed a review about forward and reverse logistics for CE in construction and concluded that "while similar methods and CE strategies are used in Forward Logistics (FL) and RL, RL operations require more integration between supply chain actors to close the loop for CE in construction".

A take-back program is essentially when a brand 'takes' or 'buys' back its own materials or products. These are either cleaned, fixed and then resold by the brand at a discount or dismantled and reused in other collections or recycled in some other way. This strategy is also starting to be implemented by the construction industry [50, 51].

There is already a trade market for second hand building products and materials, such as windows and doors (see Fig. 7.5), lumber, flooring, furniture, masonry, tiles, stones, sheathing boards, appliances, architectural/decorative, lighting, heating and cooling devices, electrical, plumbing, etc., to be commercialized and reused [52–54].

(**a**) Window (rebuydeal.com [52]) (**b**) Door (rotordc.com [54])

Fig. 7.5 Examples of second-hand building products, for reuse, being traded online

- *Material Recovery*

Material recovery refers to the process of retrieving and reusing materials from construction and demolition waste (CDW). It involves identifying valuable materials within the "waste" stream and salvaging them for reuse or resale [55]. Material recovery typically involves activities such as deconstruction, which involves carefully disassembling structures to preserve valuable components. Recovered materials may include lumber [56, 57], cross laminated timber [58], bricks [59], and other items that can be repurposed in future construction projects. The goal of material recovery is to reduce waste generation, conserve resources, and minimize the environmental impact associated with extracting new raw materials.

It should be noted that CDW may have several sources, such as man- or nature-made, as illustrated in Fig. 7.6. Regarding the man-made sources of CDW, these authors split it into 3 groups, namely: (1) Public works construction and maintenance; (2) Building construction works, and; (3) Building renovation and demolition works. The main contents of these CDW, including the nature-made sources, are also mentioned in this illustration (Fig. 7.6).

Ramos et al. [60] evaluated a local scale dynamics to promote the sustainable management of CDW and concluded that these strategies must rely on investment in local solutions to optimize logistics and cost issues, cooperation between stakeholders, and improving the market for recycled aggregates. Additionally, they stated that it is essential that support is provided such as information, awareness and training, focusing on good practices onsite and oversight procedures. While material recovery

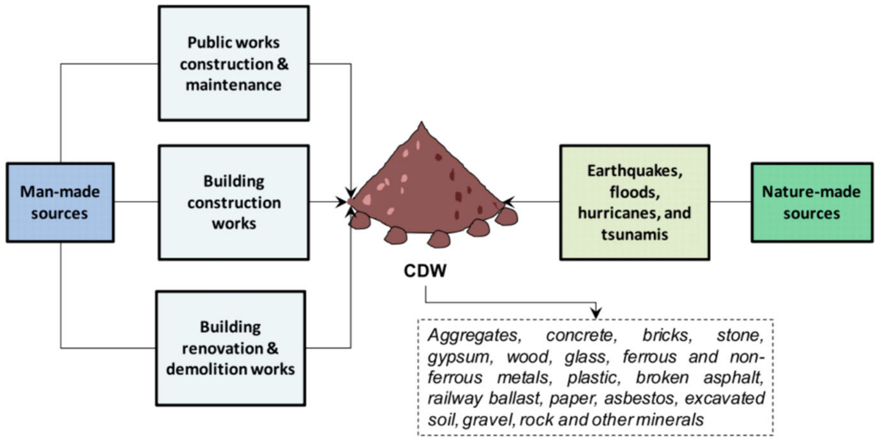

Fig. 7.6 Classification of CDW according to the source of origin [61]

focuses on salvaging and reusing whole components or materials, recycling involves breaking down waste materials to create new products or raw materials, as will be described next.

- *Material Recycling*

Recycling is an end-of-use strategy to close resource flows, by reprocessing materials to use in another product and hence avoid both waste and extraction of raw material [40]. Parts that cannot be remanufactured can be broken down into their constituent materials and recycled. While recycling should be the last option, because it means the embedded value in products and components are lost, it is vitally important as the final step that allows materials to stay in the economy and NOT end up as waste [34]. Recycling involves the transformation of waste materials into new products or raw materials, which can then be used for various purposes. In the construction sector, recycling commonly refers to the process of converting CDW into reusable materials. This can involve crushing, grinding, or shredding waste materials like concrete, asphalt, metal, and wood to create recycled aggregates [60], crushed concrete, or other materials that can replace virgin materials in construction projects.

There are a lot of studies on the viability and performance of new recycled materials, resulting from CDW, such as cement [62], concrete [63], mortars [64], gypsums [65], plasters [66], plastics [67, 68], insulation materials [69], bricks [70, 71], soil reinforcement [72] and fire-resistant materials [73]. Besides CDW, there are other sources of waste being recycled and studied to be used in the construction sector and building environment, such as: concrete [74]; mortars [75]; plasters [66, 76]; gypsum [65]; thermal break strips made of recycled tyre rubber [77, 78] and cork-rubber composites [77, 78]; plastics [79]; insulation materials such as recycled tyre rubber and silica-aerogel composites [80, 81].

7.3.2 Collaborative Approaches and Business Models

In this section, some of the innovations in business models that are affecting the construction sector in favour of CE applied to its products are collected.

1. *Circular Supply Chains and Networks*

Currently, the conversion of traditional linear supply chains into circular ones to improve the management of natural resources and reduce the volume of waste produced is included as one of the goals for the transition of the construction sector towards CE [82]. The amount of material lost in demolition processes is equivalent to 40% of the total mass of raw materials extracted in production, making the construction industry one of the most polluting industries globally [9]. In this sense, one of the most ambitious targets included in CE is "closing the loop" in the flows of raw materials and resources used throughout the life cycle of construction products [42, 49, 83]. Figure 7.7 provides a schematic overview of the relationship between the stages within the supply chain and the stakeholders.

In this general overview, a transition towards CE in the building materials supply chain requires a joint effort of all participants included in the network [84]. Therefore, it is necessary to increase transparency, avoiding possible weaknesses in the chain and gaps in the agreements. This would generate opportunities for industrial symbiosis and the integration of reverse logistics in manufacturing processes, moving towards a redesign of current industrial processes and improving coordination between resources/inventories [49]. On the other hand, the creation of a well-defined market for CDW would make it possible to increase consumer demand for these recycled products, moving towards a green supply chain that integrates the environmental costs derived from the product distribution process [26]. In addition, for a transition towards circularity in the construction sector, it is necessary to recover the secondary raw materials generated in demolished buildings at the end of their useful life and, in turn, to analyse their viability for recycling, recovery or reincorporation

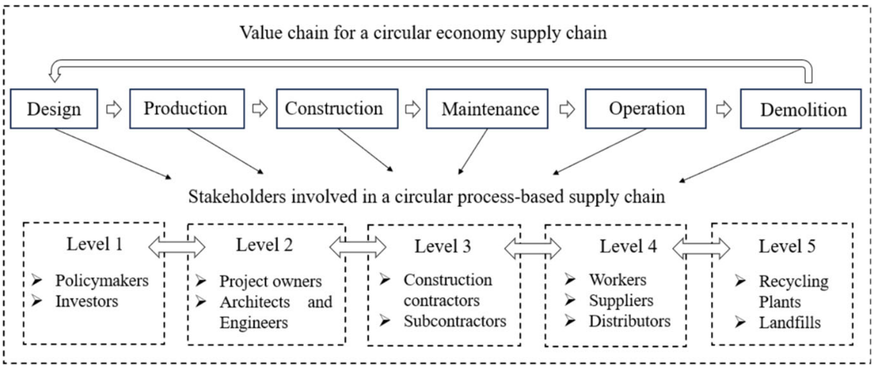

Fig. 7.7 Full supply chain cycle and stakeholders involved (*Source* own elaboration based on Cheng et al. [82])

in the production of new products [85]. At this point, several authors agree on the importance of reducing and separating CDW at source to improve its management process [86]. With this separation at the starting point, the logistical costs and environmental impact in terms of CO_2 equivalent emissions derived from transport to the processing plant would be reduced, so that both transport journeys and transported mass would be reduced.

2. *Sharing Economy and Product-as-a-Service Models*

Industrial strategies for value creation have changed radically in recent years as a consequence of globalisation and progressive technological development [87]. This evolution has affected the construction industry, which is evolving from product procurement-centred thinking towards product-service systems (PSS) [88]. In this way, building product manufacturers are forced to redesign their manufacturing processes and complexity increases in the early stages of development to accommodate this new business model [89]. By offering product-associated functionality, manufacturers are obliged to have a deep understanding of how their products behave after continuous use, which provides additional motivation to improve the skills associated with the engineering and product design stages through experience [90]. However, as in other industrial sectors, there must be a receptiveness on the part of consumers when it comes to accepting this product and service model. In this regard, Fig. 7.8 schematically shows the external and internal factors found in the literature that to a certain extent condition the acceptance of this business model in construction.

Several authors have worked with this business model trying to adapt different products to this "servitisation" process. Examples are linked to construction equipment [87], construction machinery [90], prefabricated building components [91] or building components [92]. Importantly, the product-as-a-service model brings

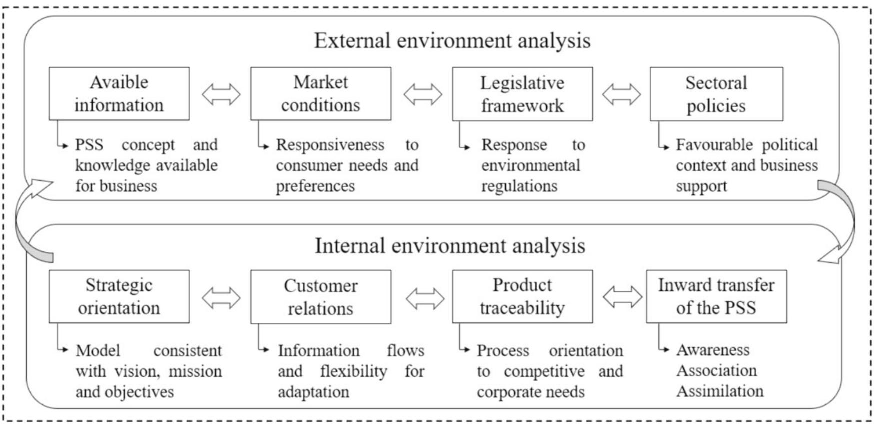

Fig. 7.8 Internal and external determinants of product-as-a-service models (*Source* own elaboration based on Cook et al. [89])

advantages from an environmental point of view, considering the full life cycle of the product and its subsequent recovery possibilities [93], as well as continuous improvement based on information sharing that boosts the sustainability of building products [88].

Finally, and in relation to the product-as-a-service business model, it is worth highlighting how in recent decades the collaborative economy has been encouraged to promote sustainability. This concept addresses the possibility of using high-priced physical assets without the need to buy them, reducing waste due to obsolescence or disuse [91]. Furthermore, thanks to the advancement of information and communication technologies, it is possible to promote a more democratic organization and reduce information asymmetries in favour of a CE in construction [94].

3. *Extended Product Responsibility*

Extended product responsibility (EPR) was first defined at the beginning of the century by Lindhqvist as a strategy to protect the environment and is intended to ensure that any product manufacturer takes responsibility for its entire life cycle, incorporating the stages of recovery, recycling, collection and disposal [95]. This approach would change the current production model affecting the construction industry by regularizing and setting the rules for the proper management of construction and demolition waste in line with the European Green Deal guidelines [1]. This approach is already being adapted for certain products around the world, such as European legislation for plastic products [96], or air conditioners and washing machines in Japan [97].

However, final construction products, understood as civil infrastructures or buildings, are complex and tailor-made entities in each design, which makes it difficult to standardize and trace the prototypes produced for the market [98]. In this sense, it is possible to think of an EPR localized to the main raw materials used in the elaboration of construction systems. However, the useful life of these is rarely less than 50 years and it is difficult to manage the final management of these products [98].

Therefore, as far as EPR is concerned, it is necessary to examine current initiatives, regulations and practices in the construction sector to understand their suitability and ability to address the issue of end-of-life management of CDW [99]. Only in this way, it will be possible to build a legislative framework for building and civil works, built on the "polluter pays" principle, encouraging producers to incorporate CE criteria in their manufacturing processes, promoting eco-design and supporting the recycling, recovery and final reuse of construction products [100, 101].

4. *Public–Private Partnerships and Policy Implications*

Public–private partnerships (PPPs) are a useful tool in the construction sector to leverage public resources and private management expertise in moving towards a circular and sustainable economy [102]. These partnerships are established based on a long-term relationship of trust, where resources, knowledge, skills and shared

Table 7.3 Advantages and disadvantages of public–private partnerships in the construction sector (*Source* Bao et al. [109])

Advantages	Disadvantages
✓ Public sectors can alleviate responsibility	✓ Long negotiation periods
✓ Private sectors can moderate investment	✓ Lack of flexibility
✓ Public sectors can draw on private sector expertise	✓ Inequality of risk and return
✓ Public–private partnership is strengthened in the long term	✓ Lack of transparency in Agreements

responsibility for decision-making are exchanged [103, 104]. However, these partnerships are not always favourable and have several advantages and disadvantages that can be seen in Table 7.3.

While it is true that PPPs are commonly accepted in the development of facilities, including design, financing and implementation [105], such as the supply of drinking water in large cities [106], in waste management for a CE there is still a long way to go. In the EU, progress is being made towards a policy framework to promote such an agreement to reduce the environmental impact of the construction sector [107]. However, this transition is slow and often not as efficient as desired and making infrastructure resilient will require a change of mindset on the part of private management and lasting support from governments [108].

7.3.3 Technological Innovations for Circular Material Usage

CE constitutes an impulse for improving the productivity of the construction sector with a need for investment in technology and digitalisation. According to Ferrer et al. [33], the scale and efficiency of networks of recycled, valued and recovered construction materials are fundamental to the following points outlined in Fig. 7.9.

Innovation ecosystems to boost re-industrialization and sustainability in the construction sector advocate the promotion and support of R + D + I (Research, Development and Innovation) and knowledge transfer instruments on: technologies 4.0; recycling and recovery of materials and components which are more complex to recycle (plastics, composites, waste); productivity improvements in component manufacturing and recovery (3D, robotics, Artificial Intelligence (AI), Internet of Things (IoT); new long-lasting materials; and materials traceability technologies (blockchain) [33].

1. *Advanced Recycling Technologies*

Resource recovery as business model and driver of CE focuses primarily on recovery of used materials or energy from waste—e.g., recycled steel and fibres, and recycled aggregates for their use in construction or in other sectors; being industrial and

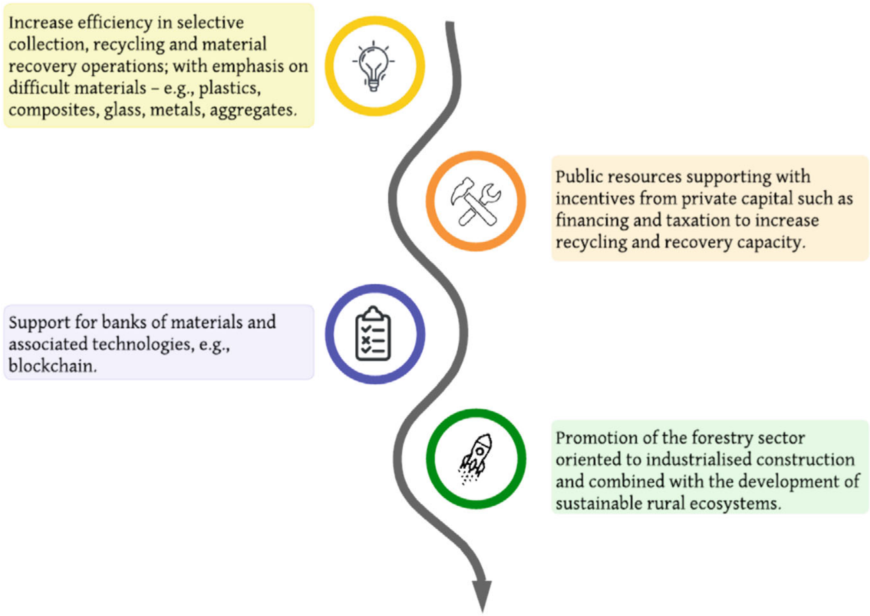

Fig. 7.9 Fundamentals in circular material usage (*Source* own elaboration based on Ferrer et al. [33])

energy symbiosis among complementary sectors essential for the adoption of the CE principles [33].

In the context of construction, disassembly and recycling best practices are employed to revalue the use of construction waste, which is often considered "low value" material. Testing methods for disassembly, treatment, and recycling would help to optimize the recovery and reuse of materials, contributing to the efficient use of resources in the production process [33]. By implementing these advanced recycling technologies, the construction industry can reduce waste, minimize the extraction of virgin resources, and promote a more sustainable approach to materials management. Furthermore, these technologies enable the transformation of waste into valuable resources, promoting the development of a CE. Recycled steel, fibres, and aggregates can be utilized in various sectors, including construction; creating a closed-loop system where materials are continuously reused and recycled. This not only reduces the environmental impact of resource extraction but also contributes to the development of a more resource-efficient and less wasteful economy [110]. Overall, advanced recycling technologies and resource recovery play a crucial role in driving the transition towards a CE by maximizing the value of waste materials and minimizing resource consumption. By adopting these technologies and principles, industries can contribute to a more sustainable and resource-efficient future.

2. *Intelligent Sorting and Separation Systems*

Intelligent sorting and separation systems are pivotal in advancing the principles of the CE by enhancing the efficiency and effectiveness of waste management and resource recovery processes. These systems leverage cutting-edge technologies such as AI, machine learning, computer vision, and robotics to accurately identify, sort, and segregate diverse materials. This enables their appropriate recycling, reuse, or recovery, thereby promoting sustainable practices. By automating the sorting process, these systems enhance the purity and quality of recovered materials, augmenting their value for subsequent reuse or recycling. Moreover, they optimize resource allocation by dynamically adjusting parameters, such as conveyor speed and sensor settings, thereby maximizing efficiency while minimizing waste. These systems also play a critical role in detecting and eliminating contaminants, thereby improving the quality of recovered materials and mitigating the risk of cross-contamination. With their exceptional accuracy and speed in sorting, they reduce manual labour requirements, increase throughput capacity, and enable the processing of larger volumes of waste. Furthermore, intelligent sorting systems generate valuable data pertaining to waste composition, quantity, and quality [33]. This data-driven approach facilitates informed decision-making, process optimization, and the development of novel recycling technologies. By integrating into circular supply chains, these systems facilitate the efficient recovery and reintroduction of recycled materials, thereby closing the loop in the CE. As technology continues to advance, these systems are poised to make significant contributions to resource efficiency, waste reduction, and sustainable material utilization.

3. *Digitalisation and Blockchain Applications*

The promotion of the guaranteed system for components and spare parts, digital traceability (European passport) and associated documentation are requirements for the delivery of sustainable and circular built environment [33]. Complementarily, financial aid for investments by industrialized and sustainable construction companies—e.g., modular design, BIM (Building Information Modelling), IoT digitalization, 3D printing, cutting robotics, …—, and support for components' banks and material passports, are proposed as drivers for offers in public–private collaboration [33].

Regarding circularity of materials, blockchain solution for materials passport embraces technology against the low transparency and traceability of the materials used—e.g., fibre plates, steels, coatings, facades. Collaborative design and manufacturing (BIM, IoT, …) benefit by the availability of new technologies which integrate design, with production and delivery systems—JIT (Just-In-Time) delivery—at the construction site.

4. *Robotic Deconstruction*

Technological innovations in deconstruction include advanced tools and techniques used to dismantle and repurpose buildings and structures in a more efficient, sustainable, and profitable manner. These innovations aim to reduce waste, minimize environmental impact, and improve safety during the deconstruction process. The use of robots for deconstruction is a promising approach that can improve efficiency and sustainability in the construction industry. Traditional demolition methods have significant risks and environmental impacts, especially in congested urban areas [111]. In Japan, alternative methods using Single-Task Construction Robots (STCRs) and semi-automated on-site factories have been developed to address legal, economic, and ecological needs. However, implementing traditional industrial robots in a deconstruction environment poses challenges, particularly in terms of human–robot interaction and collaboration. To overcome these challenges, efficient human–robot collaboration is considered in the design of deconstruction STCRs. Additionally, the application of the Robot-Oriented Design method can make the operation of the deconstruction system more efficient. Building components should be compatible with robotic applications, and connectors and joints between components should provide easy access for equipment during the disassembly phase. The use of robots for deconstruction can save energy, money, and time while minimizing casualties and disturbance to the economic environment [111]. A framework for the evaluation of robot-assisted, systemized deconstruction has been proposed, which includes performance indicators that can be adjusted based on stakeholder perspectives. Overall, the use of robots in deconstruction offers a scalable and sustainable solution for the industry.

5. *Emerging Materials and Sustainable Manufacturing Processes*

Innovation in materials, sustainable design, and the development of alternative technologies that require different materials can help mitigate supply risk. Solutions to reduce the ecological footprint and increase material recovery to improve the safety and competitiveness of production processes are within reach. However, global scenarios continue to present greater complexity and competition for natural resources [32]. The duration and footprints of carbon dioxide (CO_2), water and material consumption are lower in industrialized systems, being the environmental impact of circular and sustainable industrialized construction susceptible of different modelling scenarios of recycling percentage [33].

7.3.4 Barriers and Enablers of Circular Material Usage

Extensive literature has identified barriers and enablers to developing a circular economy in the construction sector. However, it is important to note that a circular economy is a multidimensional concept, and a closer inspection of existing literature reveals that barriers and enablers have primarily focused on the technical aspects of materials and products. According to a recent study by Charef et al. [112], barriers to the development of a circular economy in the construction sector can be categorized into six distinct types: economic (referring to market barriers), sociological (pertaining to cultural or psychological obstacles), political, organizational (involving stakeholders), technological, and environmental (concerning ecological impact). Similarly, Ababio and Lu [113] identified five categories of barriers: social and cultural, political and legislative, financial and economic, technological, and framework and theory related.

While research on barriers to circular economy development has been extensive, studies on enablers of the circular economy have yet to be conducted to the same extent. Ababio and Lu [113] have departed from classifying and listing enablers under specific categories and instead discussed them under broader themes. Generally, enablers are related to technology and innovation, policy, education and awareness, as well as financing and market creation. It is important to note that a comprehensive understanding of both barriers and enablers is critical for promoting a successful transition to a circular economy in the construction sector. This part of the report focuses on the material usage-related barriers to enablers addressed in the literature. They are discussed under four categories.

1. *Economic and Regulatory Barriers*

Numerous studies have identified insufficient and immature markets, as well as a lack of demand for reused and recycled materials, as the primary economic barriers to the implementation of circular economy practices in the construction sector [114–116]. These studies also suggest that the construction industry is often criticized for its poor flexibility in adopting innovative practices due to the perceived risk of losing profits [112, 115].

In the construction sector, adopting CE practices is met with a major challenge—the higher resource cost associated with deconstruction compared to demolition. Moreover, virgin materials tend to be less expensive than recycled materials, while recycling costs more than the disposal of CDW. Unfortunately, the recent COVID-19 pandemic has only worsened these challenges by stalling economic development and increasing the use of single-use materials. The implementation of CE practices in the construction industry requires significant investments, such as the renewal of equipment [116]. Moreover, outdated legislation and the lack of standardized guides regarding design and procurement procedures are major regulatory barriers to CE development [112, 117]. Additionally, a lack of government support and the absence of support from public institutions have been highlighted as critical barriers to CE adoption [112, 118].

In order to promote the integration of circular economy practices in the construction industry, it is necessary to adopt new business models and methods of evaluating assets that prioritize material value. For instance, long-term investments can be made to support the circular economy business case by utilizing whole-life costing. Another opportunity presented by the implementation of circular economy practices is the ability to transform the business model into a product-as-a-service contract (PSS), as noted by Rizos et al. [119]. Enablers that have been commonly identified include design-build-operate-maintain contracts and their variations, according to Ababio and Lu [113]. Furthermore, stakeholders in the construction industry have reported that implementing circular economy practices can offer more flexible working arrangements, as Torgautov et al. [117] reported.

2. *Cultural and Behavioural Challenges*

Cultural and behavioural changes can present significant obstacles to the adoption of innovative practices in the construction industry. This sector is known for its conservative nature and resistance to new ideas that challenge existing attitudes, customs, and beliefs. Some of the cultural issues that hinder the adoption of circular economy (CE) and sustainability practices among construction stakeholders include a lack of awareness, reluctance, and risk aversion. Moreover, there is a preference for virgin construction materials over reused and recycled products, which is reinforced by ingrained beliefs that circular economy practices are not feasible [112, 118].

Several studies have investigated stakeholders' perceptions of the adoption of CE practices in the construction industry. The literature reviewed in this section highlights that contractors are hesitant to use refurbished and recycled materials in their construction due to concerns about a potential decrease in the quality of their products [27, 112, 118]. Customers, on the other hand, may not prefer buildings constructed using old materials. Additionally, the quality of recovered materials is often perceived as inferior to virgin materials, further fuelling scepticism about the feasibility of CE practices [117].

3. *Stakeholder Engagement and Awareness*

In order to facilitate the widespread adoption of circular economy (CE) practices in the construction industry, it is important to address the existing cultural and behavioural barriers. This can be achieved through a variety of means, such as education, awareness-raising, and cultural change initiatives. By doing so, stakeholders can work towards creating a more sustainable and circular economy, which would not only benefit the industry but also the environment.

One effective enabling tool for increasing awareness, changing attitudes, and affecting behaviours is dialogue [113]. This can involve open and honest communication between different groups of stakeholders, including industry professionals, academics, and government officials. Through dialogue, stakeholders can gain a better understanding of each other's perspectives and work collaboratively towards finding solutions to industry challenges.

Academic curricula and professional workshops are also important enablers for capturing CE and its range of sustainable practices [113]. These educational opportunities provide stakeholders with the requisite ideas and knowledge to address industry challenges. Additionally, they help to ensure that industry professionals are equipped with the skills and expertise needed to implement sustainable practices in their work. By investing in education and training opportunities, stakeholders can work towards a more sustainable and circular economy in the construction industry.

4. *Governmental Support and Incentives*

The global construction industry is facing a significant challenge in embracing circular practices and business models due to the absence of adequate policies, laws, and frameworks. The lack of government support, such as financial aid or tax incentives, is making it less economically feasible to invest in circular models, and as a result, discouraging their adoption. The absence of regulatory pressure and strict laws also fails to establish the necessary urgency for circularity, and the required behavioural changes in the construction industry are not taking place. This is a pressing issue that needs to be addressed so that the construction industry can move towards a more sustainable and circular future [27]. Sustainable development is becoming increasingly essential, and as a result, circular buildings are gaining popularity. The main objective of circular buildings is to foster the idea of "building as a material bank" [115], where the materials used in the construction are stored and reused when the building's life comes to an end. However, this can only be achieved if there is a financial incentive to design buildings that can be easily deconstructed and reconstructed. It is worth noting that circular buildings are generally more costly than traditional buildings.

The circular economy in the construction industry is a complex issue that requires the involvement of all stakeholders, including governments, investors, designers, constructors, and users. The transition towards circular practices requires a significant change in mindset and approach, as well as the adoption of new technologies and systems. Nonetheless, the benefits of circularity in the construction industry are far-reaching, including reduced waste and carbon emissions, increased resource efficiency, and improved social and economic outcomes. Therefore, it is essential for all stakeholders to collaborate and work towards a more sustainable future for the construction industry.

7.4 Case Studies and Best Practices

7.4.1 Case Study 1—Gonsi Sócrates Bio-building (Barcelona, Spain)

Figure 7.10 shows the Gonsi Sócrates Bio-Building which was built by Construcía Company. They followed the Lean2Cradle® circular construction methodology [120]. Almost all the building materials (99%) were characterized and its components were reviewed, and up to 50 types of materials were inventoried. Among these materials, 89% (8,400 tons) will not become waste at their end-of-life but have a circular way to be reintroduced into the production process. Thus, when the useful life of the building ends, they can be reused, repaired or recycled in the way that is most convenient at that time, allowing them to preserve greater value for the next use [121].

Fig. 7.10 Gonsi Sócrates bio-building [122]

Another best practice used in this building was to have 'grey' finishes as a sustainable measure to avoid wasting possible materials in future adaptations required by new tenants. For example, laminated plasterboard partitions were removed to be recovered onsite. The plasterboards were temporarily stored in an available space in the same building. The three components of the laminated plasterboard partitions were separated: metal, plaster and rock wool and the following treatment was given to each of these materials [122, 123]:

- Metal: highly recyclable secondary material, which was easily reintroduced into the system as a material.
- Plasterboard: in the absence of a nearby recycling plant, a nearby construction building conducted by the same construction company was used to take the plasterboards. In that work, there was a shredding machine that allows the recycling of Cradle2Cradle laminated plasterboard.
- Rock wool: In this case, the remains of rock wool were concentrated to be recovered by Rockwool, which was the supplier responsible for recovering the work surplus.

7.4.2 Case Study 2—Urban Mining and Recycling (UMAR) Experimental Unit (Dübendorf, Switzerland)

The UMAR building (Fig. 7.11) was designed by Werner Sobek with Dirk E. Hebel and Felix Heisel and they considered a circular approach keeping a technological and advanced design and architectural form. Such an approach makes reusing and repurposing materials just as important as recycling and upcycling them. This conceptual emphasis means that UMAR works simultaneously as a material laboratory and a temporary material storage. The UMAR unit was designed and built as a prototype, showcase and demonstrator for a paradigm shift towards a circular building industry [124]. As such, the documentation of the materials, design, details and construction process are a crucial aspect of the process.

Several elements of this documentation have been implemented already: A material library within the unit offers samples of all materials used in construction. These samples are additionally linked to a digital material library with further information, data sheets and contact details on the project's website [125]. Some of the circular material used were [126]:

- StoneCycling® are waste-based bricks available in different colours and textures and are named according to their appearance for example "Wasabi" or "Salami" (Fig. 7.12). The construction material from rubble meets industry standards and can be used indoors and outdoors [127].
- Magna Glaskeramik is a very durable translucent material made with glass waste. Glass waste is first broken into pieces and then undergoes a complex sintering process without the addition of binders or the use of pressure, only utilising temperature and time. The colour of the material depends on the colour of the raw material used in production. It was used for the finishing material of the toilets [126, 128].
- ReWall® [129] consists of shredded and compressed beverage cartons to develop a floor-ceiling panel (Fig. 7.13). The board material is durable, moisture resistant

Fig. 7.11 Urban Mining and Recycling (UMAR) experimental unit [125]

Fig. 7.12 StoneCycling® [126]

Fig. 7.13 ReWall® NakedBoard [126, 129]

and contains no volatile organic compounds. It was used as interior partition, as alternative to gypsum boards. Similar research works have been conducted to ass the recyclability of beverage cartons [130].

– Ecor flatcor/Ecor brow. ECOR products are flexible, high density, compression moulded fibre board made from 100% waste cellulose. The plates are formed by water, heat and pressure, without any other additives [126].
– Ecobase carpet tiles gold. The tiles are equipped generally with a EcoBase™ backing, which contains recycled calcium carbonate from local drinking water companies through an upcycling process. Due to these recycling-oriented resources, the company now shifted to leasing concepts for their carpet tiles in order to be able to feed them back into the own production line after used [126].
– Natura 2. Water hyacinths or water lilies are free-swimming, perennial aquatic plants abundant in the Philippines. Cutting of the plants is required regularly to keep the waterways free for shipping and animals [126].

– Black Dapple sheets are made from recycled plastics, and available in different colour combinations. Depending on the raw material and its colour, the end product has a certain translucency. The material has a high hardness and density, good UV and weather resistance and a moderate scratch resistance. Dapple sheets are 100% waterproof. The massive material can be cut, drilled and milled [126].
– Ultratouch™ denim insulation. In the production process, cotton fabric from denim waste is shredded again into fibrous form and treated with a Boron salt solution. This gives the material mold and fungus repellent properties and ensures fire protection. The fibre mixture is then baked in a large oven and pressed to different thicknesses [126, 131].

7.4.3 Case Study 3—Open-Spaced Apartment (Prague, Czechia)

It is a small apartment renovated by Papundekl Architects, which the architects proposed to remove all the original prefabricated partitions (Fig. 7.14). All of these main elements are clad in recycled Packwall boards around their perimeter [132]. The coloured boards can also be used for the more operationally demanding parts of the furniture, such as the opening or sliding parts of the kitchen island or wardrobes. The PackWall [133] board is classified as semi-permeable, where water does not penetrate the surface, but the steam can travel through the material.

Recoma's recycled construction boards are versatile with infinites possibilities for application. Recoma's recycle 4,000,000 kg composite packaging per year which would otherwise go through waste streams where the majority of the material would have been incinerated. Material recycling instead incinerating this waste saves CO_2 emissions by 2700 tons per year. Recoma's products are also 100% recyclable without any waste, emissions or extra costs, since they can be made into new boards are RECOMA in a circular solution [134].

Fig. 7.14 Apartment designed by Papundekl Architects (left) and recovered construction board (right) [132, 134]

Fig. 7.15 *SKY techos ecosostenibles* [135]

*7.4.4 Case Study 4—"***Escuela Politécnica Superior***" (Burgos, Spain)*

Within the context of the Life Repolyuse European Project led by the University of Burgos, a new building product to reduce polyurethane waste was designed and implemented in three building case studies located in Coventry, Vitoria and Burgos (Fig. 7.15) [135]. The building product is named "*SKY techos ecosostenibles*" and is supplied by Yesyforma [136]. The panel consists of a new ceiling plate (plaster + polyurethane waste) which promotes the reuse of polyurethane waste by integrating it into new construction materials, thus prolonging the life cycle of this plastic material and avoiding its final disposal [137]. This material provides extra lightness and improves acoustic absorption compared to regular false ceiling plates, creating a more comfortable and conditioned environment.

The polyurethane foam waste comes from the refrigeration industry, specifically, it is generated from the manufacture of insulation slabs, they are those which are rejected at the production line or from those which are used for various manufacturing tests. The type of PU waste used in this research is a rigid polyurethane foam and is made out of two components which are polyol and isocyanate, this has an open cell structure.

7.5 Final Remarks

This chapter examines the primary challenges associated with using circular construction materials and suggests collaborative solutions to address them. Implementing circular principles in construction materials has the potential to transform sustainable building practices. Adopting this approach can significantly lessen the construction industry's environmental footprint, conserve natural resources, and create a more resilient built environment. Nevertheless, numerous obstacles need to be overcome to enable the broad adoption of circular construction materials.

This chapter provides specific recommendations for overcoming the challenges associated with the widespread adoption of circular construction materials and outlines future directions. The interdisciplinary study also examines strategies and principles for using circular materials in buildings, identifying various barriers, critical success factors, and enablers within this research area.

The construction sector is a major contributor to waste generation and resource consumption, yet it holds significant potential to lead the transition to a circular economy. By adopting design principles focused on circular material usage, the construction industry can reduce its environmental impact, conserve resources, and promote sustainable material practices. Key design principles for circular material usage include designing for circularity and managing material selection. Buildings should be designed to be durable, adaptable, and easy to disassemble, facilitating the reuse, recycling, and upcycling of materials at the end of their lifecycle. Construction materials should be chosen based on their environmental impact, recyclability, and durability, while construction waste should be minimized and managed to maximize material recovery. Implementing these principles requires collaboration among all stakeholders in the construction sector, including architects, engineers, contractors, and material suppliers. The benefits of a more circular construction sector are substantial: increased sustainability, resilience, competitiveness, cost reduction, innovation, and job creation.

Furthermore, it is highlighted the critical shift towards a circular economy (CE) in the building sector, emphasizing the need for collaborative business models and technological innovations. Key elements for sustainability include circular supply chains, product-as-a-service models, and extended product responsibility. While public–private partnerships show promise, they require careful management. Future efforts should concentrate on establishing robust regulatory frameworks, awareness programs, and international collaboration. Integrating technological advancements such as AI, robotics, and blockchain is essential for efficient waste management. Educating stakeholders on circular practices is crucial. Global collaboration can help standardize circular construction methods, leading to a more sustainable and resilient industry. This review advocates for a focus on resource efficiency, circular practices, innovation, stakeholder collaboration, and adaptive strategies to minimize environmental impact and enhance sustainability throughout the construction sector's operations.

Based on the conclusions drawn from this study, applying CE principles in the construction industry has significant and far-reaching implications. This research offers actionable steps for integrating these principles into practice, including design principles for circular material usage, stakeholder collaboration, technological integration, and the establishment of robust regulatory frameworks. These recommendations provide a roadmap for future implementations and a practical framework for policymakers, practitioners, and stakeholders to adopt and apply these principles. By embracing these recommendations, the construction industry can transition towards a more sustainable and resilient future, reducing environmental impact, conserving resources, and fostering innovation. Furthermore, integrating these principles supports the broader global sustainability agenda, significantly advancing CE practices beyond the construction sector.

This chapter related to implementing CE principles in the construction industry has revealed crucial insights for enhancing sustainability and reducing environmental impact. However, the slow adoption of these principles is due to industry-specific barriers such as limited knowledge and experience. Therefore, a collective effort to educate and disseminate information is essential to overcome these obstacles. Embracing innovation offers a promising path to promoting circularity. Successful case studies of circular practices can provide valuable insights for wider industry adoption. Developing robust regulatory frameworks can incentivize sustainable practices, and integrating advanced technologies can optimize waste management processes. Education on circular practices is vital, and global collaboration is essential for standardizing universally accepted approaches.

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Chapter 8
Modularity and Prefabrication

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Abstract The concepts of "modularity" and "prefabrication" require a deeper understanding being crucial to investigate their relation with the circular economy. Prefabrication involves pre-manufacturing building elements off-site and their transport to the construction site and assembly. Prefabrication can be divided into different categories: Component, Non-volumetric, Volumetric, Modular construction, Hybrid structures, or Whole building prefabrication; and can be based on linear (e.g., columns or pillars), bidimensional (e.g., walls or floor panels), or tri-dimensional elements (e.g., modules or whole prefabricated houses). The most commonly used materials are steel, wood, and concrete, although plastic, composite, and nature-based materials are increasingly being explored. While comparing the prefabricated materials, steel has high embodied impacts but recycle and reuse potential, timber has biogenic content and high reuse potential, and concrete poses transport and assembly challenges. The refurbishment of prefabricated buildings and the use of prefabricated

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elements in refurbishment are also discussed. The main benefits of adopting prefabrication are impact, cost, material, waste, and time reduction, with quality increase; and the challenges are cultural, technical, and market aspects with some investment required. A bibliometric analysis explores the relationship between modularity, prefabrication, and circular construction and concludes that the link between the three concepts seems fragile and unclear.

Keywords Buildings · Circular economy · Construction · Modularity · Prefabrication

8.1 Introduction

The concepts of "modularity" and "prefabrication" are closely linked and require a deeper understanding to grasp their similarities and differences. Furthermore, it is crucial to investigate the connection between prefabrication and modularity within the circular economy framework. This chapter will involve in-depth analysis and mapping of current knowledge across these three domains.

Prefabrication, often abbreviated as "prefab", involves a construction approach in which building elements are produced in specialised factories or temporary facilities off-site and then transported to the construction site for assembly into buildings [1, 2]. The assembled structures are composed of precast elements (for example, beams, columns, slab panels, and wall panels) that can form a part of the whole building or infrastructure [2]. Prefabricated buildings have different degrees of prefabrication and are categorised according to their size, complexity, configuration, and installation into buildings [3]. The degree of prefabrication significantly influences the amount of construction labour needed on-site; a higher degree of prefabrication results in

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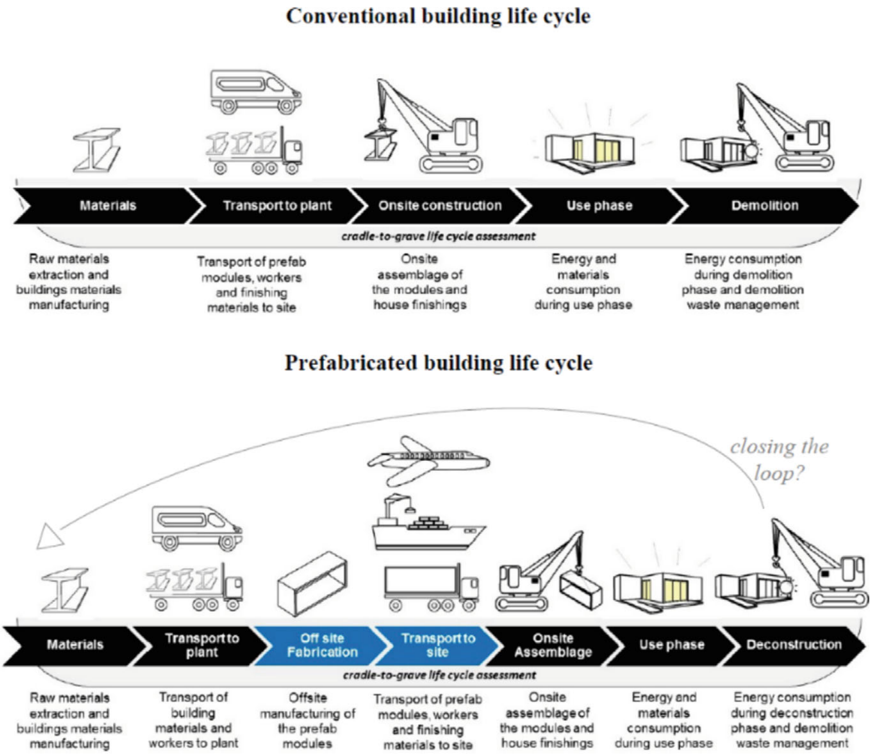


Fig. 8.1 Life cycle of a conventional building (on top) and prefabricated buildings (on the bottom). Based on [4]

reduced on-site construction labour, while a lower degree increases the need for on-site labour [3].

Compared to conventional buildings, prefabricated buildings have one extra stage, off-site fabrication, and one extra transport from plant to site. Figure 8.1 presents the life cycle (LC) of a conventional building (at the top) and the LC of prefabricated buildings (at the bottom). Table 8.1 presents the main terminology used in the field of prefabricated and modular buildings, including references.

8.2 Historical Context

One of the first references to prefabrication methodology emerged in 1624. The first houses were manufactured in England and transported to the fishing village of Cape Ann, the current city of Massachusetts. In 1790, simple timber-framed shelters also produced in England were shipped to New South Wales, in Australia, intended to be used as hospitals, warehouses, and cottages. Furthermore, some advantages related

Table 8.1 Terminology used in prefabrication and modularity, including references [4]

	Terminology	Reference (up to four)
Designations	Prefabricated	[5–7]
	Offsite	[8–11]
	Modern Methods of Construction	[12–14]
	Modular	[15–17]
	Pre-assembly	[18, 19]
	Precast	[20–22]
	Prefabricated	[1, 6, 23]
Type	By elements or components	[6, 24, 25]
	By panels	[26–28]
	By modules	[5, 29, 30]
Prefabrication level	Whole buildings	[31–33]
	Building parts (e.g., rooms, classroom, labs)	[5, 34, 35]
	Building components (e.g., walls, windows, stairs)	[15, 24, 36]
Structural materials	Wood	[37–39]
	Steel	[25, 40, 41]
	Concrete	[27, 42, 43]
	Light Steel Framed	[41, 44, 45]
	Plastic	[46–48]
	Container	[31–33]
Uses	Residential	[49–51]
	Educational	[6, 52, 53]
	Commercial	[54, 55]
	Industrial	[56, 57]

to the production of prefabricated components, such as the reduction of labour and time, were reported during the colonisation of South Africa in 1820 in the assembly of simple and shed-like systems in Freetown, Sierra Leone, and the Eastern Cape Province, compared to on-site construction methods [3].

In the 1830s, the London carpenter John Manning created a prefabricated home for his son, who was living in the Land Down Under in Australia. This way, the prefabricated components were produced in England and shipped to Australia to be easily assembled. This house was the first fully prefabricated house documented. The prefabricated house was made up of prefabricated systems of wood and panel infill. The roof was a pitched roof comprising grooved posts, floor plates, and triangulated trusses supported by vertical grooved posts. The grooved posts were bolted into a continuous floor plate, and the panels were composed of supported triangulated trusses, and wood panel cladding was fitted between them. After that, John Manning produced the Manning Portable Colonial Cottage for accommodating emigrants, which consisted of an improved prefabricated structure of the previous house with easy assembly and transport [58–60].

The most relevant example of prefabrication was the Exhibition of Great Britain in Hyde Park, London, in 1851, in which the Crystal Palace was presented. Joseph Paxton designed Crystal Palace in less than two weeks, and its construction took a few months. It is a building composed of prefabricated components manufactured off-site, using light and inexpensive materials, such as iron, wood, and glass, and assembled on-site [58]. After Britain's Great Exhibition, the Crystal Palace was disassembled and then assembled in another location [60].

Previously, balloon frame construction had emerged in the United States in 1833, near Chicago. The old city of Chicago was almost exclusively built with balloon frames before being destroyed by a fire. In the 1840s, modular construction reached the United States to meet the housing needs of the California Gold Rush. However, in the 1900s, the builder Augustine Taylor from Chicago improved balloon-frame construction by manufacturing walls off-site, transport, and speedy assembly [58, 60].

The Aladdin "built in a day" house reached popularity in the United States in the 1930s. These houses had a "ready cut" system that increased the efficiency of the assembly process of timber components. The main milestones achieved in 1932 were a wall system composed of a metal sandwich panel and the "House of Tomorrow". The "House of Tomorrow", built by George Fred Keck, is a three-story building composed of steel frames and glass infill walls, focused on cost-effectiveness, passive heating, and daylight modulation. Furthermore, for the Chicago World's Fair in 1933, the "Crystal House" was built, which allowed advances in the steel frame concept. Moreover, Sears Roebuck and Co. created a catalogue of prefabricated houses and sold more than 500 thousand in the United States from 1908 to 1940, some of which still exist. At that time, these houses cost two-thirds less than conventional buildings [58, 60].

The Structural Insulated Panel (SIP) is one of the most used prefabricated components for house construction, initially introduced in 1935 by Forest Product Laboratory (FPL) researchers in Madison, Wisconsin, in the United States and first commercialised by Dow in 1952. In the 60s, when rigid foam insulation was available, the use of SIP gained traction due to its affordability and improved thermal performance [61].

During World War II (1939–1945), prefabricated construction increased significantly due to the demand for cottages for military personnel [2]. "Quonset Huts" or "Nissen Huts" houses were implemented in the United Kingdom for domestic, military, and institutional purposes. After World War II, the United States faced a shortage of houses, being forced to appeal to prefabricated dwellings due to the return of soldiers. In addition, Europe and Japan also opted for prefabricated houses to overcome housing demands. Regarding modularisation, modular construction corresponded to 25% of all single-family houses in the United States between 1945 and 1968. Still in 1968, the prefabricated Hilton Palacio del Rio Hotel (a 500-room hotel) in San Antonio, Texas, was built in 202 days for the Texas World's Exposition [60].

In 1905, the first precast concrete panelled buildings were created in Liverpool, England. The man who invented the panels was engineer John Alexander Brodi. However, precast concrete was not widely used until the early 1950s. The prefabricated concrete panel buildings gained popularity not only in the UK but also in East European countries, the former Soviet Union and Nordic countries. The technology was picked up later in many parts of the world, where fast development created a need for affordable housing on a mass scale. The rise of concrete panel buildings in East Europe has been fuelled by the post-war housing shortage and the industrialisation programmes in the 1950s-1960s. The mass application of prefabricated concrete panel buildings in East Europe can be traced back to Khrushchev's 4–5 floor panel buildings built in the 1950s in the Soviet Union. In other East European countries, the large panel-house building programmes started later, for example, in 1965 in Hungary, 1956–1958 in Czechoslovakia, and 1958–1960 in Romania. By the end of the 1970s, prefabricated concrete panel buildings became the dominant form of construction.

In 1976, the building code started distinguishing permanent houses (which require a design based on the standard code) and mobile homes (based on the HUD code). After 1976, numerical control became widespread use and nowadays, small factories can model prefabricated components and have access to different tools, such as Building Information Modelling tools, Computer Numeric Control, and 2D laser cutting devices [60].

In conclusion, the lack of a workforce and the gradual digitalisation of the construction sector led some countries to embrace prefabrication as a construction method. Moreover, countries with cold climates also adopted prefabrication due to the weather conditions and less time working outside. For example, Sweden has approximately 84% of the total construction being prefabricated [2].

Although prefabrication is not a new methodology in the construction industry, its reputation has increased due to its multiple advantages in fostering Circular Economy principles in the built environment [60, 62]. Prefabricated components are also identified as more sustainable solutions with impact in economic, social, and environmental dimensions, and contributing to the Sustainable Development Goals (SDGs) of the 2030 Agenda of the United Nations (directly related to SDG 11, Sustainable Cities and Communities, and SDG 12, Responsible Consumption and Production) [1]. Opportunities and barriers to adopting prefabrication will be further discussed in Sects. 8.9 and 8.10, respectively.

8.3 Prefabricated Building Types

Prefabrication can be divided into different categories [3, 63, 64], namely:

- **Component sub-assembly** is the lowest degree of prefabrication and corresponds to single-assembled building elements, promoting a higher flexibility and customisation degree during the design and construction categories [3, 63, 64]. These components require joints and connections, careful alignments, and infiltration checks, so more work must be developed on-site. Some examples of component sub-assembly are stairs, roof trusses, wall frames, wood kits, and precast concrete [3].

– **Non-volumetric pre-assembly** (or panelised systems) are more complex components manufactured off-site and assembled on-site through traditional construction procedures and are not responsible for creating usable space [63, 64]. These non-volumetric pre-assembled components can be planar, skeletal, or complex units built from individual components, such as structural frames, cladding wall panels, and bridge units, among others [19].
– **Volumetric pre-assembly** units are prefabricated, pre-assembled, and pre-finished off-site and are responsible for creating usable space. These units are not part of the building structure but can be assembled within or onto an independent structural frame [19, 63]. Some examples of volumetric pre-assembly units are plant rooms, toilet pods, and shower rooms, among others [19].
– **Modularisation or modular construction** are volumetric units with a considerable dimension (such as a room-sized volumetric unit) that constitute the structure of the building itself [19, 65]. These units are standard modules that create usable space and can be manufactured in complete 3D boxlike (*volumetric*) sections, multi-section units, and stack-on units [3]. Modular construction is mostly pre-assembled and pre-finished off-site with a design for easy assembly to achieve rapid assembly on-site [3, 66]. The standard modules are predominantly finished in the factory (interior and exterior finishes), with approximately 80 to 95% of finishes completed off-site [3] and reducing the activities required on-site (reduces about 90% of activities needed in conventional construction) [63].
– **Hybrid structures** are a combination of more than one assembled prefabricated system in order to build a whole building, which is the most common combination of prefabricated panels and modular construction [3].
– **The unitised whole building prefabrication** corresponds to the highest degree of prefabrication and finishes [3, 64] and is pre-assembled volumetric units that form the actual structure and fabric of the building [64]. Although the unitised whole building is manufactured under controlled conditions of quality and speed, its bulk size and weight are limited by manufacturing and transportation capacity [3].

Regarding the manufacturing process, prefabricated components can be manufactured through two different types of methods, namely fixed platforms and production lines [1]. On the one hand, the fixed-platform method is a traditional method in which the mould is fixed on a stationary table [29, 67] and is more appropriate for profiled components with heights exceeding the limits of the line method, including beams, columns, and stairs [67]. On the other hand, the production line method is more mechanised compared to the previously mentioned one, as it consists of a production process with several operations at different stations where moulds are moving through a pallet rolling line, and workers are in a specific position in each station table [29, 67]. The production line is commonly used in producing components with standardised shapes, such as prefabricated wall panels, load-bearing walls, partitions, and laminated boards [1, 67].

8.4 Prefabrication Approaches

All buildings have some degree of prefabrication and include some prefabricated elements such as doors, windows, tiles, or equipment. However, when the prefabrication rate is increased–this is the percentage of buildings done offsite, in a plant, and after being transported and assembled onsite–buildings are considered prefabricated. Some prefabricated buildings are based on linear prefabricated elements such as columns or pillars, others on bidimensional prefabricated elements such as walls or floor panels, while others use tri-dimensional prefabricated elements such as complete modules or whole prefabricated houses. Some use a combination of linear, bi-dimensional, or tri-dimensional prefabricated elements. In fact, different degrees of prefabrication are implemented in the vast variety of prefabricated buildings.

Different approaches are also used in modular buildings, as various types of modules serve different functions within a completed building structure: four-sided modules (i.e. all four sides are clad), partially open-sided modules, open-sided (corner-supported) modules, modules supported by a primary structural frame, non-load bearing modules, special stair or lift modules, and hybrid modules that may rely on other elements to resist some or all of the imposed structural actions. Figure 8.2 summarises the different prefabrication and modular approaches.

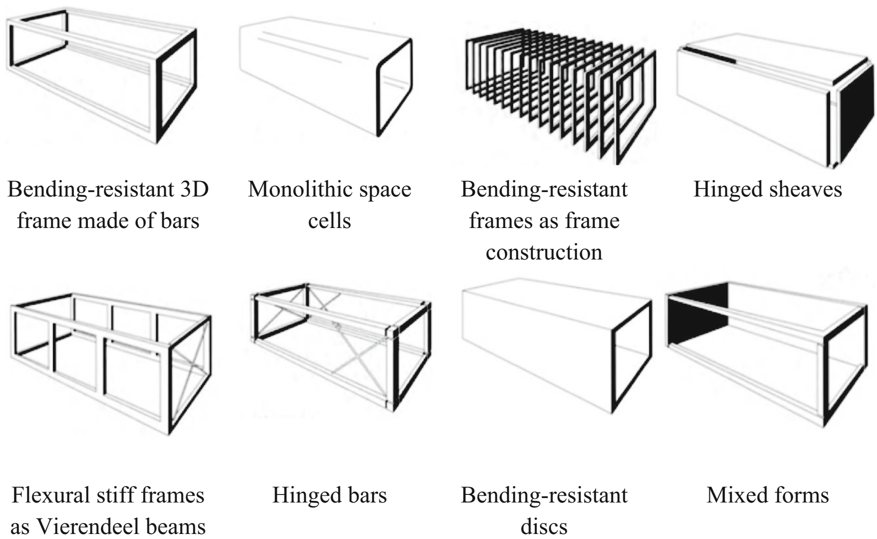


Fig. 8.2 Prefabrication and modular approaches, based on [68]

8.5 Prefabricated Building Material

As presented in Table 8.1 in Sect. 8.1, different structural materials are used in prefabricated and modular buildings. Most prefabricated buildings use conventional materials such as steel [4, 69] and wood [13, 70] which is the most widely used material, followed by concrete [57, 71]. Others use the combination of two or more materials in composite systems and usually combine concrete and steel elements. Recently, new materials have been used in prefabricated buildings, such as recycled plastic [7] or the reuse of shipping containers [32, 33].

8.5.1 Wood Prefabricated Buildings

Wood prefabricated buildings typically involve either factory-built three-dimensional modules made of wood, shipped to the site, assembled (modular construction) or wood components made from conventional light-frame construction or mass timber systems assembled on-site to form the building. Light frame construction comprises repetitive framing members, such as rafters or trusses with wood panel decking. Oriented strand board (OSB) and plywood are used interchangeably as decking and sheathing materials for floors, walls, and roof decks. Mass timber products are thick, compressed layers of wood that serve as the load-bearing structure of a building. Such components are usually made from cross-laminated timber (CLT), glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT).

8.5.2 Concrete Prefabricated Buildings

Concrete prefabricated buildings consist of whole, three-dimensional building units or building components. Both types are made in the factory using precast reinforced concrete. In the first case, the construction is usually modular, i.e. several prefabricated concrete building units are transferred on-site and assembled to form the whole building structure. In the second case, the building components (beams, slabs, columns, etc.) are made of precast concrete in the factory and, after being transferred on-site, form the central part of the building. The walls can be either constructed from preconstructed panels, such as curtain wall elements, or concrete panels or by integrating a conventional building technique, such as brick masonry, non-bearing partitioning wall elements, etc. In the latter case, the rate of prefabrication is lower.

8.5.3 Steel Prefabricated Buildings

Steel prefabricated buildings consist of a steel framework, which forms the main structural system of the building. They are composed of steel columns and beams and slab elements, more frequently concrete slabs, either prefabricated or cast in situ. In most cases, the wall elements are made of curtain walls and lightweight panels, designed primarily to support gravity and wind loads without participating in the structural performance of the building.

8.5.4 Composite Systems

Composite systems employ more than one material to form their primary structure. Among the most common are the ones made from steel frames and precast concrete walls, which are either monolithic or have the form of sandwich panels, i.e. comprise of two (or three) concrete wythes that embed a layer of thermal insulation. The main characteristic of composite prefabricated systems is that the steel and the concrete elements work together to ensure the structural performance of the building. Within this framework, it is essential to employ specially designed connectors to safeguard the structural continuity of the system and the proper load transfer.

8.5.5 Nature-Based Solutions

Some prefabricated nature-based solutions have recently been developed on a prefabricated building element scale. Vertical greening systems (VGS) can be incorporated into buildings to promote circularity through the materials and associated functions. Vertical greening refers to "vegetated surfaces in the building envelope, which include the spread of plants that may or may not be attached to the façade and can either be rooted into the ground or in pots" [72]. An example of a VGS is the vertical garden "WallGreen", a modular system that allows diverse design using the vertical space available in the building envelope. The main benefits contributing to circularity are the structure made of recycled plastic, mainly recovered from the sea, and individualised automatic watering for each plant, with the possibility of optional fertilisation (Fig. 8.3). Other operational benefits include: (i) the possibility of individual change of each plant of the system; (ii) deficient maintenance that can be carried out by undifferentiated personnel; (iii) the plants living in a good volume of substrate and can grow naturally; (iv) very resilient system to maintenance failures and irrigation system; (v) the possibility of dismantling the structure and taking it to another location; and (vi) it can be used for indoor or outdoor applications, providing different ecosystem services (Fig. 8.4).

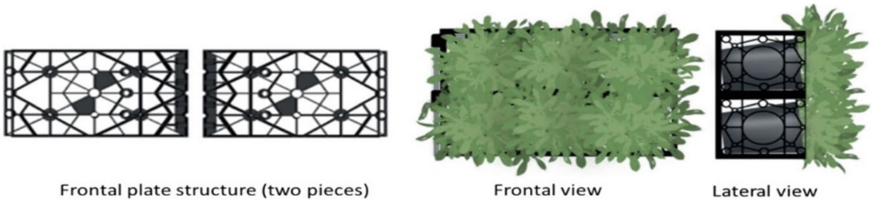


Fig. 8.3 Schematic representation of the modular system WallGreen. *Source* technical sheet from the producer

Fig. 8.4 Indoor modular system of the vertical garden WallGreen in an office building (Porto Office Park, Porto-Portugal). Credits: Cristina Calheiros

8.6 Comparison Between Prefabricated Buildings

Several research papers compare the environmental performance and cost of timber, concrete, and steel prefabricated buildings [43, 73]. Some conclude that prefabricated steel buildings have higher embodied costs and associated greenhouse gas emissions. However, steel recycling and reuse potential may compensate for initial burdens [5, 74, 75], balancing the initial impacts these buildings have at the end of life.

Timber in prefabricated buildings can be easily recovered with a high potential for reuse [75]. This is of particular significance, as wood retains a higher value when reused [74]. If not recovered in any other way, wood can be transformed into energy, as waste to energy (WtE). Finally, wood is considered a viewable material, being a solution inspired and supported by nature, simultaneously providing environmental, social, and economic benefits and helping build resilience [76].

Concrete buildings pose some challenges along the life cycle: during the transport stage because of the heavyweight; throughout the assembly, requiring specific connections; and at the end-of-life, being difficult to disassemble, often resulting in damaged components. Therefore, reusing structural concrete elements is typically unfeasible [5, 75]. Additionally, while concrete can be recycled as aggregate for new concrete production [5], it is generally in a downcycling process, in a new process with low value.

Recycled materials (e.g. plastic in [47])) and reused components (e.g. aluminium in [77]) present new prefabricated approaches that strive from circular economy principles being aligned with two of the CE principles [78]: Eliminate waste and pollution and circulate products and materials (at their highest value).

8.7 Prefabricated Buildings' Refurbishment

As described in Sect. 8.2, prefabrication was widely used during World War II (1939–1945) to respond to the demand for housing for military personnel and, after the war, to address the need for housing and all the other infrastructures the population needed in the post-war. All these prefabricated buildings built before energy efficiency codes (first introduced in the 70 s) currently need more profound renovations (if not already demolished or refurbished). Renovating and updating these prefabricated buildings is a challenge in Europe and the United States. Some research has focused on the optimised approach for refurbishing these prefabricated old buildings [79], and some national investment plans have been implemented (e.g. Portuguese national plan to refurbish schools, including prefabricated schools from the 1970s and 1980s). Moreover, some misconceptions against prefabrication exist in some European countries due to some lack of quality of these first prefabricated buildings, mainly due to some assembly error (leading to construction defects and use phase pathologies) and lack of durability. Up-to-date prefabricated buildings with modern design and construction approaches have recently overcome this misconception.

8.8 Prefabricated and Modular Components in Buildings' Refurbishment

Prefabricated components can be one answer to the EU challenge of doubling the annual renovation rate from 1 to 2% over the next decade [80]. Several EU-founded projects have focused on building stock renovation: (i) IMPRO Buildings project (2006–2008) assessed the potential to decrease the EU-15 stock impacts by implementing refurbishment measures [81]; (ii) TABULA (2009–2012) mapped residential building technologies [82]; (iii) EPISCOPE (2012–2014) aimed to assess refurbishment processes and forecast energy consumption in future building stock models [83].

One EU-founded project has supported timber-based prefabricated panels for the energy refurbishment of existing Italian buildings' façades [84] and a country-scale, while a Nordic project has focused on process optimisation being more concerned with business models [85]. Some papers have assessed how prefabricated modules or elements can be used in building refurbishment. A matching kit interface for building refurbishment processes with 2D timber modules has decreased installation time and fitting deviation [86], and a prefabricated timber façade for the energy refurbishment was studied for the Italian building stock [84]. A concrete prefabricated envelope-cladding system for building energy renovation has been shown to have lower payback times in terms of carbon, followed by energy, but a high payback cost, being superior to a building's lifespan [87]. As a potentially cheaper, faster, and more efficient solution, prefabricated and modular components may support the necessary renovation wave [88].

8.9 Benefits and Challenges of Prefabricated and Modular Construction

Prefabrication presents clear advantages within the construction activities and for buildings themselves; however, it poses some challenges that need to be discussed. In a critical review of modular buildings using a life cycle perspective, the authors identified schedule, cost, onsite safety, product quality, workmanship and productivity, and environmental performance as key benefits, and project planning, transport retrains, negative perception, high initial cost and site constraints, and coordination and communication as main challenges [34].

8.9.1 Benefits of Prefabrication

Prefabricated and modular construction presents some clear opportunities for the construction sector, enabling a faster construction speed, ensuring the compliance of the project schedule, as well as cost savings [2, 63, 89]. This construction approach capitalises on the inherent properties of prefabrication to provide the main advantages relative to conventional construction:

– **Impacts reduction** [6] through materials use reduction and waste generation;
– **Cost reduction** [89] achieved through economy of scale and a more precise construction process;
– **Waste reduction** [90] reduces error as offsite manufacturing is done in a more controlled environment;
– **Time reduction** [34] considering that offsite fabrication can be simultaneously done with site preparation works;
– **Quality improvement** [91] due to the industrialisation of the manufacturing process.

Additionally, less significant benefits include:

Reduced risks due to bad weather and reduced on-site works;
Superior quality due to factory-based quality control, repetition, and pre-design of similar modules;
Reduced on-site labour force: that can be moved for off-site, with increased value;
Improved sustainability: due to less wastage generated and upcycling of waste in controlled manufacturing environments;
Less disruption: to neighbourhood construction sites from multiple truck movements associated with conventional onsite construction.

Besides these advantages, prefabrication enables the adoption of some circular economy principles, including **Design for Deconstruction** to encourage future re-location, re-use, re-sale, and recycling of products and materials and **Design for Flexibility** to extend building lifetimes and, where possible, further extend the life of buildings by renovation and refurbishment.

Some prefabrication advantages are enhanced when comparing lightweight prefabricated buildings with conventional heavyweight ones. Table 8.2 summarises the main advantages and disadvantages of lightweight prefabricated and modular buildings compared to heavyweight traditional construction.

Regarding the perception of prefabrication among stakeholders in the Architecture, Engineering, and Construction (AEC) industry in Hong Kong, identified advantages encompass frozen design at the early design stage, reduced construction cost, shortened construction, aesthetics issues, integrity of the building, and improved environmental performance. Opposingly, the identified hindrances include inflexible to design changes, lack of research information, higher initial construction cost, time consumption, conventional method, limited site space, monotone in aesthetics, leakage problems, lack of experience, and no demand for prefabrication [106].

Indeed, modular units require the least amount of on-site construction time, as all plumbing, electrical, and even design finishes have typically already been installed in the facility. This leaves only the task of assembling the modular units to form a completed building. As modular buildings spend more time in off-site facilities during the construction process, the conditions are meticulously controlled for a significant portion of the process, leading to unparalleled efficiency and quality in large-scale commercial construction.

Modular buildings offer exceptional versatility and can be tailored to fulfil any purpose virtually. They are particularly well suited for buildings such as hotels, apartments, student housing, and any other types that typically consist of repetitive units serving similar functions.

This production approach is smarter than conventional construction methodologies with a higher flexibility and material efficiency, boosting the reduction of waste, energy, carbon footprint, and operational and environmental impact in line with circularity principles, which could be integrated into modular construction projects by identifying the most critical success factors [2, 107, 108]. It also has the potential

Table 8.2 Advantages and disadvantages (in bold) of lightweight prefabricated and modular buildings compared with heavyweight conventional construction (including references)

LC stages[a]	HEAVYWEIGHT	PREFABRICATED / MODULAR	REFERENCES
A1-A3 Product stage	Normally HEAVYWEIGHT materials + CUSTOMISED PRODUCTION More materials Increased embodied impacts Increased transport-related impacts	Normally LIGHTWEIGHT materials + MASS PRODUCTION Fewer materials Decreased embodied impacts Decreased transport-related impacts Extra material used during transport	[36, 51, 92, 93]
A4-A5 Construction stage	IMPRECISE construction process More waste generated More water used Dependency on the weather conditions	(more) PRECISE construction process Less waste generated Less water used Independence from weather Extra transport to- and from-plant Extra plant stage impacts	[94–96]
B1-B7 Use stage	HARD MAINTENANCE Unpredicted maintenance and more difficult to perform Poor performance (due to design and construction failures) Low adaptability	EASY MAINTENANCE Programmed maintenance and easier to perform Predicted performance High adaptability	[36, 97, 98]
C1-C4 End-of-life stage	DEMOLITION More waste generated Difficult to separate waste by streams	DISASSEMBLY Less waste generated Easier to separate waste by streams	[99–102]
D Benefits and loads beyond the system's boundaries	LANDFILL CDW sent to landfill Downcycling	REUSE AND RECYCLE CDW recycled Parts and modules reused Upcycling	[99, 103–105]

[a] LC stages are defined according to ISO 21930

to foster lean construction and Industry 4.0 in the construction sector (Turner et al., 2021), such as 3D printing [66]. Furthermore, prefabricated components, especially modular construction, foster the applicability of the design for disassembly in the built environment [110, 111] because they facilitate future alterations and dismantlement of a part or the whole building recovering the components and expanded their lifespan. For example, concrete columns, floor systems, and roof structures can be re-incorporated into the market and minimise waste generation from the built environment [110], which could be enhanced by construction digitalisation [112].

Prefabrication seeks to effect significant efficiencies in the construction process that should also result in considerable cost savings. A shorter project schedule further enhances cost savings. The shorter the construction period, the less construction period carrying costs, such as real estate taxes, insurance, interest, and other construction period carrying costs typically referred to as "soft costs", and the sooner the building can start generating revenue.

Summing up, prefabricated components provide certain advantages compared to traditional on-site construction, including greater control over weather, quality, and supervision; reduced environmental impact due to reduced waste, air, water, and noise pollution; streamlined project schedules by fabricating building components while the construction site is being prepared; fewer logistical challenges associated with organising crews and deliveries; more convenient storage leading to minimal instances of lost or misplaced materials; increased safety through limited exposure to unsafe weather and working conditions.

8.9.2 Challenges of Prefabrication

Although prefabricated construction offers several benefits, as mentioned above, it faces limitations that impede its widespread adoption in the industry. Factors such as transport, lifting, and other logistical considerations present challenges that must be identified. A significant initial capital investment is required to upskill labour and establish a prefabrication plant. Additionally, the costs and reservations posed by the learning curve are accentuated by the lack of expertise and knowledge regarding the design, logistics, and installation of prefabrication components, the absence of technical standards regarding the structural, fire, acoustic, and thermal performance, sustainability, and overall viability of prefabricated construction and its structural and non-structural elements, contribute to these limitations [113]. Also, some extra planning and managing effort, high initial cost, lack of skilled workers or qualified supply chain, and constraints in transport and logistics [114]. Furthermore, some threats are identified in the literature, such as difficulties in installation management due to compact spaces, extra cost-border logistics, and insufficient information on storage [115].

Some of these barriers have been grouped in the literature [113]:

Cultural aspects, including lack of necessary technical experience, the absence of technical standards, and preconception of prefabrication adoption, will reduce jobs;

Economic aspects, even though prefabrication may represent high savings, if not managed appropriately, may have high-cost overruns and difficulties in financing;

Practical aspects related to transport and handling, the lack of skilled workforce, and the inability to make changes on-site;

Technical aspects, such as BIM adoption and automation, are due to the sector's reluctance to change.

Some constraints along the life cycle stages are:

During the planning phase, there are significant expenses associated with securing funding for plant establishment, securing project financing, and dealing with resource supply shortages;

During the design phase, challenges arise due to the absence of standards and regulations, a lack of experienced designers, and constraints on design and architectural creativity;

During the off-site manufacturing phase, challenges include a scarcity of skilled labour, logistical hurdles, repetitive components, and limited tolerance;

During the on-site assembly phase, obstacles encompass difficulties in transportation and handling, a shortage of skilled labour, limitations in making on-site modifications, the intricacy of installation, and restricted tolerance.

8.10 Modularity, Prefabrication and Circular Construction

In implementing a circular economy in the built environment, prefabrication and modularity are identified as enabling production technologies. Still, the contributions of prefabrication and modularity to implementing circular buildings are unclear. We define the following questions:

- Are modular building systems in themselves circular buildings?
- If not, which strategies/principles employed in modular buildings facilitate the implementation of circular buildings?

To reply to these questions, we planned to analyse a set of case studies selected based on the three main types of modular building systems [116, 117]: frame, panel, and room module systems - to evaluate their ability to implement circular buildings. The hybrid systems will not be included.

A circular building is a building designed, built, used, and disassembled according to (i) the Circular Economy Principles [118]–eliminate waste and pollution, circulate products and materials (at their highest value), regenerate nature–(ii) the nR strategies [119]–refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose, recycle, and recover–and (iii) other Circular Economy strategies. Even though circular strategies can be implemented along the building life cycle, the early stage is crucial to striving for circular design [120].

Several frameworks are available in the literature to support the design and assessment of circular buildings; a selection has been analysed in that subtask. We compared them to identify the most appropriate framework for the case study research.

Prefabricated building systems can be designed as closed or open systems [116]:

- *Closed system:* it integrates all part systems. The entire building or partial systems (load-bearing structures, façades, or internal fit-out) are produced by a manufacturer. Elements can be only used within that system, and variety is quite limited due to the integration of the building parts;

– *Open system:* it combines various prefabricated building part systems for the shell, interior fit-out, and building envelope. The elements are standardised and dimensionally coordinated. Elements from different manufacturers can be variably combined as a partial system or for the entire building, allowing for a wide range of construction projects.

Building prefabrication is generally recognised as a potentially more energy-efficient and less resource-demanding construction method than traditional ones [117]. It reduces material waste through efficient ordering, indoor protection, pre-planning, and cutting. The final building also benefits from increased energy efficiency performance and lower energy use during its lifecycle. Prefabricated buildings can also reduce carbon footprint by minimising transportation to sites [117]. Recently, building prefabrication has raised interest in the implementation of circular buildings. Minunno et al. [110] identified seven circular strategies that building prefabrication could apply to implement circular buildings: (1) reduction of waste and lean production; (2) integration of waste and by-products; (3) reuse of components or parts; (4) design for adaptability; (5) design for disassembly; (6) design for recycling; (7) materials and components track system). Furthermore, strategies to integrate Circular Economy into modular constructions are:

– Design toward adaptability (reduction through life extension) during operational stages;
– Design toward disassembly into components to be reused;
– Design for recycling of construction materials;
– Reduction of construction waste and the lean production chain;
– Integration of scrap, waste, and by-products into new components;
– Modular buildings can be extended on demand;
– Modular units can be reused in other applications;
– Use of systems to track materials and components within their supply chain.

8.11 Bibliometric Analyses

A bibliometric analysis identified research trends in modular and prefabricated buildings toward CE in the construction sector. A five-step approach was followed: (1) conceptualisation and design; (2) data collection; (3) selection and assessment; (4) results visualisation; and, finally, (5) interpretation and discussion. This section briefly describes the bibliometric research process and summarises the main results:

(1) **conceptualisation and design:** In this stage, the research question is formulated, and the search process is defined, including the identification of the database, the formulation of the search query, the selection of the search keywords, and the definition of the inclusion and exclusion criteria for the keywords selection;

(2) **data collection:** a list of publications containing the following keywords: Circular economy; Construction sector; Prefabrication; Modular construction; and equivalent or related terms were used to select over 4500 peer-reviewed articles and reviews published in English were initially identified;
(3) **selection and assessment:** After a filtering process removed duplicated and out-the-scope articles ended up with over 600 articles, and some visuals were then built around them;
(4) **results visualisation:** two graphics present the number of publications per country (Fig. 8.5) and the number of occurrences of a keyword (Fig. 8.6);
(5) **interpretation and discussion:** figures are presented, and results are further discussed**.**

Figure 8.5 shows the country network with the average annual number of publications per country (between 1989 and 2023 and a minimum of 10 documents). Of the total of 68 countries, 21 countries meet this condition. This figure shows that China has the most published papers, followed by the United States and the United Kingdom. Emerging countries in this field are Australia, Canada, Italy, and Hong Kong (as special administrative regions of China).

Figure 8.6 presents a map of author keywords considering a minimum number of occurrences of a keyword of 5. Of the total of 1457 keywords previously identified, 96 meet this condition. This figure shows that the term "life cycle assessment" is undoubtedly the most used, followed by the terms "prefabrication" and "circular economy" (that were the main terms in this bibliometric research), and in a second level by "lean construction", "sustainability" and "construction industry". "Modular construction" appears subtly, and the link between the three initial terms; "modular construction", "prefabrication" and "circular economy" seems fragile and unclear (Fig. 8.6).

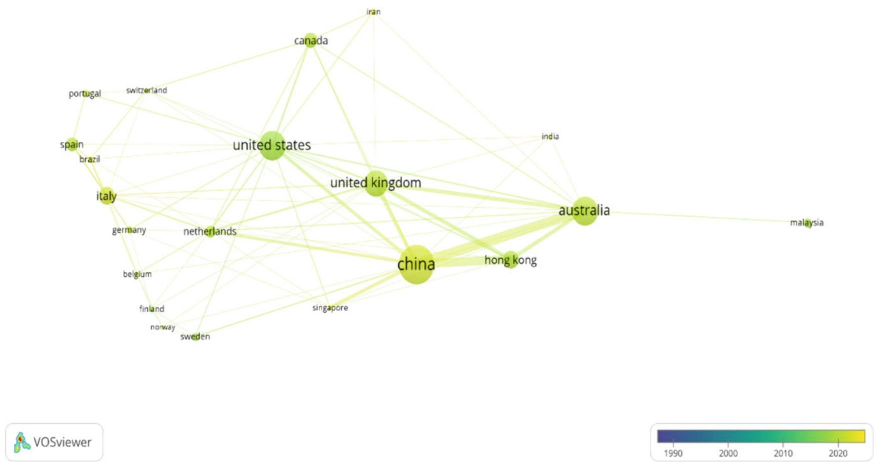


Fig. 8.5 Countries network with the average annual number of publications per country. The cutoff criteria stipulated a minimum of 10 documents per country

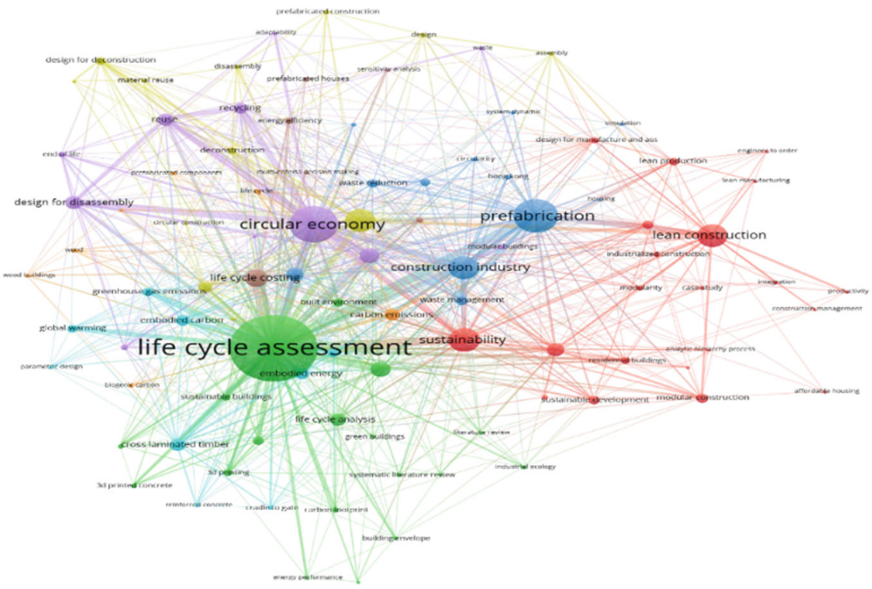


Fig. 8.6 Co-occurrence map of keywords considering. The cutoff criteria stipulated a minimum of 5 keywords

8.12 Case Studies

Based on this review, we established the criteria for selecting the case studies. Case studies will be chosen to provide a representative sample for each type of the following categories:

- types of prefabrication systems: frame, panel, room module, hybrid, and complete;
- types of prefabricated building systems: open or closed;
- types of product architectures: modular or integral.

Case studies regarding circular buildings will be analysed to establish how and in which measure modularity and prefabrication contribute to implementing circular buildings. Several frameworks are available in the literature to support the design and assessment of circular buildings; a selection was made in Sect. 8.1. For comparison, we selected the framework developed by the Arup & Ellen Macarthur Foundation [118] to apply in the case study research since it provides a set of strategies that considers the building lifecycle; modularity, and prefabrication; and indicators to assess the case studies are formalised.

A matrix was developed and implemented to identify CE principles within the prefab and modular case studies; see Fig. 8.7.

CASE STUDY DESCRIPTION

Case study name (if the case study has a name):

____

Type (e.g. Prefabricated, Modular, both, other):

____

Data source (e.g. published paper, design team, contractors, others)

____

Link to data (e.g. URL):

____

Case study description:

- authors (e.g. design team, contractors, other):

  ____

- scale (e.g. component, building element; building, neighbourhood, other):

  ____

- if building, gross floor area (GFA/m^2))

  ____

- use typology (e.g. residential, office, commercial, industrial, other):

  ____

- location (e.g. country, city):

  ____

- description:

  ____

figures: (e.g. floorplan, elevation, pictures, others)

- impact categories and units (e.g. GHG/kgCO_2eq):

  ____

- other indicators (e.g. circular material rate):

  ____

- main results:

  ____

Describe Circular Economy design strategies based on the Circular Buildings Framework (Arup, 2021) reported below. Further information on strategies, sub-strategies, and indicators is available here: https://ce-toolkit.dhub.arup.com/framework

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/$m^2$/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Case study discussion and conclusions:

____

Fig. 8.7 Matrix to assess CE principles in case studies

CASE STUDY 1–Existing Building Extension, Timber

Case study name (if the case study has a name): Vertical Timber Extensions on Existing Building: new 10 stories hotel on the top of the existing commercial centre.

Type (e.g. Prefabricated, Modular, both, other): both.

Data source (e.g. published paper, design team, contractors, others): design team WSP.

Link to data (e.g. URL): https://www.wsp.com/en-gl/projects/55-southbank

Case Study Description:

- authors (e.g. design team, contractors, other): design team
- scale (e.g. component, building element; building, neighbourhood, other): building
- if the building, gross floor area (GFA/m2) 13,000 m2 of new space
- use typology (e.g. residential, office, commercial, industrial, other): hotel
- location (e.g. country, city): Australia, Melbourne
- description: At 55 Southbank Boulevard, a six-story commercial building erected in 1989, WSP embarked on a project to enhance its capacity by adding ten additional stories using cross-laminated timber (CLT), yielding 13,000 square meters of extra space. The extension's height was constrained by existing pile capacity, precluding the possibility of installing new piles within the structure. After considering various options, including concrete slabs and composite deck slabs, CLT was chosen for its ability to accommodate ten stories without surpassing the pile capacity, unlike concrete slabs that could only feasibly support a six-story extension. Collaborating with specialists, WSP devised a Future Ready solution wherein existing building columns were reinforced, and core walls strengthened to bear the added load, incorporating CLT walls between hotel rooms. A composite slab transfer deck was designed to distribute vertical loads from walls to existing concrete columns. Two new steel cores were introduced to address heightened lateral loads, incorporating existing concrete walls into the stability system and fortifying existing core walls. Additionally, a new raft under the steel core was engineered to transfer loads to existing piles, negating the need for new piles. To maintain panoramic views, steel beams and columns were meticulously designed to support CLT floor panels and accommodate larger wall spacing around curved sections of the building.
- impact categories and units CO2 OFFSETS (TONNES): 4200
- other indicators (e.g. circular material rate): CROSS LAMINIATED TIMBER (TONNES) 5,300 NEW FLOOR SPACE (m2) 13,000
- main results:

The Future Ready design and construction of this project presented several challenges that our team had to consider, such as working on construction while the occupied floors below remained in use, integrating existing utilities and services, and avoiding the need for additional foundation piles. By employing prefabricated cross-laminated timber and embracing Circular Economy principles to repurpose the existing building, we were able to save time and money while reducing the environmental impacts associated with demolition and reconstruction. The building was inaugurated in August 2020, with a section transformed into the Adina Apartment Hotel Melbourne Southbank.

Describe Circular Economy design strategies based on the Circular Buildings Framework developed by Arup is reported below. Further information on strategies, sub-strategies and indicators is available here (Fig. 8.8):

https://ce-toolkit.dhub.arup.com/framework.

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm] 24/sqm
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Case study discussion and conclusions: The solution implemented Cross Laminated Timber (CLT) construction, enabling the existing building to support an additional 10 levels, achieving the desired room count across 13,000 square meters of new floor space. CLT, weighing approximately 20% of concrete, effectively doubled the feasible number of levels above the existing structure. Prefabricating components off-site with CLT enhanced construction efficiencies and minimised impacts on nearby buildings, presenting a more sustainable method for densifying urban areas. In light of limited available development sites, lightweight timber structures offer increased yields compared to traditional concrete and steel methods. This shift towards sustainability extends to reduced transport costs and carbon emissions, facilitated by CLT's lightweight nature. The substantial amount of CO_2 sequestered within the timber, around 4,200 tonnes, equivalent to the annual emissions of 130 homes, emphasises the environmental benefits. Timber procurement for the hotel adhered to Forest Stewardship Council certification standards, reflecting Adina Southbank's commitment to sustainability. As the world's tallest timber vertical extension, this project stands as a pioneering example of CLT and Mass Timber construction, showcasing innovative building reuse practices that have significantly enriched the site and its surroundings.

Awards:

2022 Council on Tall Buildings and Urban Habitat (CTBUH) International Conference Tall Excellence award for Renovation.

Fig. 8.8 Pictures and floorplans of an existing building extension with a timber structure

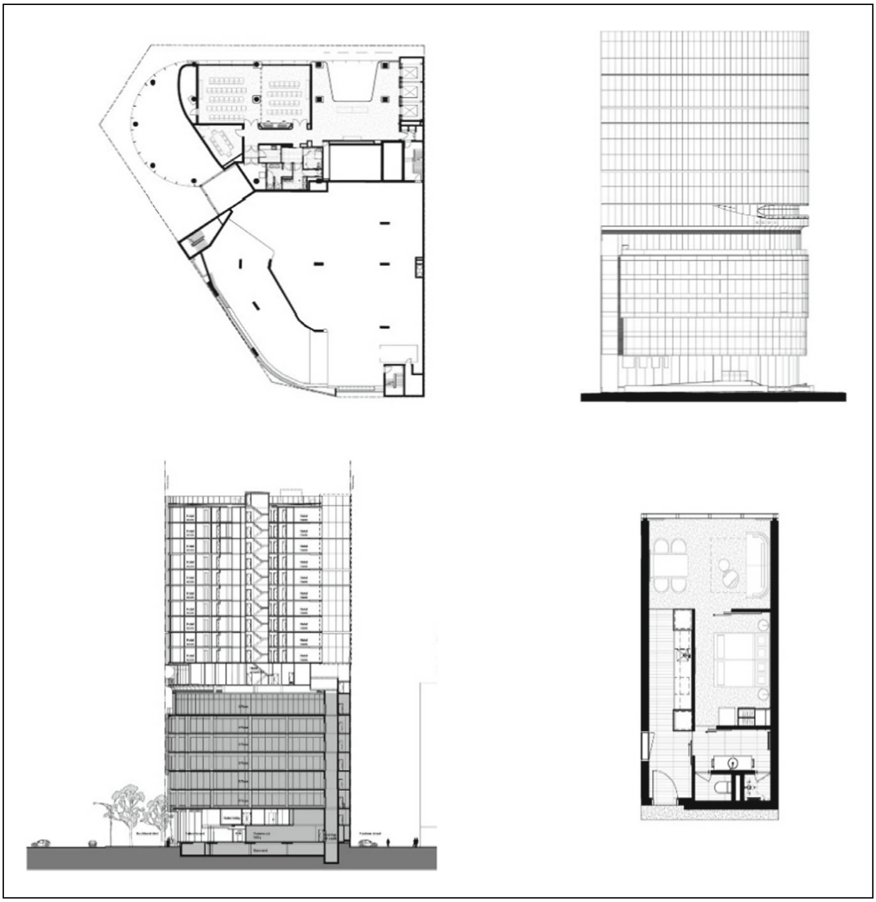


Fig. 8.8 (continued)

CASE STUDY 2–New Modular Building

Case study name: FrameUp - Optimisation of frames for effective assembling.

Type (e.g. Prefabricated, Modular, both, other): Both.

Data source (e.g. published paper, design team, contractors, others): RFSR-CT-2011–00,035 Final Report.

Link to data (e.g. URL): https://doi.org/https://doi.org/10.2777/766842 [121]

Case study description:

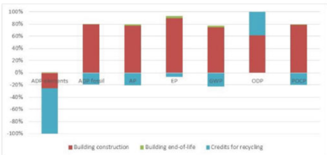
- authors (e.g. design team, contractors, other): M. Veljkovic et al.
- scale (e.g. component, building element; building, neighbourhood, other): Building
- if the building, gross floor area (GFA/m^2) 638 m^2
- use typology (e.g. residential, office, commercial, industrial, other):Residential
- location (e.g. country, city): Lulea, Sweden
- description:

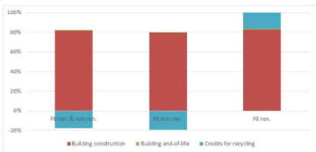
The project aims to conceptualise and conduct feasibility tests for an innovative execution technique for skeletal systems, incorporating structurally integrated 3D modules and assessing the structural performance of novel joints. The new technique involves initially assembling the roof and top floor to form a rigid body, which is then lifted using lift towers and jacks, safeguarding the structure from precipitation and moisture damage during assembly. Through research, the project will delineate the competitive scope of application for the concept compared to existing building alternatives, incorporating a comprehensive sustainability assessment (Fig. 8.9).

- impact categories and units (e.g. GHG/kgCO_2eq):
- other indicators (e.g. circular material rate):

Results of environmental categories.

Indicator	Total	Unit
Abiotic Depletion (ADP elements)	-7.46E-01	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	1.61E+06	MJ.
Acidification Potential (AP)	3.75E+02	kg SO2-Equiv.
Eutrophication Potential (EP)	4.41E+01	kg Phosphate-Equiv.
Global Warming Potential, excl biogenic carbon	1.33E+05	kg CO2-Equiv.
Ozone Layer Depletion Potential (ODP)	4.56E-03	kg R11-Equiv.
Photochem. Ozone Creation Potential (POCP)	8.68E+01	kg Ethene-Equiv





Results of environmental categories per life cycle stage.

Results of energy categories (net cal. Values) per life cycle stage.

Results of the categories of energy use.

Indicator	Total	Unit
Primary energy demand from renewable and non-renewable resources (gross cal. value)	1.91E+06	MJ
Primary energy demand from renewable and non-renewable resources (net cal. value)	1.80E+06	MJ
Primary energy from renewable raw materials (gross cal. value)	1.72E+06	MJ
Primary energy from renewable raw materials (net cal. value)	1.62E+06	MJ
Primary energy from resources (gross cal. value)	1.84E+05	MJ
Primary energy from resources (net cal. value)	1.84E+05	MJ

– main results:

The main achievement of the research project is the development of a construction process for a modular building based on a lifting-up technique. This includes the execution of a building from the roof to ground floor and the assembly of frames and 3D room modules. This process is fully visualised for the identification of possible conflicts during the execution and to promote the project goals towards industry and society for benefit of stakeholders. A portable lifting device consisting of a self-climbing device and climbing columns are developed and tested. Different types of beam-column joints are investigated in order to ensure quick assembling and to guarantee the stability of the non-braced structure even in certain earthquake regions. Verification of the resistances of joints at ambient and elevated temperatures, under monotonic and cyclic loadings are done by means of experiments and Finite Element studies. Furthermore, the robustness of a six-storey modular building is assessed, and a risk assessment of potential perilous situations are carried out. A pilot building structural frame is executed at indoor conditions and monitored in order to investigate the feasibility of the construction process. Sustainability aspects are addressed and a comparative LCC analysis is performed to verify the advantages of the concept. Experiments are conducted to investigate the building physics performances of the 3D room modules. Subsequently, design models and guidelines are developed to predict the analytical behaviour of column bases, beam-to-column joints, and column splices using the component method. These design recommendations align with and complement EN1993-1–8 standards.

– describe Circular Economy design strategies based on the Circular Buildings Framework (Arup, 2021) reported below. Further information on strategies, sub-strategies and indicators is available here: https://ce-toolkit.dhub.arup.com/framework

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

case study discussion and conclusions:

Feasibility of the novel erection concept, FRAMEUP concept, for multi-story buildings based on in situ work at the ground level and using jacks for lifting up the structure has been proved.

Beam-column joints for tubular sections, using the reverse channel and long bolts have sufficient stiffness and strength for application in non-braced frames. The beam-column joint using long bolts are more cost effective compared to the solution using the reverse channel.

The column base investigation has led to new models for possible implementation in Eurocodes.

The complete design verification, including accidental loads and assessment of robustness during the erection and at the final stage, has shown sufficient resistance for most of application within EU.

Sustainability aspects, energy efficiency and building comfort have shown satisfactory performance.

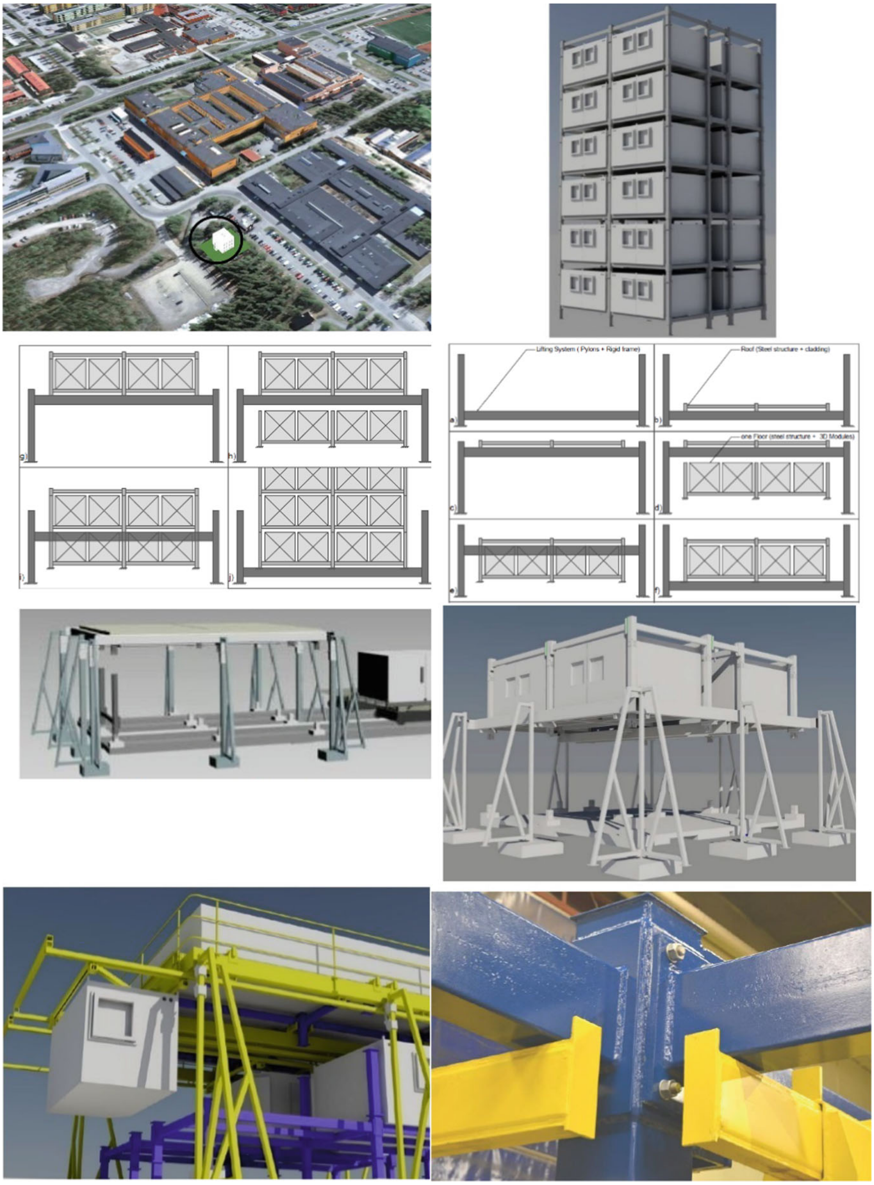


Fig. 8.9 3D views, floorplans and section from FrameUp project

Fig. 8.9 (continued)

CASE STUDY 3–Single-Family Steel Structure

Case study name (if the case study has a name): SUPRIM case study.

Type (e.g. Prefabricated, Modular, both, other): Prefabricated.

Data source (e.g. published paper, design team, contractors, others published paper, report, patent filing.

Link to data (e.g. URL):

Case Study Description:

Authors (e.g. design team, contractors, other): Research team of the Laboratory of Building Construction and Building Physics of the Civil Engineering Department of the Aristotle University of Thessaloniki & Theodoros Iliadis.

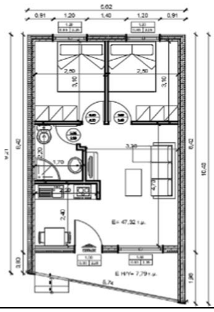
scale (e.g. component, building element; building, neighbourhood, other): building component, building.

if building, gross floor area (GFA/m^2) 47,32.

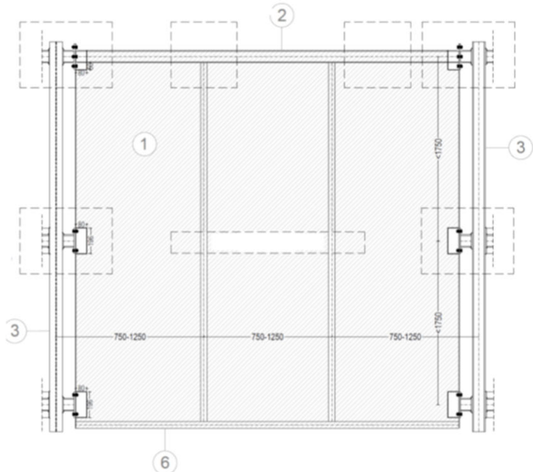
- use typology (e.g. residential, office, commercial, industrial, other): residential
- location (e.g. country, city): Greece, Thessaloniki
- description:

The case study pertains to a small, single-family building showcasing a prefabricated composite construction. Its rectangular plan extends along the south-north axis, featuring openings solely on the south and north walls. The building structure utilises a steel framework, while the walls are constructed using the SU.PR.I.M. (Sustainable Preconstructed Innovative Module) wall system. This prefabricated system underwent comprehensive testing, including structural, hygrothermal, energy, acoustic, and fire

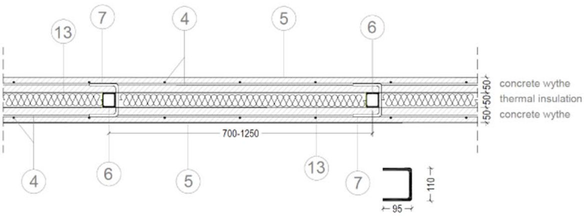
Building floorplan



Building 3D



Sketches of the SU.PR.I.M. system



1.Composite wall element; 2. HEA100 beam; 3. HEA100 column; 4. Steel bar mesh; 5. Concrete; 6. Hollow steel section (RHS/SHS); 7. Steel bar shear connector; 8. Void; 9. Steel plate (120 x 120 x 8); 10.Steel plate (150 x 196 x 8); 11. Short HEA unit; 12. M12 bolts; 13. Thermal insulation

Fig. 8.10 Floorplan, 3D image, structural system and wall composition of the SUPRIM case study performance studies, resulting in optimisation. The SU.PR.I.M. wall system comprises composite panels comprising two 5 cm thick reinforced concrete plates sandwiching vertical (occasionally diagonal) metal hollow elements. Thermal insulation boards fill the cavity between the metal elements, with the entire wall insulated using ETICS. Specially designed shear connectors link the concrete plates and steel elements, while bolted joints connect the wall panels to the main steel framework, specifically engineered for this construction type. [The SU.PR.I.M. wall system is protected by a Greek patent, with a pending European patent.] The building's inclined roof is covered with clay tiles and insulated with a 10.0 cm XPS layer, while the floor, in contact with the ground, is reinforced concrete, insulated with a 10 cm thick XPS layer. Windows feature PVC frames with double low-e glazing, boasting an average value of 2W/(m^2 K). (Fig. 8.10)

impact categories and units (e.g. GHG/kgCO_2eq): 1950kgCO_2eq for 40 years.

other indicators (e.g. circular material rate): NA.

Main Results:

The development of the innovative prefabricated wall system was shaped in order to satisfy high requirements for its operation and performance. Specifically, it was designed in order to be able to bear and deliver safely all the imposed building loads; display advanced energy performance; demonstrate excellent hygrothermal behaviour; provide acoustic insulation protection and resistance against fire actions; and minimise its environmental footprint during its life cycle.

Studies [122] showed that the examined building configuration shows better environmental performance when constructed with the SU.PR.I.M. wall system in comparison to using the conventional construction (reinforced concrete beams and columns and brickwork masonry).

Describe Circular Economy design strategies based on the Circular Buildings Framework reported below. Further information on strategies, sub-strategies, and indicators is available here: https://ce-toolkit.dhub.arup.com/framework.

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Beyond its improved energy and environmental performance, the building constructed with the SU.PR.I.M. wall system has additional advantages, as it is prefabricated and constructed according to a number of circularity design principles, such as design for longevity, adaptability and disassembly. There is further potential to increase its circularity, as:

- it can be disassembled and part of it can be reused, so it can be regarded as a partially reversible one
- part of its materials can be reused/recycled
- part of its materials can be substituted with circular materials, i.e. the concrete on the panels, etc.

Bibliography [122]

8.13 Discussion

Different types and approaches of prefabricated and modular buildings exist, offering unique benefits and applications. These can be categorised into component sub-assembly, non-volumetric pre-assembly (panelised systems), volumetric pre-assembly, modular construction, hybrid structures, and unitised whole-building prefabrication. The degree of prefabrication ranges from individual components such as stairs and wall frames to the volumetric units that make up the structure of the building itself. Manufacturing methods for these components include fixed platforms and production lines, each tailored to different types of prefabricated elements. The diversity in prefabrication types allows for greater flexibility, speed, and efficiency in construction projects.

Structural materials used in prefabricated and modular buildings encompass a range of options, including conventional materials such as steel, wood, and concrete; and novel materials such as composite systems that combine multiple materials for improved structural performance, recycled materials to promote circularity and sustainability; or nature-based solutions (e.g. incorporating vertical greening system). The choice of materials impacts the environmental performance and cost of prefabricated buildings, deeply influencing reuse, recycling potential, and end-of-life scenarios (and associated impacts). Understanding these differences and disclosing trade-offs are crucial to assessing prefabricated buildings' cost and environmental burdens.

Refurbishing prefabricated buildings presents a contemporary challenge in Europe and the United States. Initially built without energy efficiency codes, these buildings now require deep renovations. Modern design and construction advancements have overcome the misconception surrounding the quality of early prefabricated buildings. Prefabricated components play a crucial role in addressing the European Union's target of doubling the annual renovation rate, offering efficient solutions for building stock renovation and energy refurbishment. Several projects and studies have explored applying prefabricated elements in building rehabilitation, highlighting the potential for cost-effectiveness, speed, and efficiency in the renovation process.

Prefabrication and modular construction offer a set of benefits to the construction sector, reducing time and cost, and leveraging sustainability. These advantages stem from reducing environmental impact through reduced material usage and waste generation, achieving cost efficiency through economies of scale and precise construction, and improving quality due to controlled off-site manufacturing. The approach also leads to reduced project timelines by allowing concurrent off-site fabrication and onsite preparation, minimising risks associated with weather and on-site labour. Additional benefits include improved sustainability through reduced waste and circular economy principles, such as design for deconstruction and flexibility for building longevity and renovation.

However, the widespread adoption of prefabrication is hindered by several challenges. Initial capital investment and the need to up-skill labour for prefabrication plants pose economic barriers, along with challenges related to logistics, transportation, and handling. Insufficient technical standards and knowledge further limit its widespread implementation. These challenges are evident throughout the construction life cycle, from the planning and design phases to off-site manufacturing and on-site assembly, necessitating strategic planning, investment, and collaboration to overcome these obstacles and maximise the benefits of prefabrication in the construction industry.

The advancement of technology, including 3D printing and Building Information Modelling (BIM), is driving a revolution in low-cost mass production. This revolution promises more affordable construction with increased creativity, aesthetics, and flexibility. Prefabricated and modular building techniques are improving, accelerating construction timelines, and reducing costs. However, it is still being determined if these methods will consistently deliver long-term quality improvements at a lower cost compared to traditional approaches, as we are currently in a learning phase. Nevertheless, technology is expected to enable larger-scale and more cost-effective construction in the near future.

The integration of a circular economy in the built environment is facilitated by prefabrication and modularity, acting as crucial production technique enablers. However, it remains unclear how prefabrication and modularity specifically contribute to the implementation of circular buildings. This raises fundamental questions, such as whether modular building systems are inherently circular and, if not, which strategies within modular buildings support circular buildings. To address these questions, modular and prefabricated case studies, are analysed to evaluate their potential in implementing circular buildings. The distinction between closed and open prefabricated building systems is crucial, allowing for either limited integration within a single system or a flexible combination of elements from various manufacturers in a wide range of construction projects.

Prefabricated building systems, often viewed as energy-efficient and less resource-demanding, offer benefits in reducing material waste, improving energy efficiency performance, and reducing the carbon footprint. The implementation of circular strategies in prefabrication can further boost sustainability, focusing on waste reduction, waste reduction, and waste integration in new materials, design for adaptability and disassembly, recycling, and efficient material tracking systems. To align with the Circular Economy principles, design should prioritise adaptability, disassembly into reusable components, recycling of construction materials, reduction of waste, integration of waste and by-products into new components, potential extension and reuse of modular units, and effective tracking of materials and components throughout their supply chain.

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Chapter 9
Design for Circularity, Design for Adaptability, Design for Disassembly

Stella Tsoka and Katerina Tsikaloudaki

Abstract This chapter summarizes the basic principles of the Design for Circularity, Design for Adaptability and Design for Disassembly in the design face of building projects. The chapter initially provides a general overview of the circularity principles and the 10R incorporation in the design of circular buildings. At a second step, the basic actions to promote the adaptability and the modularity are presented and discussed.

Keywords Adaptability · Disassembly · Circularity · Buildings design

9.1 Introduction

According to ISO 59004, which is currently under development, circular economy "uses a systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value, while contributing to sustainable development" [1]. Its overarching goal is to intentionally offer solutions for the minimized, efficient, and effective utilization of resources, aiming to prevent emissions, losses, and environmental degradation while fulfilling societal requirements. To achieve this objective, key principles include fostering value creation, i.e. delivering solutions that concurrently enhance socio-economic and environmental outcomes while utilizing resources efficiently; promoting value sharing, i.e. collaborating throughout the value chain to distribute the created value; ensuring resource availability, i.e. guaranteeing accessibility and sustained availability of resources, thereby mitigating risks associated with reliance on virgin materials; establishing resource traceability, i.e. collecting and maintaining data to facilitate the tracking of resources throughout their value chains; and fostering ecosystem resilience, i.e. developing and implementing

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practices and strategies that safeguard biodiversity and contribute to the resilience and regeneration of ecosystems [2].

Among the main actions that foster value creation is the Design for Circularity, which as a principle integrates all the circular economy concepts. In other words, Design for Circularity is an overarching principle that incorporates all design concepts to foster the implementation of circular economy in the built environment. These design concepts are often expressed as Design for X (DFX) rules, which present specific objectives, requirements considerations and guidelines to be applied during the building design, in order to enhance its performance in terms of circularity [3]. Design for Adaptability and Design for Disassembly, along with material selection and resource efficiency, are highlighted as the early-stage design strategies that significantly contribute to the transition to a circular built environment [4].

In the next paragraphs, the concepts of the Design for Circularity, Design for Adaptability and Design for Disassembly will be presented, with the objective to map and analyses the current knowledge within the circular economy framework.

9.2 Design for Circularity

The circular design of buildings summarizes the actions along the life cycle of the building with the objective of enhancing material recovery and durability, curtailing energy and material waste, reducing reliance on virgin materials and water, and eliminating the use of release substances detrimental to human health and ecosystem resilience [1].

A bibliometric analysis on the field of circular economy and buildings, based on the Scopus database has indicated a high number of scientific research (more than 3000), which have been published since 2008 [5]. However, when the keywords are set to “design for circularity” and “buildings”, or “circular building design”, a number of only 36 relevant papers is derived, with most of them being published after 2021. Among them, the 70% are journal papers (25), 14% are review papers (5), 14% were papers published in conference proceedings (5), and only 1 contribution is a book chapter (2%). During the past decade, the transition from a linear to a circular model of building construction has emerged as an imperative need to achieve sustainability in the built environment, which would guarantee not only the minimization of energy use and emissions during the operation phase, but also the minimization of waste and the optimization of resources throughout the whole building life and beyond.

The linear model of building construction (Fig. 9.1) is built upon the one-way, cradle-to-grave philosophy, according to which raw materials are transformed into materials to be used for building components, systems and structures, and at the end of their lifespan they are eventually disposed of (Elen Mc Arthur Foundation 2013) [6]. Although today most European countries have adopted the European Waste Management Directive, only a small fraction of CDW waste is being reused or reclaimed and most of it is being down cycled [7].

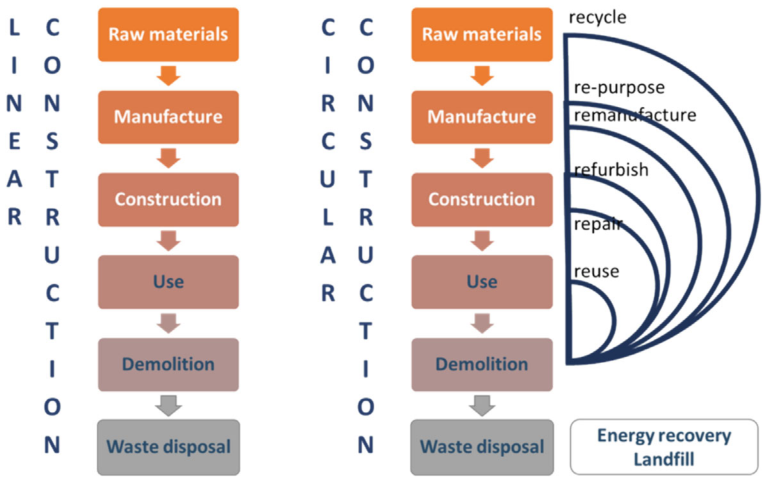


Fig. 9.1 Linear versus circular building construction (redesigned by the authors)

On the contrary, in the circular building model (Fig. 9.1) the "design out waste" is on the epicentre and it is achieved by many iterative links and loops between the building phases. The loops show the pathways through which materials and products circulate to maximize their value and minimize waste. They can be identified as short, medium and long; the smaller the loops the more efficient the resource management is [8]. The objective is to re-circulate materials, components and products through reuse, repair, refurbish, remanufacture, upgrade, repurpose, etc., and extent their service life so that the waste at the end of their life is minimized. At the same time, beyond the reduction of material waste and the enhancement of material recovery and durability, the circular building model incorporates all actions aiming at the minimization of the energy consumption, reliance on virgin materials and water, and release of substances detrimental to human health and ecosystem resilience, along the life cycle of the building [1].

The circularity loops that are synoptically presented in Fig. 9.1, combined with 'Refuse', 'Reduce', 'Recover' and 'Rethink' are part of the 10R strategy, which is presented in Chap. 1 in more detail.

The goal of circularity is pursued along the whole life cycle of the building, the successful implementation of the circularity building model requires that the circularity concepts should be considered from the initial steps of the building design, which can be roughly discerned in the phases of pre- or conceptual design, the embodiment design and the detailed design:

- The pre-design or conceptual phase is the first step of the design process. The design team, together with the building owner, defines the needs and objectives, gathers information, provides schematic solutions and preliminary plans. Emphasis is given on the goals' outlining and their implementation through the initial building design. Within this framework, the circularity design strategies to be implemented in building design are in this stage determined. For example, the need for flexibility regarding the building form, layout or purpose for covering future needs is identified in this stage and the design for adaptability concepts are adopted as approaches in the schematic design and also in the embodiment design stage that follows.

- The embodiment design or design development phase includes the architectural plans of the building, along with the studies on its structural and building systems. The selection of materials and products, the specifications and requirements are usually determined in this phase, supported by calculations and simulations. In this phase, emphasis is given on the decision making. For example, circularity design strategies and decisions upon modularity, prefabrication, disassembly, etc., are determined in this stage.
- The detailed design phase is the last one before bidding and construction. It includes the finalization of material selection and sizing of the components, which leads to complete engineering drawings and construction details, the final bill of materials, etc. In this phase, emphasis is given on documentation. With reference to the previous example, the construction details enabling the assembly and disassembly of the building components are elaborated in this stage.

All building circularity principles, strategies and frameworks presented briefly in this chapter -and in detail in other chapters (i.e. 1, 6 and 7)-should be considered during the building design phase. In order to further enable their implementation, it is useful to identify the extent of their consideration on each individual design phase. An example is presented in Table 9.1., where the above-described design phases are associated with the circular design strategies proposed in the Circular Buildings Toolkit [9] presented in Chap. 6. It is shown that the strategies that are mostly related with the building scope and form are associated with the pre-design phase; the concepts for longevity, adaptability, disassembly and minimization of components are addressed during the embodiment phase and explicitly refined in the detailed phase; the strategies that are related to the selection of materials are mostly addressed during the detailed design phase of the building.

Following the same route, the principles of the 10R strategy have been associated with the building design phases (Table 9.2). It is evident that most of the R-strategies require an in-depth study and are addressed merely during the detailed design stage of the building. Furthermore, they are merely associated with the extension of use and lifespan of the materials, components and products, i.e. the building and its layers in general. The 'Refuse', 'Reduce' and 'Rethink' strategies are introduced from the first stage of building design as they refer merely to the design philosophy and function.

In the existing bibliography, besides analysing the introduction of the circular economy principles in the design stages of a project, the Design for circularity is presented together with its enablers, i.e. the tools and digital technologies, such as BIM, LCA and material passports. BIM, defined as the digital representation of a building's geometric and non-geometric data, provides the ability to store information in the digital model, such as planning, time-related functions, costs, environmental aspects, etc. [11] Apart from the bill of quantities and materials, BIM tools contribute

Table 9.1 The consideration of circular design strategies along the building design phases: an example for the circular design strategies (CDS) proposed in the circular buildings toolkit [9]

Phase	CDS1	CDS2	CDS3	CDS4	CDS5	CDS6	CDS7	CDS8	CDS9	CDS10
Pre-design	●●	●		●						
Embodiment		●●	●●	●●	●●	●●	●	●	●	●
Detailed			●●	●●	●●	●●	●●	●●	●●	●●
● association					●● strong association					
CDS1: refuse new construction CDS2: increase building utilisation CDS3 Design for longevity CDS4: design for adaptability CDS5: design for disassembly					CDS6 Refuse necessary components CDS7: Increase material efficiency CDS8: Reduce the use of virgin materials CDS9: reduce the use of carbon intensive materials CDS10: design out hazardous polluting materials					

Table 9.2 The consideration of 10R strategy principles [10] along the building design phases

Phase	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Pre-design	●●	●	●							●●
Embodiment		●●	●●	●	●	●	●	●		●●
Detailed		●●	●●	●●	●●	●●	●●	●●	●●	●●
● association					●● strong association					
R1: refuse R2: reduce R3 reuse R4: repair R5: refurbish					R6 remanufacture R7: repurpose R8: recycle R9: recover R10: rethink					

to the assessment of circularity of different design options, through their capabilities to evaluate the building environmental impacts along the entire lift cycle, optimize construction processes, accommodate databases with information on the materials (e.g. recycled content), facilitate the collaboration among stakeholders, etc. BIM digital tools, together with LCA and LCC analyses and material passports that can be integrated in those tools, can play an important role in the decision-making process, in particular during the design phase, i.e. for selecting among different design solutions (renovation vs demolition; reversible vs conventional construction, etc.), construction solutions and materials, in order to minimize waste and maximize the resource efficiency [12].

9.3 Design for Adaptability

The term adaptability in the dictionary would refer to the capability of a person or a system to "adapt or being adapted" suggesting the ability to "change so as to fit the requirements of new circumstances". Yet, when it comes to the built environment, the definition of adaptability is a rather controversial point [13], with different definitions being reported in the literature; the ISO 21929 describes adaptability as "the ability to be changed or modified to make suitable for a particular purpose" [14], while [15] describes buildings adaptability as "the ability to fit within new conditions or needs by means of reuse or upgrading", giving emphasis to changes in the performance for existing structures. In the same context, Ross et al. [16] define adaptability as "the ease with which buildings can be physically modified, deconstructed, refurbished, reconfigured, repurposed, and/or expanded" suggesting changes not only in use and function but also in buildings configuration, layout and components. Towards this direction, other researchers define buildings adaptability as the ability "[…] to cope with future changes with minimum demolition, cost and waste and with maximum robustness, mutability and efficiency" [17] or "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life" [18].

Despite the discrepancies within the reported definitions, the main principle that is addressed by the term "adaptability" is the response of buildings to changes that will occur throughout their whole lifecycle. As underlined by [13], changes in buildings may occur due to technical, financial, environmental, legislative reasons or a combination of the above-mentioned factors. Similarly, Askar et al. [19] have suggested that the main motives for change would involve the buildings obsolescence and the premature need of demolition, the new needs of the buildings' users and, also, different environmental, social or other external parameters. Other researchers have defined the need of altered building's use or function as the predominant motivation for change [20], giving thus a person-centric perspective in adaptability since users will adjust their behaviour so as to address change (i.e. change of a room space or change from an office to a residential use).

Undoubtedly, decoding the factors that lead to change is the first step so as to design adaptable buildings that will respond to the diverse operational variables during their lifecycle. While many scholars focus on the adaptability of existing buildings so as to deal with structure obsolescence, premature demolition and the respective waste management, the adaptability challenges should be addressed even from the early design stages [18]. Besides, incorporating the adaptability concept in the design process is key for the application of circular economy in the built environment. In other words, Design for Adaptability (DfA) should establish different end-of-life scenarios even at the initial stages of the design process of a building, while also enabling the integration of modifications at any stage of a building's life, that would promote an extended operational life with low requirements for maintenance or replacement of its components [21]. This temporal dimension on the design process is crucial as buildings are not considered as a static system, only addressing the present day needs but they are conceptualized in a way to fit in potential future needs without however undergoing extensive refurbishment [13].

Adaptable buildings have gained great scientific attention during the last 20 years due to their key role for the application of circular economy in the built environment. A bibliometric analysis on the field, based on the Scopus database has indicated an increasing number of scientific research published during the period 2010–2023 (Fig. 9.2). The keywords that have been applied were "design for adaptability", "adaptability" combined with "buildings" or "built environment" and the research has been eliminated in the fields of "engineering", "environmental studies" and "energy". A number of 95 relevant papers has been identified with most of them being published during the period 2018–2023 (Fig. 9.2). Moreover, scientific articles and conference papers represent 45% and 42% respectively of the identified publications, with the rest 10% and 3% involving review papers and book chapters correspondingly. To continue, promoting adaptability requires actions and strategies both during the design and the operation phase of the buildings. Design-based strategies are implemented during the design phase of the building to increase its adaptability, while process-based strategies focus on management approaches in terms of supply, construction, and operational period of a building [13, 16, 22].

In this chapter, the emphasis is given on the design phase and according to the existing literature, the following actions promoting adaptability are identified:

- Layering the components and the systems of a building

This concept was initially introduced by Brand [23] and was later complemented by other researchers such as Leupen [24], without however modifying the main, Brand's idea. Brand suggested that the modification or replacement of the various buildings' components and systems occurs at different temporal rates. Based on the cycle-time of each element of a building, he introduced the concept of the: "6 S's" representing "Site, Structure, Skin, Services, Space Plan, and Stuff" (Fig. 9.3). Each one of the proposed "S" defines a different layer of a building element, also characterized by a specific change timescale. The proposed layering is one of the most commonly reported design-based enablers, given that this separation enables

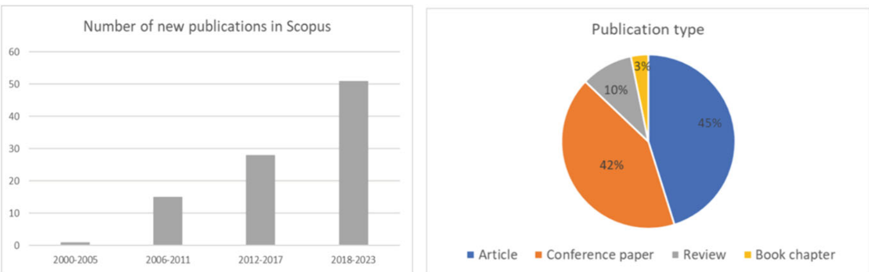
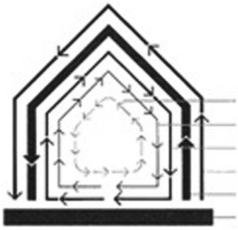


Fig. 9.2 Number of scientific studies published during the period 2000–2023 in scopus database, identified with keywords 'design for adaptability', 'adaptability' and 'buildings' and the type of publication



Layer	*Example constituent components*	*Change timescale*
Stuff	Furniture, equipment, possessions, etc.	Daily
Space plan	Internal layout, partitions, finishes, etc.	3-30 years
Services	Heating, ventilation, plumbing, etc.	7-15 years
Skin	Cladding, roof, glazing, etc.	20 years
Structure	Beams, columns, foundations, etc.	30-300 years
Site	Physical location, legal boundary, etc.	Eternal

Fig. 9.3 Building layers along with respective components and timescale of change [23]

the independence among different layers. Components belonging to one layer can be adjusted or modified without compromising neighboring layers and their elements, while the cost and the duration of future refurbishments is also reduced [13].

- Accurate information

The retention of accurate information regarding not only the materials and components' technical characteristics, but also details on any building plans, models, technical and maintenance reports, or records after any modification is crucial for further adaptation projects and the respective decision-making. Towards this direction, the use of Building Information Modeling (BIM) can be a valuable tool to organize all these data and share it among the involved stakeholders [16].

- Reserve capacity

Providing higher load carrying capacity in buildings and designing structural elements so that they could accommodate future higher loads, without further structural modifications has been considered by researchers as an efficient strategy for adaptable buildings [13]. Reserving capacity could also address future changes in the legal framework so as to comply with climate change adaptation strategies, increase flush floods loads etc. [25]. Yet, the extent of a building's overdesign is not a simple question to answer, given the high risk of excessive usage of materials, cost and carbon emissions. In light of this, McFarland et al. [26] suggest that the evaluation of the opportunities or restrictions that may occur for a given design load is the first crucial step before deciding to overdesign the building's structural elements.

- Simplicity

The simplicity of a structural system can significantly increase the level of a building's adaptability given the lower uncertainties and misunderstandings for future designers and engineers [16, 26]. The key design strategies that lead to a structural simplicity involving regular, rectangular shapes, and repetitive building floor layouts, are also in line with the best practices for load design, reduced construction and material cost [27]. Yet, a potential limitation of this approach lies on the reduced architectural and artistic elements that could be introduced in the building structure such as irregular load paths.

- Open layout plans

An open building layout involves spaces that are mostly free of structural or mechanical obstructions and, thus, they can be easily repurposed for different functions. The openness of a layout plan is defined even from the early design stages since it is influenced by the number and the distance between vertical bearing structures, the height of the building floor, the positioning of immovable internal partitions etc. [13, 28].

- Access

Access to all different systems and components of a building is critical so as to evaluate their functionality and determine the need for maintenance or replacement. Following the "layering" strategy, previously described, all buildings elements can be assigned to different layers so as to enable their evaluation without however interfering with their adjacent systems [26]. A valuable tool in this direction could also be remote sensing, as it enables distance monitoring and immediate actions if needed.

- Commonality

Commonality refers to the use of components with similar size and technical details when designing and constructing a building. The repetitiveness of the same components in parallel to the "simplicity" enables the rationalization of the construction activities, while reducing uncertainties and extra cost [29]. As emphasized by Watt et al. [13], rationalization is a key enabler for the circular economy application in the built environment, while also promoting other enablers such is Desing for Disassembly which will be discussed in the next section.

- Modularity

Modularity refers to the incorporation of components that can be easily added, removed, or reconfigured so as to accommodate different functions. While quite similar to the "commonality", ([30, 31]) the modularity mainly focuses on the connection details between the components rather than on the number of the unique components of the building, addressed by "commonality". As suggested by [16] if a structure is constructed entirely using standardized modules and interfaces, it can exhibit a high level of modularity and a minimal level of commonality. Promoting standardized connection details across the construction industry would greatly benefit Design for Disassembly (DfD) and Circular Economy (CE). However, achieving this would necessitate collaboration and agreement across various industries, which is rather difficult to happen in the years to come and thus, concentrating on smaller, product-scale components in construction, like services or cladding, might seem more feasible [13]. Modularity and prefabrication are presented in detail in the previous chapter.

- Mechanical Connections

Employing simple and standardized mechanical connections facilitates the removal and incorporation of the building components during a building's lifespan or at its end-of-life. The application of mechanical connections instead of chemical bonding, composite glues or welds and its benefits has been discussed by many scholars ([13, 16, 32]). Besides, this strategy supports the separation of the building layers and the access to the components, fundamental principles of Design for Disassembly (DfD) which is discussed in the next section.

- Appropriate Materials

Opting for materials with high durability can diminish the need for repairs and maintenance while simultaneously extending the design lifespan of building elements [26]. This extension in lifespan contributes to the overall sustainability of a structure, providing more time for adaptive measures to be implemented ([13, 28]). Still, the selection of higher durability materials for their associated benefits should be carefully balanced with any potential increases in financial and carbon costs [26].

- Design for Deconstruction

As suggested by [16] Designing for Deconstruction (DfD) involves considering the end-of-life of buildings even at the initial design phases; building components are thus specifically crafted with the goal of preserving their functional value after the disassembly, enabling their reuse in subsequent projects. For instance, DfD techniques steer clear of actions such as drilling large holes into solid members as these activities can pose challenges during deconstruction, decreasing the potential of the component to be recovered and reused.

9.4 Design for Disassembly

The term building's "disassembly", often reported in the literature along with the term "deconstruction", refers to the recovery and reuse of buildings components and materials to move from a linear use of resources to a circular one, while decreasing the dependence on new materials and waste disposals in landfills [33].

Disassembly in the building sector has been defined by [34] as the separation of individual components that comprise the structure of a building, such as wall cladding, non-structural wall panels, flooring, kitchens, and internal finishes. While [34] makes a distinction between disassembly and deconstruction, defining the latter one as "the removal of the buildings' structural elements and the relocation of part of or of the whole building", Tatiya et al. [35] links the two terms by suggesting that deconstruction can be considered as a sustainable approach to disassemble existing buildings and reuse or recycle the components. In the same vein, Rios et al. [36] have defined disassembly as a process of deconstruction in order to recover materials for recycle or reuse.

In line with the above-mentioned definitions, Design for Disassembly (DfD) is a sustainable design strategy that focuses on making buildings easy to take apart at their various components at the end of their life cycle so as to efficiently recover materials and components for recycling, refurbishment, or reuse [37]. DfD constitutes

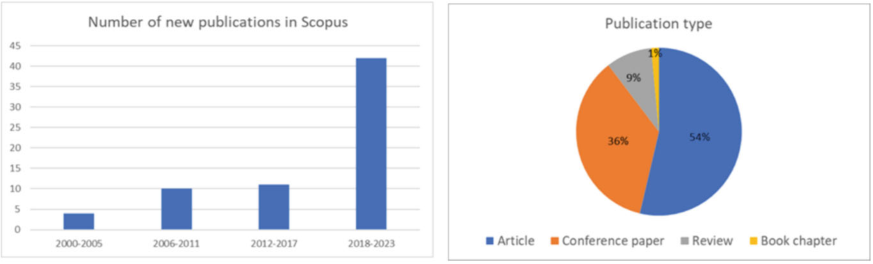


Fig. 9.4 Number of scientific studies published during the period 2000–2023 in scopus database, identified with keywords 'design for disassembly', 'deconstruction' and 'buildings'

a practice that has been embraced by the scientific community and the industry during the last 20 years as it can play a crucial role in fostering circular economy principles in the built environment. A bibliometric research on the field, based on the Scopus database and using the keywords "design for disassembly", "deconstruction" combined with "buildings" or "built environment" and again, eliminating the research in the fields of "engineering", "environmental studies" and "energy" has shown an increasing trend on relevant scientific research published during the period 2018–2023 with the highest number of publications reported during the last 3 years. More precisely, a total of 67 publications have been identified for the previously mentioned keywords, 64% of which have been published during the last 5 years. The majority of the relevant studies are scientific papers in peer reviewed journals (i.e. 54%), while conference and review papers represent 36 and 9% (Fig. 9.4).

Up to the present time, several researchers ([30, 37–39]) have proposed a series of guidelines so as to promote an efficient disassembly in building projects. In this context, Crowther [37] defined a list of 27 principles to follow, while also establishing a hierarchy on the recycling and the reuse in order to decide what to disassemble for a given end-of-life scenario.

The proposed hierarchy includes the materials reuse/recycle, the component reuse and the building relocation. Given that every project has its own characteristics, each of the 27 principles is rated as 'highly relevant', 'relevant', or 'not normally relevant'. This classification may be a helpful tool for a designer to evaluate the principles, based on the technical benefits they might yield.

Based on the existing evidence, for an efficient DfD a detailed documentation of the materials and the methods for deconstruction would be required, including the use of detailed as-built plans, the labelling of the individual materials and components along with their connections, and finally, a detailed "deconstruction plan". All these actions play a role in promoting the effectiveness of the disassembly processes.

Building materials should be also selected with foresight for future impacts so as to maintain value and/or be more viable for reuse and recycling. Besides, the greater utilization of recycled materials will not only foster the development of new recycling technologies by both industry and government but will also contribute to the establishment of more extensive support of markets for future recycling endeavours.

In addition, the simplicity of the design of the building's plans and layout, the consideration of uncomplicated shapes and the use of standardized dimensional grids, allowing for standard sizes of recovered materials can considerably facilitate both the construction and the deconstruction process. Moreover, a decrease in the number of different types of components will also minimize the required disassembly procedures to be established [37]. Moreover, the separation of the structure from the cladding, the internal walls and the building services can significantly facilitate the disassembly since the process can occur at some of the building layers, without affecting others. Besides, a structure with load-bearing walls is less adaptable compared to one with a distinct structural frame with infill.

Another principle that should also be followed involves the design of accessible and simple connections and with the lowest number of different connection types. Besides, the type of connection that is used between the various building elements will strongly determine the efficiency of the ease of the disassembly. To enable a simple and rapid process, while ensuring that the process is not challenging for the workers to comprehend, standardized connectors should be better used for the building components. Mechanical connectors rather than chemical ones also promote the fast and efficient disassembly. The different types of component connections should be as few as possible while they should be easily accessible, visually, physically, and ergonomically to eliminate the need for costly equipment or extensive safety measures for workers [30]. Given the significance of the connection types on DfD, Morgan and Stevenson [39] have summarized the pros and cons of various fixing types as presented in Table 9.3.

DfD should also take into consideration the safety issues and thus, components should be also optimized for easy removal using standard mechanical equipment can reduce labour intensity, promote the accommodation of various skill levels while also assuring lower costs and risks [30].

The design for disassembly has been widely implemented in modular/prefabricated buildings ([40, 41]) while there also many projects of timber-framed

Table 9.3 Advantages and disadvantages for different connection types [39]

Connection type	Advantages	Disadvantages
Screw fixing	– Can be easily removed	– Limited reuse and cost
Bolt fixing	– High resistance and high reuse potential	– Can seize up making removal difficult
Nail fixing	– Speed of construction, Cost	– Difficult removal usually destroying a key area of element-ends
Friction	– Keeps construction element whole during removal	– Relatively undeveloped type of connection structural weakness
Mortar	– Can be made to variety of strengths	– Cannot be reused, difficult to separate bonded layers
Adhesives	– Strong and efficient – Variety of strengths – Applied in awkward joints	– Virtually impossible to separate bonded layers – Cannot be recycled

buildings. A relevant project, named Two Family House is the one of the Austrian company KFN. The proposed design involves a simple, rectangular plan and the structure is made of a modular timber-frame of 5m x 5m $\times$ 2.7m three-dimensional grid. The structure is separated from the building envelope, made from lightweight materials providing thus an increased adaptability potential in the design of the building. The description of this project along with many others employing DfD is given in the report of Guy and Ciarimboli [30].

Still, DfD is rarer in buildings made of concrete. This is mainly because concrete, as a composite material, poses challenges in the disassembly of its components. Especially for cast-in-situ concrete framed buildings [42], the environmental impact and the challenges for deconstruction become even higher. To date, the prevailing end-of-life scenario for such concrete buildings and their components is demolition. Sometimes, the demolished concrete undergoes a recycling process where it is crushed to separate aggregates from the reinforcing steel and the resulting crushed material is then utilized, for instance, in the construction of roads [43].

Given that this recovery process may involve high CO_2 emissions, many researchers have focused on methods to improve the environmental impact of the recycling process of concrete buildings, enhancing thus their circular perspectives [44].

Yet, concrete as a composite material presents multiple benefits regarding the strength and resistance of the respective elements; to enhance its reuse and promote DfD in concrete buildings, many previous studies have proposed the use of precast concrete panels, so as to allow production in a controlled environment, standardize the connection of the components, reducing thus installation time. A relevant project that based its design on the reuse of precast concrete elements previously used in other building projects is presented in the study of Stacey et al. [45]. More precisely, designers used large panel precast concrete panels, developed with the so called “Plattenbau” method, a technique that was extensively used in 1960–1970 in Germany so as to quickly respond to the high demand of residential buildings. Apart from the environmental benefit, the designers have estimated a reduction of about 30% in the construction cost, compared to the respective value for new rather than reused, precast concrete panels.

Besides, the use of precast concrete panels is quite old in the building industry but nowadays, they can also address the DfD and CE challenges in the built environment since they exhibit favorable characteristics for their future disassembly, such as standardized sizes, control of quality etc. Still, there is still the need for further research so as to increase the recovery potential, provide systematization, detailed specification of elements etc. [43].

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Chapter 10
Reversible Buildings and Products. Transformable Buildings

Katerina Tsikaloudaki

Abstract Nowadays design for reversibility and transformability are gaining interest in the field of architecture and sustainable design and are directly connected with the circular economy framework. This chapter will attempt to map and analyse the current knowledge on the concepts of reversible and transformable buildings, by presenting the basic background and terminology, their application on the material, component and whole building level, the challenges and barriers, as well as the benefits and enablers for implementing reversibility and transformability in structures. Paradigms of reversible and transformable buildings are synoptically presented at the end of the chapter, in order to highlight how these concepts can be actually applied to real life constructions.

Keywords Reversible buildings · Transformable buildings · Building adaptability · Disassembly · Circular building concepts

10.1 Introduction

Design for reversibility and transformability are concepts that are gaining interest in the field of architecture and sustainable design within the sustainability and the circular economy framework. The difference between these two concepts is subtle; They both refer to structures designed on the basis of flexibility and adaptability, allowing for future modifications. Reversible buildings are designed to further enable disassembly and reuse of their components/materials to rebuild the same or other constructions, while transformable buildings are capable of changing their form, layout, or purpose dynamically in response to various factors, such as occupant preferences, environmental conditions, functional requirements, etc.

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This chapter will attempt to map and analyse the current knowledge on the concepts of reversible and transformable buildings within the circular economy framework.

10.2 The Background

In general, reversibility refers to the ability to reverse or undo a process or change and return to the original state or condition. With this overall definition, the term is met in many sciences, such as physics, chemistry, mathematics, psychology and cognitive sciences, medicine, etc. In this framework, the term "reversibility" is also met in the building sector as a principle applied to the monuments' restoration [1], in order to highlight processes and interventions that do not harm the historic building and allow it to return to its initial state, while at the same time they respect the original material, structural system and autonomy of the architectural members.

In the field of circular buildings, the term "reversibility" is met frequently but not always with the same, explicit definition. It is commonly mentioned in conjunction with deconstruction, disassembly, reuse, flexibility, etc. In some cases, it is encountered as moveability [2], relocate ability [3] and expandability [4], but discrete boundaries and definitions between these terms are not denoted.

In most cases, reversibility refers to the ability of a construction to be dismantled to its individual components, which are then reused and reassembled to form the same or a similar structure. In praxis, it exploits the advantages of disassembly, which, according to ISO 14021, "enables the product to be taken apart at the end of its useful life in such a way that it allows components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream" [5]. Reversibility actually takes the process one step further to the reuse of the building components/materials keeping their primary intended purpose, with the ultimate objective to minimise waste.

The research project Buildings as Material Banks (BAMB), funded by the EU Horizon 2020 research and innovation programme under grant agreement No 642384, focused on the reversibility of buildings and structures and defined reversibility as "a process of transforming buildings or dismantling its systems, products and elements without causing damage" [6]. Furthermore, according to BAMB's interpretation, "disassembly, adaptability and reuse form the nucleus of building reversibility and as such determine the level of spatial, structural and material dimensions of reversible buildings".

Spatial reversibility addresses mainly the "transformable buildings", which can change their form, layout, or purpose dynamically in response to various factors. Transformable buildings employ various technologies and mechanisms for their adaptability, including but not limited to kinetic systems, modular components, advanced materials, robotics, Internet of Things (IoT), and automated controls. Design principles for transformable buildings often revolve around modular design, multipurpose spaces, reconfigurable layouts, and parametric modelling. Researchers emphasise the importance of incorporating these principles into the initial design phase to ensure effective transformation and maximise building functionality.

10.3 Applying Reversibility in Building Structures

Reversibility concepts can be applied at the whole building level, at the building component level and at the building material level.

Reversibility at the whole building level is associated with the ability of the building to be dismantled and reconstructed. Within this framework, key features of a reversible building include: (i) modularity, in the sense that the components can be easily assembled, disassembled, or rearranged in various configurations, (ii) flexibility, i.e. so as the interior spaces and layout can be easily adjusted or modified to suit different functions or user requirements, (iii) adaptability, with the objective to accommodate changes in use, technology, or occupancy by integrating flexible systems and designs and (iv) longevity—durability, with the aim to endure changing needs, maximising its lifespan and reducing the need for complete reconstruction.

Beyond the above aspects, reversibility at the whole building level also reflects its capability to change and adapt in order to cover various needs. It focusses on the capacity of space and structure to accommodate different functions without causing major reconstruction works, demolition and material loss. This aspect is better known as "spatial reversibility" and addresses the transformation on the building level within the circular framework [6]. Transformable structures are designed to anticipate future changes and allow adaptation in a much more efficient way. This is certainly not a new concept. Nomadic tribes exploited the elasticity of local materials to create vernacular structures that could easily be disassembled, transported and reused. All around us, common objects such as umbrellas or camping tents use principles of transformation to provide adaptability to changing needs and environments [7].

According to BAMB, the three major types of transformations are identified as: mono-functional transformation options, trans-functional transformation options, and multidimensional transformation, which integrates the former two along with exchangeability and relocation [8]. More specifically, mono-functional transformation concerns buildings that have the capacity to transform their layout typology without changing their volume or use. Trans-functional transformation concerns cases where the buildings can change use and layout typology without extensive reconstruction. In multidimensional transformation, the buildings have the capacity to change their layout and use, but also their volume, i.e., they can expand or shrink according to the needs.

Reversibility at the building component level is highly associated with their dismantle and reuse capabilities and is often referred to as "technical reversibility". In order to further assess the reversibility potential, the building components are discerned into structural and non-structural elements. The disassembly and reuse of the structural building components is not always possible and depends on the construction technique and the connection type among the members. In conventional buildings, with a structural system with load-bearing masonry or reinforced concrete members, it requires special tools, equipment and specialised labour force [9, 10]. The case is different for buildings made of prefabricated components, which generally have a high degree of deconstruction, as discussed in bibliography [11], and in Chaps. 2 and 8 of this book. The non-structural building components, such as partitions or external walls, doors and windows, cladding, floor and finishes, technical installations, are generally easier to be dismantled and reused, depending on the way they were initially integrated in the building, the materials and their durability [12].

Additionally, for the optimal design of the components within the reversibility framework, it is recommended to use a standard structural grid, minimise the number of different components to be assembled and disassembled, avoid composite materials and floor systems, secondary finishes and use of adhesives and coatings, use lightweight materials and components, dry construction techniques and, when possible, high-performance materials [13].

Nevertheless, in non-monolithic constructions, the connections play a significant role in determining whether the components in conjunction can be disassembled, without causing serious damage to the members, and further reused [14]. Chemical connections, which have the advantages of speed and low cost, or welding lead to difficulties in deconstruction and reuse. On the other hand, dry mechanical connections, such as bolts, screws, etc., are preferred. Additionally, simple, visible and accessible connections contribute to efficient disassembly of structural and non-structural elements, allowing for their further reutilisation and reassembly [13, 15].

Reversibility at the material level is merely related to the ability to reclaim building materials and products and reuse them. An extensive review on the reuse potential of various materials has been made in Chaps. 2 and 7 of this report.

10.4 Challenges and Barriers for Reversible Buildings and Products

Designing buildings or components with the intention of being easily disassembled and reassembled in another location or to form another structure has many potential benefits in terms of sustainability but also presents several challenges:

Structural morphosis: the configuration of a building system that can be easily taken apart and reassembled without compromising its structural integrity requires the right balance between structural stability and disassembly feasibility. As such it is a complex engineering task, requiring expertise, special calculation tools, time and effort.

Material selection: Critical parameters that influence the design for reversibility concept, beyond the environmental footprint, the durability and the after the design life potentials, are the weight, the compatibility with other materials in the construction, the stability/integrity through time and the potential to be reused. At the moment, concrete's potential for reuse is difficult to be defined due to its numerous uses, composition, strength and form [16], but in general in situ reinforced concrete cannot be easily removed and further reused within construction; stone and bricks can be reclaimed and reused if the mortar is lime-based; steel is easily reclaimed, but it requires additional processes to verify structural integrity [17], while further considerations include high cost, low demand, time constraints and the presence of existing coatings on steel members; glass cannot easily be reused in its initial form due to practical reasons; timber can be reused, especially when engineered timber solutions are concerned [15].

Maintenance throughout the service life: Over time, the repeated assembly and disassembly of building components can lead to wear-and-tear, affecting the quality, functionality, and longevity of the components and their connections. Proper maintenance and repair will enhance the durability of the components, prolong their lifespan beyond the design life and safeguard that the buildings will be functional and safe.

Performance certification: The lack of confidence in the structural properties and performance of reused components may be an obstacle in the diffusion of reversible buildings. The quality of the reclaimed components should be tested and certified before being integrated in a new construction. Relevant tests, requirements and specifications should be developed in order to guarantee the quality of the components and materials that will form a robust and safe new building.

Costs: Specialised design, materials and construction techniques may increase the initial cost with regard to conventional buildings. Moreover, the conventional demolition of a building after its design life is usually faster and cheaper than following the chain of reversibility, i.e. disassembly of building parts, transportation to storage, repair of components, transport to site and reassembly [16]. Additionally, the need for transportation and storage of the reclaimed building components till their reassembly may increase the cost of the construction.

Skilled workforce: Reversible buildings may require specialised skills and training for construction workers to efficiently disassemble and reassemble the structure. Ensuring a sufficient pool of skilled labour and providing training can be a challenge.

Environmental impact: For long time, sustainability in the built environment has been associated with high building energy performance. Although the building operational stage is still important in the environmental building performance assessment, circularity principles target merely to the resource and material efficiency and waste management. Studies has shown that the environmental impacts of reversible buildings compare favourably to conventional buildings, especially when at least one reuse occurs in the future [18]. It is highlighted that thorough studies that take into account the production, transportation, and potential disposal of unutilised building materials and components should be conducted, in order to guarantee a low ecological footprint [11]. Tools, databases and inventories supporting the life cycle assessments should be regularly revised and expanded to reflect all potential after design life impacts of the materials [15].

Regulatory and policy frameworks: Existing building codes and regulations have been configured in line with the linear model of construction and they have not integrated provisions for the reversible buildings yet. In most countries, building circularity is currently addressed in regulatory frameworks only with regard to C&D waste management, leaving all the other principles outside the box.

User awareness: Engineers and final users may be sceptical and show limited acceptance for reversible buildings, due to prejudice and lack of awareness on the potential of this practice. Additionally, users and occupants of reversible buildings may need to adapt to different approaches of building usage, maintenance, and potential relocation.

Architectural design and aesthetics: The need for simple building designs, that will enable modularity, standardisation, as well as easy assembly, disassembly and reuse may limit the perspectives of the architect and reduce the architectural value of the buildings.

Despite these challenges, ongoing research and innovation in materials, design, construction methods, and industry collaboration aim to address and overcome these obstacles to make reversible buildings a more viable and sustainable option for the future.

10.5 Benefits and Enablers for Reversible Buildings and Products

According to the Ellen Mac Arthur Foundation, circular economy is an industrial system that is restorative by design and it is based, among others, upon the following two principles: Design out waste and build resilience through diversity (including modularity, versatility and adaptability) [19]. Within this framework, the aligned strategies are Build nothing; Build for long-term value; Build efficiently; Build with the right materials.

It is obvious that the reversible buildings reflect the above-mentioned principles and strategies. Their overall objective is to reconstruct the entire building from its initial components or at least reuse as much of its components as possible, so as the waste disposal is minimised, in contrast to conventional buildings of the past, where no particular case for the produced C&D waste was taken.

Among the benefits of reversible buildings, the following can be added [16]: (i) Reduction of the virgin material use; (ii) Proper removal and handling of hazardous materials through the disassembly of the building; (iii) Exploitation of embodied energy and embodied carbon of materials and components; (iv) Reduction of cost of C&D waste disposal due to less waste generation; (v) Creation of local market-places for reclaimed components, leading to long term economic benefits and new opportunities for employment and business development.

The key features that will enable the reversibility in building design lay on the building design, materials, technology and policy making: More specifically, the key building design actions that enable reversible buildings include [9]: (i) Reduced building complexity; (ii) Modular construction; (iii) Simple and accessible connections; (iv) Reduced number of components; (v) Reduced weight of components.

The material selected should be: (i) With durability and reusable; (ii) With decreased environmental impact; (iii) With declared performance.

Technology will trigger the reversibility of buildings by advancing the tools supporting BIM, developing protocols and quality tests for reclaimed materials and evolving the databases of building materials properties and life cycle assessments.

Standard specifications and building codes to address the disassembly and reuse of building materials and components will set the scene for reversible buildings, which could be further developed with proper and tailor-made financial incentives [20].

10.6 Examples of Reversible Buildings

In this section a few paradigms of reversible buildings are synoptically presented. They concern temporary and permanent buildings, designed as exemplary cases that show how reversible buildings can function, in favour of circular and sustainable design.

People's Pavilion, 2017, by Overtreders W & Bureau SLA. The building was constructed for the Dutch design week that took place in Eindhoven in 2017. It was designed in order to promote the value of a circular construction system, which goes beyond the life of the building and minimises waste. Within this context, it was made from borrowed and recycled construction materials that were returned to their original owners when the temporary building was dismantled after the festival [21, 22].

The framework was formed of 12 concrete foundation piles and 19 wooden components that created eight meters high primary structure for the 250 m^2 building. For this purpose, the designers devised a construction technique that didn't use glue, screws or nails, but tie-down straps, tension belts and cable ties [21, 22]. Such a system was unusual and required extensive testing before its implementation. The glazing of the lower part of the Pavilion was reclaimed from the refurbishment of an office building in Utrecht and after the disassembly of the building it was used for another project [21, 22]. The exterior walls were cladded with shingles/tiles made of recycled plastic household waste.

Brasserie 2050, 2018, by Overtreders W. The building was constructed in 2018 as a reversible barn to house a zero waste restaurant for the Lowlands Festival in Biddinghuizen in the Netherlands. The architects conceived this building as the barn of the future, which promotes sustainable and circular food management, along with sustainable and circular construction [21, 23].

It was also constructed of borrowed, hired and dismountable standard building materials. The structure of the barn was made of standard pallet racking, which is used to build storage systems in warehouses. A stack of vertical farming cabinets filled with herbs forms the facade of the pavilion. Sacks of grain stacked on pallets around the perimeter acted as weights to prevent the building blowing away, while tables were made of recycled plastic [21, 23].

Triodos Bank, 2019, by RAU Architects and Ex Interiors. The building houses the headquarters of Triodos Bank and it is located in Driebergen-Rijsenburg in the Netherlands, covering an area of 12,994 m^2. The architects conceived the building as "a temporary combination of products, components and materials with a documented identity" and describe it as "the first building in the world to be conceived as a material bank" [21, 24].

The structure of the five-storey building is made entirely of timber with only the basement making use of concrete to prevent flooding. Components of laminated timber, cross-laminated timber and unprocessed timber were joined with screws, in order to enable their reuse in future. It is surprising that the building is literally screwed together with 165,312 screws [21, 24]. According to the architects, the value of the materials would remain the same after deconstruction.

Koodaaram Kochi-Muziris Pavilion, 2018, by Aragram Architects. The building was constructed in 2018 for the Kochi-Muziris Bienale, which is the largest contemporary art festival in Asia, held once every two years in Fort Kochi-Mattancherry, in Kerala, South India [25]. Built in a record time of two months, the pavilion was designed to completely dismantle into components salvageable for reuse, leaving the site largely unmarked, to allow for its rewilding over the coming two years [25].

Stadium 974, 2022, by Fenwick Iribarren Architects. The Stadium 974 was constructed in 2022 in order to host the FIFA World Cup and it is located near the Hamad International Airport overlooking the Gulf Coast in Doha, Qatar. It has a capacity of 44,089 people and it was designed to be the first FIFA-compliant stadium that can be fully dismantled and re-purposed after the tournament ends [26].

Stadium 974 is constructed entirely from shipping containers and modular steel elements. More specifically, it incorporated 974 recycled shipping containers in homage to the site's industrial history and the international dialling code for Qatar. According to the architects, with their sustainable design the stadium construction requires fewer materials, creates less waste and reduces the carbon footprint of the building process, all while reducing the time to as little as three years [26].

It must be noted, however, that the environmental impact of the stadium might be higher than the initially estimated one, and may be higher than that of permanent structures, mainly due to the use of more durable materials that enable the dismantling and reassembling. The advantages of reversible buildings will arise depending on how many times and how far the stadium will be transported and reassembled.

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Chapter 11
Adaptive Reuse of Existing Buildings

Maria Beatrice Andreucci and Selin Karagözler

Abstract Amid the introduction of the United Nations' Sustainable Development Goals, the longevity and lifecycle of heritage and modern buildings and the process of redevelopment have come under greater scrutiny. Through adaptive reuse, i.e., changes that involve both a functional and a physical component, practitioners can give a second life to existing buildings. To define the state of the art in the scientific research focused on building adaptive reuse, the authors conducted a rapid evidence assessment. It emerged that adaptive reuse is comprehensive topic that deals with social, economic and environmental issues. The goal of the adaptive reuse studies varies from social to environmental topics such as human-centred adaptive reuse, and energy efficient adaptive reuse. A comprehensive approach to adaptive reuse requires integrated strategies aimed at preserving valuable pre-existing human artifacts in the Anthropocene era, characterized by unsustainable consumption and transience of data and images. Adaptive reuse combines pragmatism and creativity and requires sensitivity in the selective approach on existing structures, contexts, and materials. Adaptive reuse projects call for specific skills and targeted strategies that falls into different action categories: reuse, restoration and renewal, i.e., innovative transformations of the "old and degraded" into "new and performative". Overall, adaptive reuse optimizes environmental sustainability, efficient regeneration processes, increased community interest, and profitability, making it an attractive opportunity for stakeholders seeking to revitalize urban and peri urban areas. Adaptive reuse projects deliver workable solutions, support heritage and cultural preservation, while meeting the changing needs of communities.

Keywords Heritage buildings · Cultural heritage · Circular economy · Urban regeneration · Sustainable urbanization

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11.1 Introduction

As is now well known, buildings consume a significant share of the planet's energy. When they are demolished and removed, the energy spent is lost, and additional energy is used to replace them. For this reason, since the XX century, the transformation and reuse of existing buildings through an adaptive reuse process manifests our collective responsibility to address the global climate crisis. Moreover, after a century in which much of the original building stock of our urban centers has been lost as a result of urban development, practitioners and decision makers are advocating that it is our duty to find new ways to reuse buildings and benefit from their restoration, as they often represent significant collective historical and cultural value.

Adaptive reuse is a strategy to be able to preserve cultural pre-existence in the Anthropocene era, characterized by heavy consumption and transience of data and images. Adaptive reuse combines pragmatism and creativity and requires sensitivity in the selective approach on existing structures, contexts, and materials. Adaptive reuse projects require specific skills and precise strategies that falls into different categories: reuse, restoration and renewal, transformation of the "old and degraded" into "new and performative".

11.1.1 Materials and Methods

A literature search was conducted for the period 2018–2023, and using a very specific set of keywords related to adaptive reuse of existing buildings: ('*design for adaptive reuse*') AND ('*built environment*' OR '*building*' OR '*construction*' OR '*civil engineering*' OR '*urban environment*') AND ('*approach*' OR '*method*' OR '*strategy*' OR '*concept*' OR '*framework*' OR '*principle*' OR '*taxonomy*' OR '*guideline*' OR '*guide*').

The search strings were searched applying four criteria:

- Publications must contain at least one building design and/or construction strategy that is explicitly related to building adaptive reuse and its synonyms.
- The strategy/strategies must focus on optimizing the building's resource consumption, waste generation and/or embodied environmental impacts in accordance with the Circularity in building and construction concept [1].
- The strategy/strategies must focus solely on the design and construction for adaptive reuse, i.e., strategies related to building renovation as well as building extensions.
- The study must provide a sufficient level of information about the building design and construction strategy/strategies and their application following an adaptive reuse approach.

The different search engines used—Google Scholar and Scopus—returned a total of 2,081 publications. Review of the title, abstract and keywords against the selection criteria stated in the protocol and excluding irrelevant subject areas and duplicates reduced the number of publications to 116. Further reading of the introduction and conclusion, resulted in the selection of 31 publications.

The conducted rapid evidence assessment was not intended as an exhaustive study, but rather as a representation of the state-of-the-art design for adaptive reuse of existing buildings.

As building adaptive reuse has also been addressed in grey literature, 16 grey literature publications, some of which were already known by the authors to meet the scope and selection criteria of the study, were also included. Additionally, backward snowballing [2] was performed between these papers, resulting in the inclusion of 15 additional papers. In total 41 publications were analysed in full text for the synthesis. The outline of the study method is shown in Fig. 11.1.

A narrative literature review follows in the following pages to synthesize a description of existing building adaptive reuse goals, intervention strategies, and assessment tools.

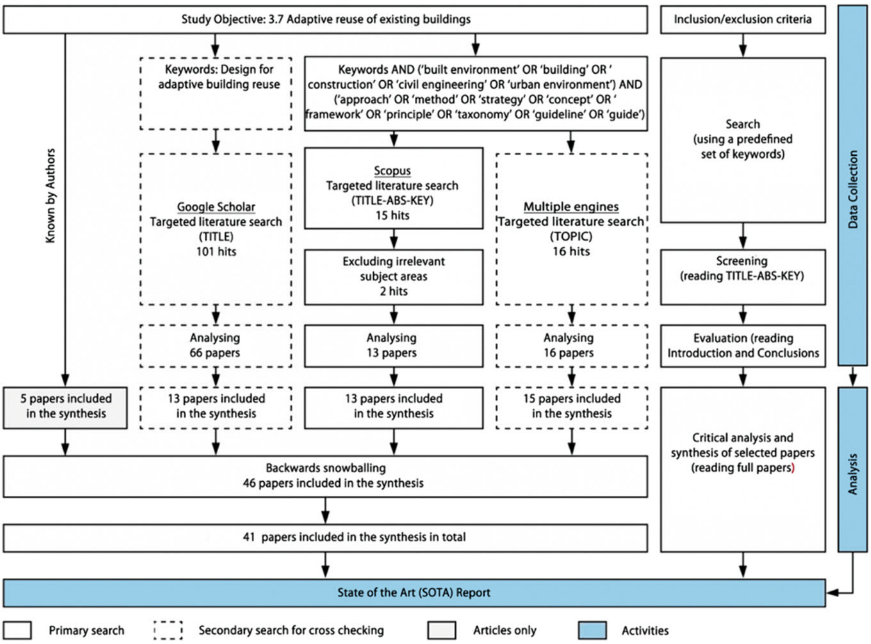

Fig. 11.1 Outline of the study methodology. *Source* authors

11.2 Results and Discussion

Adaptive reuse is comprehensive topic that deals with social, economic and environmental issues. In the literature, the goal of the adaptive reuse studies varies from social to environmental topics such as human-centred base adaptive reuse, to energy efficient adaptive reuse. Sustainable adaptive reuse, energy efficiency, lifecycle assessment, and determination of new functions are some of the goals that emerged from the selected articles on adaptive reuse (Table 11.1).

The sustainability of adaptive reuse is divided into environmental sustainability (e.g., resource efficiency), economic sustainability (e.g., cost efficiency), social sustainability (e.g., memory preservation). Several studies suggest frameworks/methods/strategies to provide sustainable adaptive reuse [3–8]. Hampel developed a holistic framework for sustainable adaptive reuse which comprises economic, environmental, technical, context, social, and regulations and policy issues [4]. Jiang et al. have suggested a new preliminary framework for the adaptive reuse of historic buildings which balances heritage conservation and energy efficiency [9]. Kitagorsky identified new construction modules as a strategy to implement adaptive reuse process [5]. Smart specialization strategies for adaptive reuse projects were analysed to provide for circular adaptive reuse [6]. While the majority of the selected studies deal with strategies at building level, Celluci has suggested interventions at room, home and urban level [7]. Hamida et al. have examined circular building adaptability approaches as applied into multiple case studies. According to their study, functional reconversion and building restoration are the strategies which are required to develop [3].

Other studies suggest frameworks/methods/strategies which are not directly focused on the sustainability dimensions. Daub has examined the interventions as a strategy, such as adaptive reuse, façadism and demolition [10]. Lotfi et al. have analysed the context-based adaptive reuse strategies from the point of cultural and political view [11]. Human-centred adaptive reuse of historic buildings has been analysed to provide better investment decisions [12].

Table 11.1 Overview of goals and objectives pursued through building adaptive reuse design and/or construction from the literature ranked according to occurrences within the selected literature

Goal	Method	Article
Sustainable adaptive reuse	Generate sustainable adaptive reuse framework/method/strategy	[3–7, 25]
Assessment of adaptive reuse	Generate sustainable adaptive reuse framework/method/strategy	[10–13, 25]
Energy efficiency, LCA, climate change mitigation	Energy efficient adaptive reuse framework	[14–19, 25]
Urban regeneration	n.a	[20–22]
Function	Finding the new function	[23–25]

Popescu et al. have analysed the challenges varying from materials reuse to support from the local community and users of repurposed buildings, while framing the circular adaptive reuse [8]. Takva et al. have examined how the contemporary strategy of adding volumes to existing buildings, as adaptive reuse strategy, meet the needs of historical buildings to provide sustainability [13]. Jiang et al. have examined the PV application to historical buildings as an adaptive reuse strategy [9].

While some studies suggest new strategies, some of them examine the existing strategy for sustainable adaptive reuse. Shao et al. have analysed the innovative strategies for adaptive reuse which were determined in the AdapSTAR model. They classified the types of innovative design according to the criterion of the AdaptSTAR model, which is tool to promote sustainability in the built environment [14]. The reuse of materials is one way to enable adaptive reuse of circularity. Bertin et al. have examined the cycle of material with a life-cycle perspective. According to the study, the reuse of the structural elements contributes to reducing environmental impacts [15]. Rodrigez et al. have performed the eco efficiency assessment for a historic building to assess alternative retrofit strategies and uses [16]

The built environment has potential to climate change mitigation and reducing waste generation and energy use. The reuse of the building elements and materials cut the greenhouse gas emissions to produce building elements and materials. Therefore, adaptive reuse is also addressed as a sustainable tool for climate change mitigation. Conejos et al. have mentioned adaptive reuse as a strategy for carbon neutral cities [17]. Aigwi et al. have discussed the applicability of the adaptive reuse concept as a sustainable tool for climate change mitigation [18]. Yung et al. have examined the implementation challenges to the adaptive reuse of heritage buildings from the point of low carbon cities [19].

Low carbon cities can be generated by the integrated efforts of heritage conservation and urban regeneration. Armstrong et al. have developed tool for evaluating adaptive reuse as an urban regeneration strategy through understanding vacancy [20]. In the study conducted in Seoul, it is stated that adaptive reuse of the apartments will contribute not only to heritage value but also to overall sustainability from the perspective of urban regeneration [21]. Döner have established the framework for adaptive reuse as a solution tool for social sustainability in urban regeneration processes [22].

The decision on function(s) of adaptive reuse of historic buildings is a complex problem. The new function must not damage historic buildings' value. The aspects of the historical buildings have importance at adaptive reuse process to preserve its value. Architectural, historical, environmental, social, cultural, economic, and political are only some of the aspects of historic buildings that are examined in academic papers. Vordopoulos et al. analysed the economic, political, environmental, socio-cultural, technical and legal aspects with AHP method (Table 11.2).

This paper examined the potential of adaptive reuse practices by enhancing strengths and opportunities as well as counteracting weaknesses and threats [23]. Abastante et al. suggested a method to find an appropriate function for iconic buildings. According to the study, multicriteria decision-making tools were used to find a

Table 11.2 Selected literature highlighting specific goals pursued through building adaptive reuse

Citation	Article	Authors	Date	Goal (cultural versus energy efficiency; climate adaptation etc.; new functions)
[24]	The introduction of the SRF-II method to compare hypothesis of adaptive reuse for an iconic historical building	Francesca Abastante, Salvatore Corrente, Salvatore Greco, Isabella M. Lami, Beatrice Mecca	2022	Determining new function. Previous Function (The Stock Exchange). Suggested Function (Art school, Sport center, Restaurant, Gaming area, Museum, Wine palace) Decided Function (Wine Palace)
[15]	Design for Reuse (DfReu) applied to buildings; anticipate disassembly for the End-of-Life (EoL), in order to preserve resources	Ingrid Bertin, Adélaïde Feraille Fresnet, Bertrand Laratte, Robert Le Roy	2019	Framework: Setting up an infinite cycle of use of materials by their reuse and answering in particular to the problems of circular economy
[7]	Circular economy strategies for adaptive reuse of residential building	Cristiana Cellucci	2021	Strategies: determining strategies of circular regeneration of residential buildings through adaptive solutions at room level, home level and urban in pursuit of human wellbeing
[14]	A Research on Knowledge Theory of Innovative Design for Adaptive Reuse of Old Buildings in Public Space	Shao Dan	2019	Identifying the adaptive reuse of historic buildings has a richer meaning to new buildings, which could be integrated with sustainability and innovation in environmental design
[10]	Welcome to the [Growth] Machine: An Analysis of Heritage Conservation in the Intensifying City	Ben Daub	2022	Strategies: examining the three main intervention types: adaptive reuse, façadism, and demolition in Toronto
[3]	Circular building adaptability in adaptive reuse: multiple case studies in the Netherlands	Mohammad B. Hamida, Hilde Remøy, Vincent Gruis, Tuuli Jylhä	2022	Strategies: explore to which extent circular building adaptability strategies are applied in adaptive reuse projects
[4]	A framework for sustainable adaptive reuse of industrial buildings	Friedrich Hampel	2020	Framework: testing developed framework for adaptive reuse which covers economic, environmental, technical, context, social, and planning aspects

(continued)

Table 11.2 (continued)

Citation	Article	Authors	Date	Goal (cultural versus energy efficiency; climate adaptation etc.; new functions)
[9]	Adaptive reuse and energy transition of built heritage and historic gardens: The sustainable conservation of Casa Jelinek in Trieste (Italy)	Li Jiang, Elena Lucchi, Davide Del Curto	2023	Energy efficiency (providing framework to balance heritage conservation and energy efficiency, listing potential opportunity and risk in energy transition)
[5]	A Concept for Sustainable Building Projects Using Hybrid Modular and Adaptive Reuse Strategies	Joshua Kitagorsky	2022	New construction modules: Proposed hybrid modular construction for adaptability
[13]	Sustainable Adaptive Reuse Strategy Evaluation for Cultural Heritage Buildings	Yenal Takva, Çağatay Takva, Zeynep Yeşim İlerisoy	2023	Strategies: determine the adaptive reuse strategies and to observe how contemporary additions are integrated to maintain a sustainable form of conservation
[12]	The "Intrinsic Value" of Cultural Heritage as Driver for Circular Human-Centered Adaptive Reuse	Luigi Fusco Girard, Marilena Vecco	2021	New Circular Business model for adaptive reuse project
[8]	Circular Economy and Religious Heritage Conservation: Adaptive Reuse Challenges	Mara Popescu, Daniela Staicu	2022	AR&CE: identify how the circular economy practices are already embodied in adaptive reuse
[6]	Circular Economy Concepts for Cultural Heritage Adaptive Reuse Implemented Through Smart Specialisations Strategies	Jermina Stanojev, Christer Gustafsson	2019	Strategies: smart specialisation strategies for adaptive reuse practices with CE

solution for complex problems [24]. Li et al. have examined the building suggested function according to the theory of adaptability [25].

The adaptive reuse interventions can be grouped into different categories, i.e., interventions required to satisfy physical requirement requested by new functions, interventions to restore building integrity; and interventions to improve overall building sustainability. Celluci has suggested integrated strategies in adaptive regeneration/reuse aiming at combining functional, structural, energy, and social interventions. According to this study, space/volume addition can be mentioned as a functional strategy, while reinforcement and construction of new structures are building physics strategies. Replacement/integration of the envelope and/or equipment can be considered energy efficient interventions. Adding multifunctional space for gathering to existing buildings are common interventions suitable for society-oriented adaptive building reuse [7].

The requirements of a specific building change according to its function. As an example, the required space, levels, height, openings, or materials for a restaurant building vary from similar requirements for a museum building. The internal layout also changes according to the functional desired traits. As a consequence, the choice of new functions, in an adaptive reuse project, has a significant role to play. Abastante et al. have discussed the process of determining new functions for historic buildings such as restaurants, schools, sport centers, museums, wine stores, and game centers alternatives. Adding mezzanine floors, creating partitions, merging spaces, installing removable units, installing new utilities were some of the suggested interventions to pursue alternative functional goals [24, 26]. Kitagorsky suggested hybrid modular construction systems for adaptive reuse [5]. Celluci examined the suggested interventions at room level, home level and urban level from the point of view of circularity [7].

Strategies for sustainable adaptive reuse of historic buildings encompass interventions to provide energy efficiency as well as decrease carbon emissions. Jiang et al. have suggested replacement of the windows, thermal insulation, applying HVAC as retrofit interventions (i.e., any work to a building over and above maintenance to change its capacity, function or performance) for adaptive reuse. In this study, building integrated and building applied photovoltaic panels were analysed as useful intervention for adaptive reuse [9]. Rodrigez et al. have suggested exterior wall retrofit, roof and floor retrofit and window replacement as an energy efficient retrofit for adaptive reuse [16]. Adding new volumes to existing buildings can also be considered a valid strategy for adaptive reuse to provide building inhabitability and sustainability. Takva et al. have examined how the contemporary additions to historical buildings meet the needs of sustainable reuse of historical buildings [13] (Table 11.3).

The adaptive reuse strategies must preserve historical buildings values. In the literature, there are several papers discussing strategies after implementation has taken place. Dan et al. have examined adaptive reuse projects within the scope of innovative design to provide sustainable adaptive reuse [14].

Table 11.3 Overview of building adaptive reuse design and/or construction interventions from the literature and their level of application ranked according to occurrences within the selected literature

Intervention requirements	Type of intervention	Article
Physical requirements	Reinforcement, rehabilitation	[5, 23, 27]
Functional requirements	Adding mezzanine floor, adding partitions, merging two space, installation of removable unit, installing new utilities	[5, 23, 25, 27]
Sustainability requirements	Energy efficient retrofit interventions	[9, 13, 17, 19]

According to the EU Quality Principles report, when new functions are considered, these shall be compatible with the heritage status, responding to community needs, and sustainable. As a consequence, suggested/implemented interventions should aim at preserving heritage value, satisfy community needs, and contribute to overall sustainability [28].

In the literature, adaptive reuse projects are assessed in two stages: before implementation and after implementation. Before implementation assessments comprise the decision-making of the function, of the interventions, etc. While this process ensures the preservation of the values of the historical building, it also creates an opportunity to determine whether the decisions taken ensure social, economic and environmental sustainability. After evaluation, the action taken are scrutinized, thus offering suggestions for improvement, if any. Adaptive reuse design and/or construction assessment/decision making tools from the literature can both be used for evaluation purposes.

Multi criteria decision making (MCDM) methods are used for complex problems such as adaptive reuse. These methods enable us to determine the relative importance of historic building values, the most appropriate functions, the impacts produced etc. Della Spina has suggested a hybrid framework for ranking adaptive reuse strategies by using MCDM tools. In this paper, the analytical hierarchy process (AHP) was used to find appropriate function which can provide financial sustainability [29]. Hamida et al. have used decision making tools to select circular building adaptability-related strategies [3]. Ovo et al. have applied a multicriteria decision analysis (MCDA) with the combination of economic and qualitative indicators to define the most appropriate function for adaptive reuse [30]. Della Spina et al. have combined hierarchical process analysis (AHP) and SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to optimize investment alternatives for a more efficient allocation of public resources [31].

There is also a tool already developed for analysing adaptive reuse strategies. Cojenos et al. have examined the AdaptSTAR tool to analyze if a building is suitable and shows potential for future adaptive reuse, already at the time a building is designed. In the tool they used, physical, economic, functional, technological, social, legal, and political categories enable to calculate an adaptive reuse START rating [32, 33]. Kaya et al. have used the historic urban landscape (HUL) toolkit as a multicriteria decision making tool to select adaptive reuse strategies to reduce environmental impacts [34]. Foster et al. have studied determining the circular city adaptive reuse of cultural heritage indicators to measure investment opportunity. Composite indicators and scoreboards (COIN) tool developed by the European Commission Joint Research Center were used to determine indicators [35].

Some studies were aimed at evaluating post-adaptive reuse. Dişli et al. have developed a method to analyze the application of the circular economy to existing buildings and their preservation method [36]. Chan et al. have analysed the environmental and economic impacts of the adaptive reuse building construction by using input–output models [37]. Durukan et al. have analysed the adaptive reuse application of the historic complex by comparison of the sustainability dimensions [38].

11.3 Conclusion and Way Forward

The conducted rapid evidence assessment has identified key adaptive reuse issues that need to be addressed by policy makers, developers and owners during the development stages of the planning and design process so that efforts toward circularity and overall sustainability can be encouraged.

Addressing building adaptive reuse can significantly reduce whole life costs and waste, lead to improved building functionality, extend durability, increase attractiveness and economic potential, reinforce cultural identity and social inclusion, while contributing to urban regeneration.

The identification of drivers and barriers can enable a balanced view of adaptive reuse opportunities, and all stakeholders should devote attention to synergies and trade-offs embedded in making such choices, especially in relation to heritage buildings.

In the conducted research, it was revealed that key drivers for building adaptive reuse focus on solving lifecycle issues, inserting new functions within existing urban areas, improving aesthetic qualities of buildings and districts, as well as taking advantage of existing financial incentives and urban regeneration programmes.

From a city and regional perspective, building adaptive reuse can be an effective strategy for regenerating brownfields and post-industrial buildings, increasing density, reducing urban sprawl, and encouraging proximity (e.g., the "15-min" city concept).

The barriers to building adaptive reuse, on the other hand, include required investment and maintenance costs, outdated building regulations, inertia of "business-as-usual" development criteria, and the inherent risk and uncertainty associated with the intervention on degraded building stocks.

More empirical research is required to examine the role and benefits of building adaptive reuse in the context of its contribution to circularity and overall sustainability, if it is to become an effective strategic approach to circular urban regenerative urbanization that drives the formulation of public policy and public–private practice for addressing the intertwined ecological, environmental, social and economic issues associated with existing building stocks.

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Part III
Criteria and Indicators for Circularity in Construction

Rand Askar

Acknowledging the significance of applying Circular Economy (CE) principles across the various scales of building composition, Part III of this book methodically explores circularity criteria and indicators, progressing from materials to components, systems, and ultimately whole building design, all within a lifecycle framework.

Materials, as the foundational elements of any building, are where circularity begins. This involves not only their responsible sourcing but also their management throughout the project lifecycle as they integrate into more complex components and systems. The opening chapter of Part III delves into construction materials, outlining both general criteria and indicators applicable to industrial products and specific criteria tailored to the nuances of building processes and practices. It encompasses indicators for different lifecycle stages, together with environmental aspects. The chapter sheds light on the circularity of traditional construction materials such as steel and concrete, alongside innovative materials that have recently emerged to enhance sustainability and circularity.

Advancing through the hierarchy of building entities, the second chapter focuses on products derived from construction materials and the systems formed by these products. It examines how the condition of individual systems impacts the overall circularity of a building, emphasising the importance of prioritising criteria for each system, which often varies depending on the lifespan of its constituent products. This aims to pave the way towards creating a comprehensive weighting method for different building systems based on the relevance of circularity characteristics to be evaluated.

The final chapter addresses the building as an integrated whole, highlighting criteria and indicators put forth by international initiatives, European frameworks, and national efforts aimed at optimising and disseminating circularity practices among stakeholders across the value chain. It categorises these criteria and indicators

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into various aspects of buildings, including materials and resources, energy, water, economic factors, social wellbeing, waste management, and ecosystem impact.

By systematically analysing circularity criteria and indicators—from materials through products and systems to the building in its entirety—Part III clarifies the intricate relationships between building elements and the different considerations and requirements at each level of the building and each stage of the lifecycle, using a bottom-up approach.

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: Cement–limestone and clay Ecological cements	Concrete element
Concretes: Biological concrete Conventional concrete Conventional reinforced concrete Photocatalytic concrete 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_2e/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_2e/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: Cement–limestone and clay 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: Biological concrete Conventional concrete Conventional reinforced concrete Photocatalytic concrete 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.

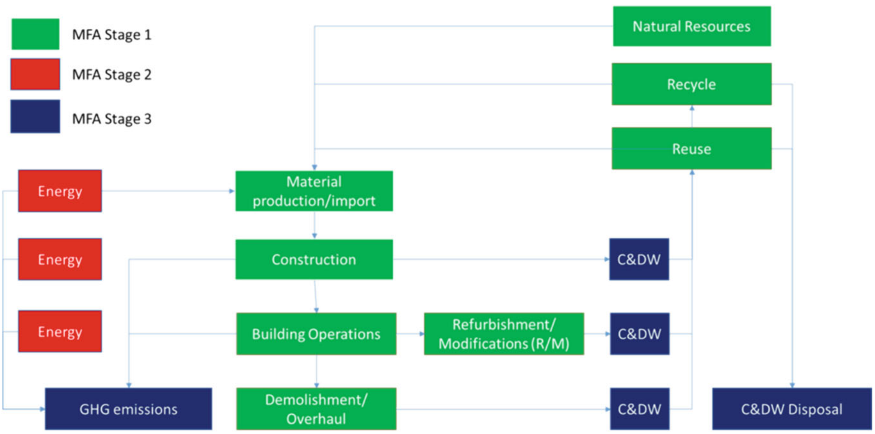

Fig. 12.1 Resource flow cycle at a country-level construction sector

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.

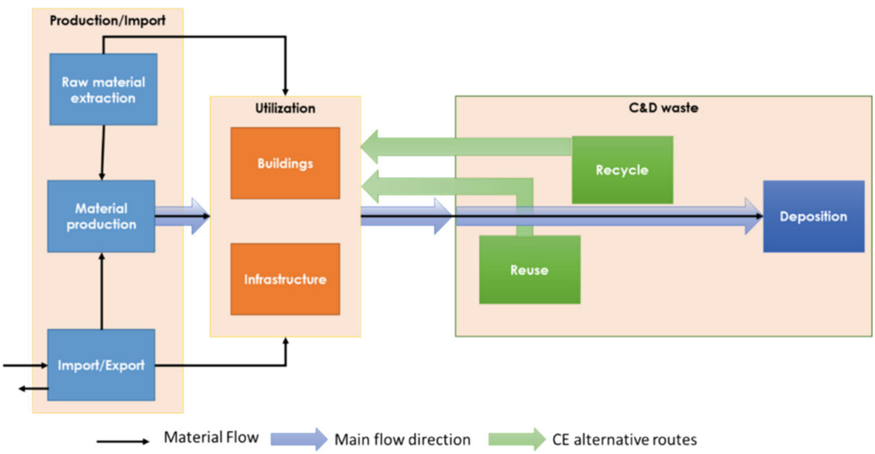

Fig. 12.2 Material flow directions for buildings and infrastructures' construction activities

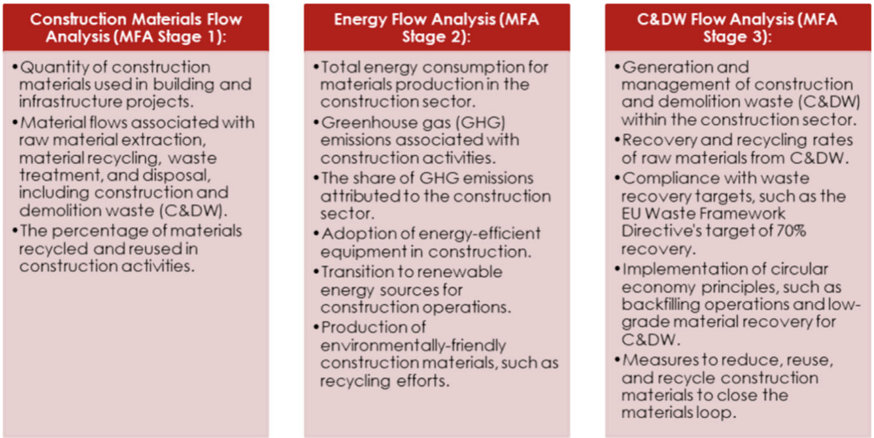

Fig. 12.3 Strategic indicators for MFA in the construction sector

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: Cement–limestone and clay Ecological cements		○		●	
Concretes: Biological concrete Conventional concrete Conventional reinforced concrete Photocatalytic concrete Recycled concrete		○ ○ ○		● ●	
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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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 • 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 • 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.

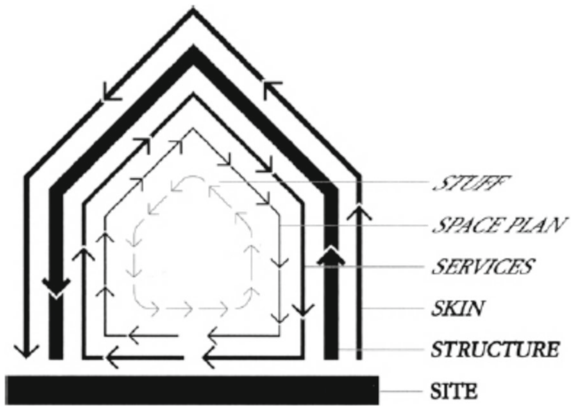
However, adaptability can also be applied to buildings not originally designed with adaptability in mind. This can be achieved through adaptive reuse strategies, which involve the "reconfiguration" of systems during the operational stage to prevent a premature EoL [17]. Adaptive reuse, or reconfigured 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] Level(s) [23]
	Positioning of columns/design complexity	AdaptSTAR [22] FLEX 4.0 [24] Level(s) [23]
	Greater ceiling heights for surface routes	FLEX 4.0 [24] 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] 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] 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] 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

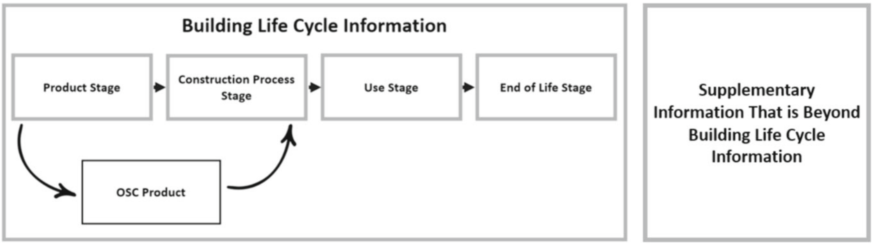


Fig. 13.2 Cradle to grave–LCA model (adapted from [46], OSC stands for off-site construction)

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 Durability of the components	[69]	Circular material use rate (cei_srm030) Contribution of recycled materials to raw materials demand-end-of-liferecycling input rates (EOL-RIR) (cei_srm010) Trade in recyclable raw materials (cei_srm020) Material footprint (cei_pc020) Greenhouse gas emissions from production activities (cei_gsr011) Material import dependency (cei_gsr030) 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 Reuse rate Recovery rate Recycling rate Separate collection rate Reused products from C&DW	[75]	Waste generation per capita (cei_pc034) Generation of waste excluding major mineral wastes per GDP unit (cei_pc032) Generation of packaging waste per capita (cei_pc040) Generation of plastic packaging waste per capita (cei_pc050) Recycling rate of all waste excluding major mineral waste (cei_wm010) Recycling rate of packaging waste by type of packaging (cei_wm020) 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 Protocols for incentivisation of CE practices use Procurement that covers circular products Voluntary agreements Sequence of disassembly, recommended tools, and safety guides	[75, 83]	Private investment and gross added value related to circular economy sectors (cei_cie012) Patents related to recycling and secondary raw materials (cei_cie020)
Stakeholder involvement	Initiatives on reuse Construction companies that prioritise the use of circular methods and components Stakeholders' engagement in the design process 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 life-cycle 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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Chapter 14
Circularity Criteria and Indicators at the Whole Building Design Level

Bahar Feizollahbeigi, Ricardo Mateus, Elena Goicolea Güemez, and Marta Gómez-Gil

Abstract The built environment accounts for approximately 50% of total raw material extraction and 25% of all waste in the European Union, much of which comprises materials with significant potential for reuse and recycling. Given the finite nature of the planet's resources, transitioning to a circular economy (CE) approach within the built environment, particularly at the building design level, is essential for sustainability. Indicators serve as vital tools for assessing circularity and guiding the implementation of CE principles in the design, construction and management of buildings and infrastructure. This chapter examines international, European, and national policies and standards, highlighting the most pertinent circularity indicators at the whole building design level. It provides a categorised list of the most widely used indicators for measuring circularity. A bibliographic-analytical approach is employed to evaluate the prevalence and alignment of various sustainability and circularity indicators within international and European policies and standards at the building level. The efforts of European countries, with particular reference to Portugal and Spain, in developing circularity frameworks for the construction sector, are also explored. The identified indicators are classified into seven categories based on their impact areas: Material and Resources, Energy, Water, Waste Management, Ecosystem, Social, and Economic. Each category and its subset indicators are analysed in detail. Finally, the chapter provides recommendations for further research to enhance the integration of CE principles into the design processes of the construction sector, thereby contributing to a more sustainable built environment.

Keywords Circularity indicators · Building design · International policies and standards · Circular design

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14.1 Introduction

This chapter undertakes an investigation on the most relevant international, European, and national policies, standards, and references associated with the circular economy (CE) within the scope of building design. The aim is not just to list these regulations and guidelines but to delve into their main principles and objectives, significance, relevance, and implications for promoting circularity within the built environment. By adopting an analytical approach, the frequency and alignment of several sustainability and circularity criteria and indicators at the building design level in national and international policies and standards have been investigated, providing you with confident research findings.

Additionally, an analysis has been conducted on how sustainability and circularity indicators are incorporated into those policies and standards. The chapter presents the most relevant and commonly applied circularity indicators and criteria specific to the building design, offering insights into how they can support the evaluation of sustainability and resource efficiency in construction projects.

14.2 Review of Policies and Standards Related to Circularity Indicators in Building Design-Level

14.2.1 European Policies on Circularity Indicators in Building Design-Level

EU Circular Economy Action Plan (CEAP). This Action Plan aims to establish a framework for European policies on products, emphasising sustainability by reducing products' consumption footprint and doubling their circular material use rate. This initiative arises from the imperative need to transition towards a new production model that returns to the planet more than what is extracted from it, avoiding exhausting its natural resources [1].

Within this Action Plan, key stakeholders and product value chains—or product markets—are identified with 'Construction and buildings' highlighted as a central focus. This emphasis is due to the industry's substantial resource requirements and significant waste generation, leading to considerable greenhouse gas (GHG) emissions [1].

In the context of the construction and building industry, the European Commission is advancing the Strategy for a Sustainable Built Environment through this Action Plan. This strategy encompasses criteria for recycled content, considerations of asset longevity and adaptability, incorporation of life cycle assessments, targets for material recovery, and efforts to reduce soil sealing. The Action Plan serves as a framework for future actions and does not propose any specific indicators.

European Taxonomy. The EU Taxonomy serves as a tool to assist investors, companies, and project promoters in navigating the shift towards an economy that is low-carbon, resilient, and resource-efficient [2]. This Taxonomy establishes a list of economically sustainable activities centered on environmental criteria. Aligned with the European Green Deal, its purpose is to combat greenwashing and guarantee that significant investments in sustainable initiatives truly support environmentally friendly activities [3].

The EU Taxonomy Regulation establishes specific criteria for assessing the environmental sustainability of an economic activity. According to these criteria, an activity must meet several requirements, including being categorised under a specific taxonomic activity by the EU, making a significant contribution to one of six specified environmental objectives, avoiding significant harm to the remaining environmental objectives, and adhering to a set of minimum social performance parameters [4]. The six defined environmental objectives are [2]:

1. Climate change mitigation.
2. Climate change adaptation.
3. Protection of water and marine resources.
4. Transition to a circular economy.
5. Pollution control.
6. The protection of ecosystems.

Currently, technical screening criteria are available only for the first two objectives within the EU Taxonomy. The Real Estate sector, being a major economic activity, falls under the purview of the Taxonomy Regulation. Within this sector, the development of new structures is included, encompassing the building design level [5]. However, due to limitations in whole life cycle GHG emissions data, the focus primarily centres on the operational stage rather than the other life cycle stages [6].

The EU Taxonomy for new building construction considers a structure supportive of climate change mitigation if it exhibits markedly lower energy consumption (10% below the specified threshold for national nearly zero-energy building requirements). Verification of this is mandated through an Energy Performance Certificate, which assesses airtightness and thermal integrity.

New buildings are required to adhere to "Do No Significant Harm": criteria across various aspects, including climate adaptation, water management, CE practices, pollution prevention, and biodiversity. In addition to making substantial contributions to climate change adaptation, they must incorporate both physical and non-physical solutions, known as 'adaptation solutions,' to effectively mitigate the most critical physical climate risks associated with their specific activity. A comprehensive climate risk and vulnerability assessment for identified physical climate risks is also mandatory [5]. Table 14.1 presents the circularity criteria for construction and real estate activities contributing to climate mitigation and adaptation among all substantial contribution criteria.

Table 14.1 Technical screening criteria regarding circularity in construction and real estate activities

Do No Significant Harm criteria (DNSH)	Indicator
Circular economy	– Construction and demolition waste (excluding naturally occurring material referred to in category 17 May 2004 in the European List of Waste established by Decision 2000/532/EC) generated on the construction site is prepared for reuse, recycling, and other material recovery, including backfilling operations using waste to substitute other materials, in accordance with the waste hierarchy and the EU Construction and Demolition Waste Management Protocol (296) – Operators limit waste generation in processes related to construction and demolition, following the EU Construction and Demolition Waste Management Protocol, considering the best available techniques, using selective demolition to enable removal and safe handling of hazardous substances and facilitate reuse and high-quality recycling by selective removal of materials, using available sorting systems for construction and demolition waste – Building design and construction techniques support circularity and, in particular, demonstrate, regarding ISO 20887 (297) or other standards for assessing the disassembly or adaptability of buildings, how they are designed to be more resource-efficient, adaptable, flexible, and dismantlable to enable reuse and recycling

European Green Deal. The Green Pact was launched as a comprehensive roadmap for formulating policies and implementing measures in response to one crucial challenge: the one related to climate and environmental protection. Aligned with the United Nation's 2030 Agenda and the Sustainable Development Goals (SDGs), this document, spearheaded by the European Commission, envisions a future EU that is prosperous, modern, fair, and capable of sustained social and economic growth without depleting natural resources [7].

At its core, the European Green Deal defines objectives and guidelines that underpin several European action plans and strategies. Notably, it serves as the foundation for initiatives such as the EU Circular Economy Action Plan, which, as previously discussed, deals with materials and resources within the construction sector, among other aspects. Furthermore, the Green Deal promotes the Renovation Wave strategy, aimed at accelerating and deepening sustainable building renovations, therefore contributing to circularity within the construction sector.

Nevertheless, it is essential to note that while the European Green Deal outlines overarching goals and strategies, it does not provide a specific framework of indicators of circularity in the construction sector.

Level(s). Level(s) is a common European framework first introduced in 2018 to aid professionals in the construction industry in assessing and monitoring the circularity and sustainability of buildings throughout their entire life cycle. Its primary goal is to act as a bridge between the objectives established in the SDGs and the European Green Deal, including initiatives like the Renovation Wave, the New European

Bauhaus, and the Circular Economy Action Plan, and the real-world challenges faced by the construction sector [8].

Level(s) is not a certification scheme but rather a framework designed to ensure that all existing building sustainability assessment tools evaluate the same priorities, enhancing consistency and homogeneity within the certification market [8]. Therefore, it does not directly conduct sustainability evaluations of buildings and projects but instead aims to streamline sustainability and circularity thinking by reporting requirements on different aspects.

The Level(s) framework comprises 16 indicators (see Table 14.2), grouped into six macro-objectives that fall under three thematic areas [8]. These fundamental sustainability indicators assess carbon emissions, materials usage, water consumption, health considerations, comfort levels, and the impacts of climate change across the entire life cycle of a building [9]. Level(s) operates as a flexible framework with three levels of application depending on the stage of the building project being analysed: conceptual design, detailed design, and post-construction evaluations. In addition, users have the flexibility to choose which indicators to use, depending on the purpose of the assessment and the specific needs of the project.

Level(s) advocates for circularity under its macro-objective 2, aiming to establish resource-efficient and circular material life cycles by evaluating key opportunities to enhance resource efficiency and circularity. Implementing indicators of this macro-objective can significantly enhance a building's performance in line with circularity principles, conserving and reducing the consumption of raw materials, identifying possibilities for reuse or recycling, and ensuring buildings can be easily adapted to meet occupants' changing needs over time [9].

EU Circular Economy Monitoring Framework. In May 2023, the European Commission implemented a revised EU Monitoring Framework to oversee progress in achieving a CE, complementing its action plan. This monitoring system enables the European Commission and policymakers to track progress and evaluate the effectiveness of their actions [10].

This framework is split into five thematic areas that are broader in scope and do not specifically target the built environment or any of its components, such as building design considerations. Table 14.3 illustrates these areas along with the criteria and indicators employed within the EU Monitoring Framework for the CE.

Eco-design Directive. The EU Eco-design Directive provides a framework requiring manufacturers of energy-consuming products to minimise energy consumption and mitigate adverse environmental effects throughout the product life cycle. This directive is complemented by the Energy Labelling Directive [12].

Under the Eco-design Directive, manufacturers are required to adhere to performance criteria to ensure the legal market entry of their products. However, the Directive currently lacks specific measures, standards, or overarching energy-saving targets. An updated version of the Directive expands its scope to include, in principle, all energy-related products [12].

Table 14.2 The level(s) macro-objectives and indicators [8]

Thematic areas	Macro-objectives	Indicators
Resource use and environmental performance	1. Greenhouse gas emissions along a building's life cycle	1.1. Use stage energy performance (kWh/m^2/year)
		1.2. Life cycle Global warming potential (CO_2 eq./m^2/year)
	2. Resource-efficient and circular material life cycles	2.1. Bill of quantities, materials, and lifespans
		2.2. Construction and demolition waste
		2.3. Design for adaptability and renovation
		2.4. Design for deconstruction
	3. Efficient use of water resources	3.1. Use stage water consumption (m^3/occupant/year)
Health and comfort	4. Healthy and comfortable spaces	4.1. Indoor air quality
		4.2. Time out of thermal comfort range
		4.3. Lighting
		4.4. Acoustics
Cost, value, and risk	5. Adaption and resilience to climate change	5.1. Life cycle tools: scenarios for projected future climatic conditions
		5.2. Increased risk of extreme weather
		5.3. Sustainable drainage
	6. Optimised life cycle cost and value	6.1. Life cycle costs (€/m^2/year)
		6.2. Value creation and risk factors

While this framework primarily targets equipment and devices, typically those that are electrical and energy-consuming, it does not specifically address the construction industry.

Organisation Environmental Footprint (OEF) and Product Environmental Footprint (PEF). The European Commission has developed the Product Environmental Footprint (PEF) and Organisational Environmental Footprint (OEF) as methodologies for conducting life cycle assessment (LCA), aimed at evaluating and communicating the environmental impact of products and organisations throughout their life cycle. Together, these methods form the basis of the EU Environmental

Table 14.3 Thematic areas and circularity indicators of the EU circular economy monitoring framework [11]

Thematic areas	Criteria	Indicators
1. Production and consumption	Material consumption	Material footprint (tonnes per capita)
		Resource productivity (index 2000 = 100)
		Green public procurement
		Total waste generation per capita
	Waste generation	Total waste generation per capita (Kg per capita)
		Generation of waste, excluding major mineral wastes per GDP unit kg per thousand-euro, chain-linked volumes (2010)
		Generation of municipal waste per capita (kg per capita)
		Food waste (kg per capita)
		Generation of packaging waste per capita (kg per capita)
		Generation of plastic packaging waste per capita (kg per capita)
2. Waste management	Overall recycling rates	Recycling rate of municipal waste (%)
		Recycling rate of all waste, excluding major mineral waste (%)
	Recycling rates for specific waste streams	Recycling rate of overall packaging (%)
		Recycling rate of plastic packaging (%)
		Recycling rate of Waste from Electrical and Electronic Equipment (WEEE) separately collected (%)
3. Secondary raw materials	Contribution of recycled materials to raw materials demand	Circular material uses rate (%)
		End-of-life recycling input rates (EOL-RIR), aluminium (%)
	Trade in recyclable raw materials	Imports from non-EU countries (thousand tonnes)
		Exports to non-EU countries (thousand tonnes)

(continued)

Table 14.3 (continued)

Thematic areas	Criteria	Indicators
		Intra-EU trade (thousand tonnes)
4. Competitiveness and innovation	Private investment, jobs, and gross value added related to circular economy sectors	Private investments (% of gross domestic product (GDP) at current prices)
		Persons employed (% of total employment)
		Gross value-added % of gross domestic product (GDP) at current prices
	Innovation	Patents related to waste management and recycling (number)
5-Global sustainability and resilience	Global sustainability from the circular economy	Consumption footprint (Index 2010 = 100)
		GHG emissions from production activities (kg per capita)
	Resilience from the circular economy	Material import dependency (%)
		EU self-sufficiency for raw materials, aluminium (%)

Footprint (EF), which incorporates established approaches and complies with international standards, such as the ISO 14040 series and the European International Life Cycle Data System (ILCD) [13].

An EF study encompasses mandatory life cycle stages:

– Raw material acquisition and pre-processing.
– Manufacturing.
– Distribution.
– Use stage.
– End of life.

The PEF and OEF methodologies, developed through consensus-building processes, require modeling all waste flows across manufacturing, distribution, use, and end-of-life stages using the Circular Footprint Formula (CFF). This formula comprises three elements: a material formula, an energy formula, and a disposal formula. This comprehensive approach ensures the consideration of recycled or recyclable materials entering or leaving the system [13].

The material component of the formula applies to every stage of the value chain where recycled materials replace virgin raw materials. The energy aspect pertains to the amount of material utilised for energy recovery at the end of the product's life. Lastly, the disposal segment of the formula computes emissions and resource usage associated with the disposal of all materials not recycled or employed for energy recovery [13].

It's important to note that this framework is designed broadly for all sectors, including forestry, packaging production, agriculture, and related transportation activities. It does not specifically target the construction sector.

Waste Framework Directive. The EU Waste Framework Directive (WFD) is a crucial legislation in the European Union, defining fundamental concepts such as waste management, recycling, and recovery. It sets out essential waste management principles and mandates to ensure the proper handling of waste, aiming to European Commission [14]:

- Safeguard human health and the environment.
- Avoids risk to water, air, soil, plants or animals.
- Prevent nuisance through noise or odours.
- Protect the countryside or places of special interest.

To meet the goals outlined in this Directive, EU member states had to implement measures to attain the following targets:

- By 2020, increase the preparation for re-use and the recycling of household waste materials (e.g., paper, metal, plastic, and glass) to at least 50% by weight.
- By 2020, increase the preparation for re-use, recycling, and other material recovery, including using waste for backfilling operations in non-hazardous construction and demolition waste, to at least 70% by weight.
- By 2025, increases the preparation for re-use and recycling of municipal waste to at least 55% by weight, with further targets of 60% by 2030 and 65% by 2035.

Additionally, the Commission is developing end-of-waste criteria for priority waste streams, specifically iron, steel, aluminium scrap, glass cullet, and copper scrap [14].

While the WFD has been instrumental in improving waste management practices, full compliance with all targets has not been achieved uniformly across EU countries. For instance, it introduced recycling and recovery targets to be achieved by 2020 for household waste (50%) and construction and demolition waste (70%). However, as of 2021, only 13 EU countries had achieved the target of a 50% recycling rate for municipal waste set by the WFD [15]. Accordingly, continued efforts and investments are necessary to enhance waste prevention, separate collection, and recycling infrastructure to align with the directive's objectives. Additionally, however, this Framework Directive does not directly refer to the implementation of the CE in the building design, it serves as a foundational piece of legislation that supports and facilitates the transition to a CE within the EU. By promoting waste reduction, recycling, and responsible resource management, it aligns with the principles of circularity.

Packaging Waste. EU regulations on packaging and its waste address both the design and management aspects of packaging. The primary goals include addressing the rising volume of packaging waste, which exacerbates the environmental challenges, and eliminating market barriers arising from varying packaging design rules across

EU member states. The Packaging Directive is designed to achieve the following goals [16]:

– Harmonise national measures related to packaging and packaging waste management.
– Provide a high level of environmental protection.
– Ensure the smooth functioning of the internal market.

While the EU rules on packaging waste align with circularity, they do not explicitly address indicators specific to building design aspects.

14.2.2 International Frameworks on Circularity Indicators in Building Design-Level

Ellen MacArthur Foundation/Arup Circular Building Design Toolkit. The Ellen MacArthur Foundation (EMF) stands as one of the foremost global organisations advocating for the CE and developing circularity principles and indicators. It has created various tools and frameworks to measure circularity across numerous sectors, including construction and the built environment.

According to the Ellen MacArthur Foundation's definition, the CE presents a systematic solution framework addressing pressing global challenges such as climate change, biodiversity loss, waste, and pollution. At the design level, it operates on three core principles [17]:

– Design out waste and pollution: This principle emphasises the need to design products, processes, and systems in a way that eliminates waste and pollution, aiming for a closed-loop system.
– Keep products and materials in use: The principle focuses on extending the lifespan of products and materials through strategies like repair, reuse, refurbishment, and remanufacturing.
– Regenerate natural systems: This principle highlights the importance of restoring and regenerating natural resources and ecosystems, aiming to preserve and enhance the overall natural capital.

In cooperation with Arup, a prominent British multinational professional Engineering consultancy, the Ellen MacArthur Foundation has designed a comprehensive and practical Circular Building Design Toolkit to assess and measure the circularity within building design. This toolkit was first introduced during COP26 Glasgow's climate conference. The principles, strategies, and indicators of this design toolkit are presented in Table 14.4.

The toolkit is developed to achieve Net-zero in the built environment and help designers, construction clients, asset owners, and operators. It provides a practical framework and tools to enable stakeholders across the building life cycle to optimise

Table 14.4 The Ellen MacArthur Foundation's/Arup circular economy principles in the built environment [19]

Principles	Strategy	Indicators
Build just what is needed (build nothing beyond what is strictly necessary)	1. Refuse unnecessary new construction	Reuse of existing usable surface: Share of reused floor area as a percentage of total project gross floor area (%)
Build for long-term use	2. Increase building utilisation	Total building utilisation: Cumulative hours of occupancy, defined as total hours*person spent in the building on a weekly basis, and normalised per square meter (hrs/m^2)
	3. Design for longevity	Value retention and recovery over the whole life cycle: EU Level(s) Whole Life Cycle Costs (\$/m^2/yr)
	4. Design for adaptability	Adaptability potential: Adaptability Score, defined as per EU Level(s) Indicator 2.3. Adaptability, Table 6 (quantitative rating resulting from a qualitative assessment)
	5. Design for disassembly	Disassembly and recovery potential: Ease of Recovery + Ease of Reuse and Recycling Scoring, defined as per EU Level(s) Indicator 2.4 Design for deconstruction (Assessment methodology based on DGNB TEC1.6 Ease of recovery & recycling)
Build efficiently	6. Refuse unnecessary components	Conceptual material efficiency: A material used intensity factor per functional unit over the building life cycle (The functional unit is to be set depending on the building typology, for example, total material use intensity per workstation/hotel bed/resident, etc.) (kg/unit/yr)

(continued)

Table 14.4 (continued)

Principles	Strategy	Indicators
	7. Increase material efficiency	Material use efficiency: Total material use intensity by area and over the whole building life cycle, a counting for all building materials (kg/m^2/yr)
Build with the right materials	8. Reduce the use of virgin and non-renewable materials	Material Circularity Indicator (MCI) from the Ellen MacArthur Foundation
	9. Reduce the use of carbon-intensive materials	Whole life cycle GHG emissions: Carbon emissions intensity measured over the whole building life cycle, as defined under Level(s) Indicator 1.2 Life cycle Global Warming Potential (kgCO_2eq/m^2/year)
	10. Design out hazardous/pollutant materials	Environmental cost: Whole life cycle environmental impact cost per floor area, and over the whole life cycle period as defined by the Dutch MPG methodology (€/m^2/year)

assets for circularity, leading to reduced waste and carbon for a healthier planet and people [18].

14.2.3 International and European Standards on Circularity Indicators in Building Design-Level

CEN/TC 350—Sustainability of construction works. CEN/TC 350, a dedicated technical committee under the European Committee for Standardisation, focuses on developing standards related to the sustainability of both new and existing construction works. Its broader scope extends to evaluating the sustainability performance of construction works, including buildings and civil engineering works [20].

The committee's mandate includes creating standardised methods to assess sustainability aspects within the framework of the UN Sustainable Development Goals and CE principles. These methods cover the entire life cycle, from the design and construction phases to operation and end-of-life management. This technical committee covers the following aspects [20]:

– Assessment of environmental performance, encompassing circularity principles, energy efficiency, decarbonisation, responsible resource usage (including efficiency and waste reduction), and environmental and biodiversity preservation.
– Assessment of social performance, considering aspects such as health and comfort, safety and security, adaptability, and accessibility in response to user needs. Additionally, evaluating resilience against external events like the impacts of climate change and emphasising responsible sourcing of materials.
– Assessment of economic performance, covering life cycle costs, overall expenses throughout the lifespan, and economic value implications. This includes consideration of 'green finance' initiatives, particularly taxonomy, and implementing standards to align with evolving trends in digitalisation (e.g. BIM, CAD).

In all construction stages, including the design level, circularity implies optimising resource use, minimising waste, and promoting the reuse, refurbishment, and recycling of building materials and components [20]. Accordingly, the connection between CEN/TC 350 and circularity lies in the committee's efforts to enhance sustainability and decrease environmental impacts within the built environment. The committee also plays a remarkable role in supporting the CE principles within the construction industry by developing standards and guidelines and promoting awareness initiatives that support the integration of circularity across various aspects and stages of construction. Subsequent sections analyse how each main standard developed by the CEN/TC 350 committee addresses circularity at the building design level.

EN 15804:2012+A2:2019 Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products. EN 15804, a European Standard overseen by CEN/TC 350, is widely recognised as the leading global standard for generating Environmental Product Declarations (EPD) for construction products [21]. It establishes a standardised format for EPDs within the construction sector, ensuring transparency and comparability of information [22].

The EN 15804 standard offers a framework for creating type III declarations, outlining the methodology for calculating the technical performance of construction products. It defines various modules covering the product's entire life cycle, addressing specific stages from raw material extraction to end-of-life considerations. Calculation rules and data for a set of indicators are provided for each of the life cycle stages [23].

It's important to note that EN 15804 focuses solely on assessing environmental performance at the product level and does not include evaluations of social and economic performances. It provides a comprehensive set of environmental indicators for this purpose as illustrated in Table 14.5 [21].

EN 15804 provides a comprehensive framework of environmental indicators designed for assessing the environmental performance of construction products. Many of these indicators align with those used in measuring circularity within the

Table 14.5 The environmental indicators used in EN 15804 [21]

Category	Indicators
Environmental impact	– Global Warming Potential (GWP) – Ozone Depletion Potential (ODP) – Acidification potential (AP) – Eutrophication potential (EP) – Formation potential of tropospheric ozone (POCP) – Abiotic depletion potential for non-fossil resources (ADP elements) – Abiotic depletion potential for fossil resources (ADP-fossil fuels)
Resource use	– Use of renewable primary energy, excluding renewable primary energy resources used as raw materials – Use of renewable primary energy resources used as raw materials – Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) – Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials – Use of non-renewable primary energy resources used as raw materials – Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) – Use of secondary material – Use of renewable secondary fuels – Use of non-renewable secondary fuels – Use of net freshwater
Waste category	– Hazardous waste disposed – Non-hazardous waste disposed – Radioactive waste disposed
Output flow	– Components for reuse – Materials for recycling – Materials for energy recovery – Exported energy

construction industry, including indicators related to resource use or waste categorisation. Consequently, it can be claimed that this standard is in line with the principles of CE to a great extent.

EN 15643:2021 (WI = 00350031) Sustainability of construction works—a framework for assessment of buildings and civil engineering works. EN 15643 comprises a set of European Standards within the scope of CEN/TC 350. These standards establish a framework for assessing the sustainability of buildings and civil engineering works, encompassing environmental, social, and economic performance. The assessments consider technical attributes and functionalities and employ a life cycle approach, applicable to diverse construction endeavours. For new constructions, the entire life cycle is assessed, while for existing structures, the focus shifts to their remaining service life and eventual end-of-life stages [24].

The standard series aims to evaluate the environmental, social, and economic performance of a building simultaneously and equitably, considering consistent technical characteristics and functionalities. This assessment incorporates various types of information, providing values for different indicators, building scenarios, and life cycle stages, resulting in a comprehensive sustainability assessment for buildings and civil engineering works. [25]. EN 15643-1:2010 serves as the foundational standard for three complementary standards: prEN 15643-2, EN 15643-3, and EN 15643-4. These standards pertain to the assessment framework for environmental, social, and economic performance at the building and product levels [26].

EN 15643-2:2011 not only outlines the requirements for environmental assessment, including the relevant life cycle phases and their constraints, but also defines the indicators for the assessment as illustrated in Table 14.6. Additionally, prEN 15643-3 is designed to assess the social impacts and aspects associated with buildings and their surrounding sites. Its purpose is to facilitate decision-making in sustainability matters, focusing on social aspects such as health, well-being, and functionality [26].

EN 15643 aligns with CE principles by promoting a sustainable approach throughout the building life cycle, from design to the end of its product life cycle. This approach encompasses assessing environmental performance across the building's life cycle and encouraging resource efficiency and waste reduction, thereby supporting the shift towards more circular and sustainable construction practices. The nexus between EN 15643 and circularity is evident in the standard's approach for assessing the environmental performance of buildings, particularly through the specifications outlined in EN 15643-2.

CEN/TC 350/SC 1—Circular Economy in the Construction Sector. In 2021, CEN/TC 350 established a new sub-committee, CEN/TC 350/SC 1, dedicated to developing CE standards within the built environment. This sub-committee aims to define circularity principles, guidelines, and requirements, providing tools and processes to support the shift towards a more sustainable CE. The standards cover all stages of life cycles, spanning from design to deconstruction and end-of-life scenarios. They apply to both new and existing construction works, including buildings, civil engineering works, products, materials, and components. CEN/TC 350/SC 1 tackles technical aspects of circularity and addresses environmental, economic, and social challenges [29].

The purpose of CEN/TC 350/SC 1 is to integrate CE principles into construction practices [30]. In terms of building design, the objective is to develop materials that facilitate the transition from a linear to a CE within the construction sector. This supports the advancement of a climate-neutral and resource-efficient industry [18]. Although the standards of this new sub-committee are still under development, they are geared towards achieving several macro-objectives for buildings and building products [30]:

– Design for disassembly.
– Design for adaptability (durability, reduction of raw materials, repairability, and preventing degradation).
– Design for reuse (reusability and recyclability).
– Next life cycle performance.
– Structural design for recyclable construction works.

Table 14.6 EN 15643 sustainability indicators in building life cycle including design level

Parts	Categories of aspects	Indicators
prEN 15643-2: Environmental assessment [27]	Environmental impacts	– Acidification of land and water resources – Climate change – Destruction of the stratospheric ozone layer – Autrophication – Ormation of ground-level ozone
	Material and energy use	– Use of renewable resources other than primary energy – Use of non-renewable primary energy – Use of renewable primary energy – Use of freshwater resources
	Secondary raw materials, waste and exported energy	– Materials for recycling – Materials for energy recovery – Non-hazardous waste to disposal – Hazardous waste to disposal (other than radioactive waste) – Radioactive waste to disposal
EN 15643-3: Social aspects and impacts [28]	Accessibility	– Accessibility for people with specific needs – Access to building services
	Adaptability	– The ability to accommodate individual user requirements – The ability to accommodate the change in user requirements – The ability to accommodate technical changes – The ability to accommodate the change of use
	Health and comfort	– Acoustic characteristics – Characteristics of indoor air quality – Characteristics of visual comfort – Characteristics of water quality – Electromagnetic characteristics – Spatial characteristics – Thermal characteristics
	Loadings on the neighborhood	– Noise – Emissions to outdoor air, soil and water – Glare and overshadowing – Shocks and vibrations – Ocalised wind effects
	Maintenance	– Maintenance operations

(continued)

Table 14.6 (continued)

Parts	Categories of aspects	Indicators
	Safety/security	– Resistance to climate change (resistance to rain, wind, snow, flood, solar radiation, temperature) – Resistance to accidental actions (earthquakes; explosions; fire; traffic impacts) – Personal safety and security against intruders and vandalism – Security against interruptions of utility supply
	Sourcing of materials and services	– Responsible sourcing and traceability of products and services
	Stakeholder involvement	– The opportunity for interested parties to engage in the decision-making process for the realisation of a building
EN 15643-4: Economic aspects and impacts [25]	Cost	– Economic performance expressed in cost terms over the life cycle
	Financial value	– Economic performance expressed in terms of financial value over the life cycle

ISO 15392:2019 Sustainability in buildings and civil engineering works—General principles. This standard outlines general principles to facilitate the transition of buildings, civil engineering, and other construction projects toward sustainable development. It addresses the entire life cycle of construction works, spanning from inception to end-of-life [31].

ISO 15392 applies to both new and existing construction works, encompassing individual and collective entities, along with materials, products, services, and processes throughout their life cycle. The standard aims to offer universal principles to elevate sustainability in building construction, serving as a shared framework and guide for stakeholders in the construction industry. It seeks to encourage sustainable practices and minimise the environmental impact of building projects at all stages, including the design level [31]. This standard outlines six objectives for integrating sustainability into buildings, concurrently fostering sustainable development, and enhancing the construction sector and the built environment, namely [32]:

1. Reduction of adverse impacts while improving value.
2. Stimulation of a proactive approach.
3. Stimulation of innovation.
4. Decoupling of economic growth from increasing adverse impacts on the environment and/or society.

5. Reconciliation of contradictory interests or requirements arising from short-term and long-term planning or decision-making.

To reach the abovementioned objectives, ISO 15392 applies nine general principles, listed alphabetically as follows [32]:

a. Continual improvement.
b. Equity.
c. Global thinking and local action.
d. Holistic approach.
e. Involvement of interested parties.
f. Long-term consideration.
g. Precaution and risk.
h. Responsibility.
i. Transparency.

While these objectives and principles do not explicitly refer to circularity or provide specific indicators, they indirectly address its principles by promoting the necessity of decoupling economic growth from increasing adverse environmental impacts. They are also aligned with the principles of CE in terms of setting the priorities of designing out of waste and pollution and promoting the regeneration of natural systems.

The standard's focus on decoupling economic growth from worsening environmental and societal impacts suggests an alignment with CE principles. In addition, the principles of "long-term considerations" within these goals can be linked to "Design for Longevity", a key aspect of CE principles in building design.

ISO 21929, Sustainability in building construction Sustainability indicators. Framework for the development of indicators and a core set of indicators for buildings. The ISO 21929 series, including ISO 21929-1 and ISO 21929-2, aims to establish a framework, recommendations, and guidelines for developing and selecting suitable sustainability indicators throughout the life cycle of buildings and construction works. The framework encompasses key environmental, social, and economic impact indicators, with defined rules for their usage. While some indicators are mandatory, others are recommended for assessing sustainability. However, these standards do not provide guidance on the weighting or aggregation of indicator results [26]. The proposed indicators are collected and presented in Table 14.7. They can be applied to all building life cycle stages, including the design stage.

The connection between the ISO 21929 series and circularity lies in the attempt of this standard to introduce a Framework for developing indicators, including a set of environmental indicators, such as using renewable resources, water consumption, waste production, etc., which are under the principles of the CE.

ISO/DIS 59020 Circular economy—Measuring and assessing circularity. This standard defines an assessment framework for organisations to measure circularity, allowing them to actively contribute to sustainable development [31]. The framework offers guidance on objectively, comprehensively, and reliably measuring and

Table 14.7 ISO 21929-1 overall list of sustainability core indicators in the building life cycle [32]

No.	Category	Indicator
1	Emissions to air	– Global warming potential – Ozone-depleting potential
2	Use of non-renewable resources	Amount of non-renewable resources consumption by type (natural raw materials and non-renewable energy)
3	Freshwater consumption	Amount of freshwater consumption
4	Waste generation	Amount of waste generation by type (hazardous and non-hazardous wastes)
5	Change of land use	Change of land use, assessed with the help of criteria
6	Access to services	Access to services by type, assessed with the help of criteria: – public modes of transportation – personal modes of transportation – green and open areas – user-relevant basic services
7	Accessibility	Accessibility, assessed with the help of criteria: – accessibility of the building site (curtilage) – accessibility of the building
8	Indoor conditions and air quality	Indoor conditions and air quality assessed with the help of the following criteria: – indoor thermal conditions – indoor visual conditions – indoor acoustic conditions – indoor air quality
9	Adaptability	Adaptability assessed with the use of the following criteria: – change of use or user needs – adaptability to climate change
10	Costs	Life cycle costs
11	Maintainability	Maintainability assessed with the support of different criteria
12	Safety	Safety assessed with the support of the following criteria: – structural stability – fire safety – safety in use
13	Serviceability	Serviceability
14	Aesthetic quality	Aesthetic quality

assessing the circularity performance of an economic system through indicators and complementary methods. It is designed to assess the effectiveness of circular actions by public and private organisations. The standard aims to assist organisations in gathering information essential for implementing circular economic practices aimed at minimising resource use, facilitating a circular flow of resources, and contributing to sustainable development [31].

The framework enables the consideration of social, environmental, and economic impacts in assessing circularity performance, incorporating input from diverse complementary methods [31]. Considering that this standard is under development, the specific indicators to be promoted, especially within the construction and building design, remain uncertain at present.

Alignment of Circularity Indicators of International Standards at the Building Design-Level

Several international and European frameworks and standards have been developed focusing on sustainability assessments within the built environment. These frameworks express principles and, in some cases, provide a set of indicators that are partially compatible with CE principles. However, comparing them proves challenging as they may not all reference the same core indicators used at identical stages of the building life cycle, specifically at the design level. Nevertheless, Table 14.8 demonstrates the alignment matrix showcasing the indicators introduced by these standards and frameworks.

14.2.4 National-Level Standards, Policies, and Regulations on Circularity Indicators in Building Design-Level

European countries, especially after the release of the European Union Circular Economy Action Plan in 2015, have been actively developing national-level standards, policies, and regulations on the CE to promote sustainable practices and reduce waste. Although these efforts are not explicitly targeting the built environment and building lifecycle, including the design stage, they include, among others, energy efficiency targets and water and waste plans, which can be applied for assessing the circularity of buildings throughout their lifecycle, from design and construction to demolition and material recovery. As an example of the ongoing efforts in implementing CE indicators in the EU, this section presents the efforts carried out by Portugal and Spain to establish national-level standards, policies, and regulations on the CE, which can also be applied in the building design stage.

Portugal

Action Plan for Circular Economy in Portugal (APCE)-2017: In December 2017, the Portuguese Council of Ministers adopted Portugal's Action Plan for Circular Economy (APCE). The plan aims to reorganise the economy in a closed loop cycle

Table 14.8 The alignment matrix of the international standards and Arup/Ellen MacArthur Foundation circularity indicators at the building design level

Arup/Ellen MacArthur CE principles		European taxonomy	European green deal	Level(s)	EU CE monitoring framework	CEN/TC 350/SC 1	EN 15804	BS EN 15643	ISO TR 21929-1
Build only what you need	Build nothing	–	–	–	–	–	–	–	Change of land use
Build for long-term use	Increase building utilisation	–	–	–	–	–	–	–	–
	Design for longevity	–	– Life cycle costs – Value creation and risk factors	–	– Trade in recyclable raw materials	–	–	– Financial value – Life cycle costs – Maintenance	– Life cycle costs – Maintainability – Serviceability
	Design for adaptability	–	–	Design for adaptability and renovation	–	Design for adaptability (durability, reduction of raw materials, repairability, and preventing degradation)	–	Adaptability	Adaptability
	Design for Disassembly	–	–	Design for deconstruction	–	Design for disassembly	–	–	–

(continued)

Table 14.8 (continued)

Arup/Ellen MacArthur CE principles		European taxonomy	European green deal	Level(s)	EU CE monitoring framework	CEN/TC 350/SC 1	EN 15804	BS EN 15643	ISO TR 21929-1
Build efficiently	Refuse unnecessary components	–	–	–	–	–	–	–	–
	Increase material efficiency	–	–	Bill of quantities, materials and lifespans	– Material consumption – Waste generation – Overall recycling rates – Recycling rates for specific waste streams – Material import dependency (%) – EU self-sufficiency for raw materials, (%)	– Design for reuse (reusability, recyclability) – Structural design for recyclable construction works	–	–	– Freshwater consumption

(continued)

Table 14.8 (continued)

Arup/Ellen MacArthur CE principles		European taxonomy	European green deal	Level(s)	EU CE monitoring framework	CEN/TC 350/SC 1	EN 15804	BS EN 15643	ISO TR 21929-1
Build with the right materials	Reduce the use of virgin and non-renewable materials	–	–	–	Contribution of recycled materials to raw materials demand	–	– Use of secondary material – Use of renewable secondary fuels – Use of non-renewable secondary fuels – Use of non-renewable primary energy resources used as raw materials – Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) – Use of net fresh water	– Secondary raw materials, waste, and exported energy – Sourcing of materials and services – Material and energy use – Environmental impacts	Use of non-renewable resources

(continued)

Table 14.8 (continued)

Arup/Ellen MacArthur CE principles		European taxonomy	European green deal	Level(s)	EU CE monitoring framework	CEN/TC 350/SC 1	EN 15804	BS EN 15643	ISO TR 21929-1
Build with the right materials	Reduce the use of carbon-intensive materials	–	–	Life cycle global warming potential	–	–	– Global Warming Potential (GWP)	Environmental impacts	–
	Design out hazardous / pollutant materials	–	–	– Construction and demolition waste	Total waste generation per capita	–	– Acidification potential (AP) – Eutrophication potential (EP) – Formation potential of tropospheric ozone (POCP) – Hazardous waste disposed – Non-hazardous waste disposed – Radioactive waste disposed		– Waste generation – Emissions to air – Indoor conditions and air quality – Safety

and set targets to work towards 2050 objectives, including a carbon–neutral economy, innovation, resilience, and societal inclusivity [33]. This action plan adopts a multi-level approach, considering Macro, Meso, and Micro levels [34].

The APCE does not establish explicit targets; instead, it seeks to support the achievement of goals outlined in various plans and strategies with aligned objectives. Examples include national waste plans, water and sanitation plans, climate action plans, energy plans, and goals advocated at the European and international levels, such as sectoral directives, Portugal 2020, Paris Agreement, and SDGs [34].

Based on strategic macro-goals, the APCE proposes guidelines for different sectors, particularly the built environment. Within the built environment, four guidelines are suggested: design, manufacture, reuse and recycling, and transversal. These specific guidelines are prepared and adjusted based on the principles contained in the SDGs, EU Circular Economy Action Plan, and Portuguese national policies. Table 14.9 presents APCE indicators for the built environment. The overarching goal of this guideline is to Ministry of Environment [34]:

– Increase the introduction of secondary raw materials into the economy.
– Reduce waste production, demand for raw materials (primary), and water.
– Consumption.
– Reduce GHG emissions.

For the building design stage, the following guidelines are proposed:

– Building renovation and use: This involves creating protocols that encourage component reuse, using recovered or recycled materials, developing and/or using material passports, and promoting the use of "empty" built space, whether public or private.
– Circular construction: This guideline aims to promote public and private infrastructure, and projects that demonstrate the application of circular solutions (e.g., reuse of components, environmental product declarations, deconstruction guides, eco-labels, cradle-to-cradle design).

Portuguese Roadmap for Carbon Neutrality (RNC2050): In 2016, during the 22nd Conference of the Parties to the United Nations Convention on Climate Change in Marrakech, Portugal set the goal of attaining Carbon Neutrality by 2050. This objective provided clear directives for the substantial decarbonisation of the national

Table 14.9 APCE indicators for the built environment

Complementary indicators	No. of voluntary agreements signed, and sectors covered
	No. of reuse initiatives
	No. of guides developed
	No. of quality protocols developed (materials from CDW)
	No. of projects incorporating smart design
	Rate of compliance with the obligation to use at least 5% of recycled materials in construction contracts under the Public Contracts Code

economy, aligning with the ambitious objectives outlined in the Paris Agreement framework [35].

The Carbon Neutrality Roadmap 2050 (RNC2050) is rooted in a strategic vision that advocates for the decarbonisation of the economy and the transition to carbon neutrality by 2050. This vision is founded on a democratic and equitable model of national cohesion that fosters wealth generation and efficient resource utilisation. Eight fundamental principles underpin this strategic vision, with the first principle explicitly highlighting circularity. Specifically, it aims to promote the transition to a competitive, circular, resilient, and carbon–neutral economy, fostering increased wealth, employment, and well-being.

While RNC2050 discusses the transition to a comparative, circular, resilient, and carbon–neutral economy and investigates the role of circularity in the transition to carbon neutrality, the construction sector falls under the industry and industrial processes sub-sectors. Only some construction circularity strategies are mentioned in the document without introducing specific criteria or indicators. The RNC2050 construction circularity strategies are as follows:

- Increasing urban rehabilitation, incorporating the reuse of construction components, and reclaimed or recycled materials.
- Using "empty" built public spaces.
- Implementing passive buildings with a zero-energy balance (NZB: Net Zero Energy Buildings).
- Promoting multifunctional and shared buildings with reduced built area.
- Adopting new, more sophisticated, more energy efficient, and durable materials.
- Using renewable materials with a lower carbon footprint (e.g. wood and cork).

Portuguese National Waste Management Plan (PNGR2030): The PNGR2030, or Portuguese National Waste Management Plan, is a strategic initiative promoted by the Portuguese Environmental Agency (APA) to replace the previous PNGR2020 and guide waste management policies up to 2030. The PNGR2030 serves as the "umbrella" of the national strategic waste policy [36]. This plan operates at a macro level, outlining guidelines that will inform the Strategic Plan for Urban Waste (PERSU 2030) and the Strategic Plan for Non-Urban Waste (PERNU 2030) [37].

PNGR2030, in conjunction with the Strategic Plan for Municipal Waste (PERSU2030), primarily aims to facilitate the shift towards a more resilient and circular economy. This goal is achieved by measures such as waste prevention and reduction in terms of quantity and hazard, elevating recycling rates, and enhancing materials recovery. The overall goal is to contribute to a CE and mitigate adverse environmental impacts through integrated and sustainable waste management practices [36].

While the objectives of PNGR2030 generally align with the CE principles, especially in strategic objective SB2, as presented in Table 14.10, where the CE is directly addressed and can be generally extended to the construction sector, the strategies and targets are too generic. The plan lacks specific objectives, targets, or indicators addressing the building's life cycle stages, including the building design level.

Table 14.10 PNGR2030 objectives, targets, and indicators

Strategic objectives	Target	Indicator
SB2: Promote resource efficiency, contributing to a circular economy	Decouple Economic growth from material consumption	Gross domestic products/ domestic consumption of materials (k€/t)
	Decouple economic growth from waste management	Waste generation/gross domestic products (k€/t)
	Increase the availability of waste for the economy	Recovery (non-energy)/ waste generation %

PERNU 2030- Strategic Plan for Non-municipal Waste: As previously mentioned, PERNU 2030 serves as the National Strategic Plan for the management of Non-municipal Waste in Portugal. This strategic plan aims to promote prevention and integrated waste management throughout the product's life cycle, with a specific focus on the CE and ensuring greater efficiency in natural resource consumption through prevention and waste management practices [37].

However, while PERNU 2030 emphasises the promotion of the CE and aligns with circularity principles to a significant extent, it can be considered too generic. Although it highlights significant considerations in this regard, particularly concerning the construction and construction and demolition waste management, it does not provide principles, goals, or indicators at the building design level.

Portugal Operational Program for Sustainability and Efficient Use of Resources (PO SEUR2020): PO SEUR 2020, formulated through an Execution Decision by the European Commission in 2014, is part of the programs designed to implement the Portugal 2020 Strategy (PO SEUR, 2014). This strategy represents a partnership agreement between Portugal and the European Commission, encompassing the actions of five European Structural and Investment Funds. The programming principles within this agreement delineate the economic, social, and territorial development policy to be pursued in Portugal from 2014 to 2020 [38].

PO SEUR 2020 aims to support the realisation of the Europe 2020 Strategy, specifically focusing on fostering sustainable growth and addressing the transitional challenges toward a low-carbon economy through more efficient use of resources. The envisaged strategy for PO SEUR 2020 encompasses a multidimensional perspective of sustainability grounded in the following thematic objectives [39]:

– Supporting the transition to a low-carbon economy across all sectors.
– Promoting adaptation to climate change and risk prevention and management.
– Protecting the environment and promoting resource efficiency.

While PO SEUR 2020 does not explicitly underline circularity, it briefly mentions the promotion of the CE. Its general objectives, for instance, "protecting the environment and promoting resource efficiency", inherently lead to the realisation of the principles of the CE in its general sense. Nevertheless, upon close examination of the objectives at the sectoral level, there are no specific principles, objectives, or indicators that address circularity within the built environment and, consequently, the different stages of the building life cycle, including the design level.

Spain

Circular strategy: Spain Circular 2030 establishes the groundwork for advancing a novel production model that emphasises maximising the value of the economy's products, materials, and resources while minimising waste generation. The strategy aims to use any unavoidable waste to the greatest extent possible. This strategy aligns with Spain's broader objectives of fostering a sustainable, decarbonised, resource-efficient, and competitive economy. The implementation will occur through a series of successive three-year action plans [40].

The Strategy provides a list of 21 indicators in categories of waste management, Secondary material, competitiveness and innovation, and climate change (Table 14.11) is closely tied to recent global initiatives aimed at ensuring environmental well-being, including the Paris Agreement on climate change, the 2030 Agenda for Sustainable Development, and the Ministerial Declaration of the United Nations Assembly on the Environment titled "Towards a Planet without Pollution," endorsed in December 2017 in Nairobi. Additionally, it aligns with key European Union initiatives, such as the European Green Deal and two European Commission Plans addressing the same concerns. Key Objectives for 2030 include [40]:

– Reduce by 30% the national consumption of materials.
– GDP, taking 2010 as the reference year.
– Reduce waste generation by 15% compared to what was generated in 2010.
– Increase reuse and preparation for reuse until reaching 10% of the municipal waste generated.
– *Reduce the emission of greenhouse gases below 10 million tonnes of* CO_2 *equivalent.*
– Improve by 10% the efficiency in water use.

14.3 Categorisation of Circularity Indicators in Building Design-Level

The indicators presented in this chapter were classified into seven categories based on their impact areas [42]: material and resources; energy; water; waste management; ecosystem; social (health and well-being); and economy. As presented in Table 14.12, the majority of indicators fall under the materials and resources, and energy categories, indicating a strong emphasis on these aspects of circularity. Conversely, the water category exhibits the fewest circularity indicators, suggesting a comparatively lower focus on water-related circular practices in the context discussed. At the same time, the water category has the least number of circularity indicators.

Additionally, the Material and Resource category indicators emphasise resource extraction and efficiency, mainly refer to refuse, reduction, and reuse of materials.

Table 14.11 Indicators by category in the spanish circular economy strategy [41]

Category		Indicators
Waste management	Prepare for reuse	Municipal waste recycling rate (%) Municipal waste recycling rate excluding mining waste (%) Recycling rate excluding mining waste (%)
	Valorisation	Packaging waste recycling rate (% t) Plastic packaging waste recycling rate (% t) Timber packaging waste recycling rate (% t) Recycling rate for waste electrical and electronic equipment (% mass) Organic waste recycling rate (Kg/person) Construction and demolition waste recycling rate
Secondary material	Contribution of recycled materials to the demand for raw materials	Recycling rates for end-of-life product waste (%) Circular material rate (%)
	Trade in recycled raw materials	Imports to third countries Exports to third countries Intra-community imports Extra-community imports
Competitiveness and innovation	Private investment, employment, and gross value added in the circular economy sectors	Gross investments in tangible assets (%) Number of jobs (%) Added value (%) Added value at factor cost (%)
	Patents related to recycling and secondary raw materials as a representation of innovation	Number
Climate change	National Inventory of Greenhouse Gases	Contribution of greenhouse gases in the waste sector CO_2eq (kt)

These are among the 10R circular strategies to avoid or reduce the raw material input in construction activities. The energy category mainly focuses on energy consumption-based indicators and is divided into renewable and non-renewable resources. Special attention is given to renewable sources, emphasising the necessity of energy transition. On the other hand, indicators regarding material and energy import and export can be applied to assess the local capacity to supply material and energy sources endogenously, enhancing circularity through resource self-sufficiency.

Table 14.12 Categorisation of circularity indicators in building design-level

Material and resources	Energy	Water	Waste management	Ecosystem	Social (health and well-being)	Economy
Reduce the use of virgin and non-renewable materials	Use of renewable resources other than primary energy	Characteristics of water quality	Materials for recycling	Whole life cycle GHG emissions	The ability to accommodate individual user requirements	Value retention and recovery on the entire life cycle
Reduce the use of carbon-intensive materials	Use of non-renewable primary energy	Amount of freshwater consumption	Amount of waste generation by type (hazardous and non-hazardous wastes)	Climate change	The ability to accommodate technical changes	Economic performance expressed in terms of cost over the life cycle
Refuse unnecessary components	Use of renewable primary energy	Use of net fresh water	Radioactive waste disposed	Emissions to outdoor air, soil, and water	The ability to accommodate the change of use	Economic performance expressed in terms of financial value over the life cycle
Increase material efficiency	Materials for energy recovery		Components for reuse	Ozone Depletion Potential (ODP)	Acoustic characteristics	Private investment, jobs, and gross value added related to circular economy sectors
Reuse of existing usable surface	Use of renewable primary energy, excluding renewable primary energy resources used as raw materials		Waste generation	Global Warming Potential (GWP)	Thermal characteristics	Life cycle costs

(continued)

Table 14.12 (continued)

Material and resources	Energy	Water	Waste management	Ecosystem	Social (health and well-being)	Economy
Disassembly and recovery potential	Use of renewable primary energy resources used as raw materials		Overall recycling rates	Formation potential of tropospheric ozone	Characteristics of Visual Comfort	Value creation and risk factors
Conceptual material efficiency	Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)		Recycling rates for specific waste streams	Acidification potential (AP)	Indoor conditions and air quality	Environmental cost
Amount of non-renewable resources consumption by type (natural raw materials and non-renewable energy)	Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials		Construction and demolition waste	Eutrophication potential (EP)	Accessibility for people with specific needs	
Use of secondary material	Use of non-renewable primary energy resources used as raw materials			Global sustainability from the circular economy	Access to building services	

(continued)

Table 14.12 (continued)

Material and resources	Energy	Water	Waste management	Ecosystem	Social (health and well-being)	Economy
Material consumption	Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)			Design out hazardous/pollutant materials	Green public procurement	
Resource productivity	Use of renewable secondary fuels					
Design for deconstruction	Use of non-renewable secondary fuels					
Disassembly and recovery potential	Exported energy					
Trade in recyclable raw materials	Use stage energy performance					
Material imports dependency (%)	Increased risk of extreme weather					
EU raw materials self-sufficiency (%)						

Water-related indicators mainly focus on freshwater consumption and quality rather than providing more requirements. Furthermore, reviewing the indicators of the waste management category, it is possible to conclude that it primarily refers to the recycling strategy and focuses on the amount and characteristics of the produced waste in terms of toxicity and radioactivity potential. Moreover, indicators of the ecosystem category mainly highlight GHG emissions, and the environmental impact of construction works on the ecosystem components, including acidification and eutrophication. And lastly, the economic category underscores indicators regarding economic performance and lifecycle costs of the construction works. To summarise, while the reviewed references primarily focus on sustainability indicators and do not explicitly address the concept of the CE, they partially align with circularity principles. This demonstrates an interconnected relationship between circularity and sustainability, indicating that circularity cannot be entirely separated from sustainability.

14.4 Conclusion and Remarks

In conclusion, the analysis of circularity criteria and indicators at the building design level demonstrates significant international, European, and national efforts to implement CE principles. Although various criteria and indicators exist internationally, a unified approach is lacking due to the diversity of regulations and frameworks.

Organisations like CEN and ISO are addressing this by promoting mandates to standardise circularity principles in the building design stage. Nationally, in some EU countries, such as Portugal and Spain, policies are in place to support sustainability and circularity. Still, they remain broad and lack specific indicators tailored to the building design stage. Hence, future work should focus on developing a harmonised set of circularity indicators and guidelines specifically for building design, ensuring practical application across different contexts. Additionally, creating detailed, actionable guidelines and enhancing implementation and monitoring mechanisms are crucial to achieving circularity in building design. Efforts should also include country-specific adaptations and capacity-building initiatives to raise awareness and expertise in circular building practices.

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Part IV
Design-Support Tools and Assessment Frameworks for Circularity

Rand Askar

In the ongoing pursuit of sustainable development within the construction sector, the integration of Circular Economy (CE) principles has become paramount. Part IV of this book delves into the tools and frameworks designed to support and assess circularity in both existing and new buildings, as well as the potential of digitalisation to enhance these efforts. This part, composed of five chapters, offers a comprehensive exploration of methodologies, tools, and frameworks that are instrumental in advancing circularity throughout the lifecycle of buildings.

Chapter 15 focuses on existing buildings, providing a detailed analysis of circularity tools and methods specifically tailored to the built environment. By examining both quantitative and qualitative approaches, this chapter underscores the necessity of continuously updating these tools to reflect the latest data, trends, and technologies, thereby guiding the construction and urban development sectors towards enhanced sustainability.

Chapter 16 shifts the focus to new buildings, highlighting the challenges and opportunities in assessing circularity during the early stages of design and construction. It reviews existing assessment parameters and tools, discussing the need for more practical, standardised approaches that effectively integrate circularity and environmental performance goals.

Chapter 17 explores the synergy between digitalisation and the circular economy, illustrating how digital tools can drive the twin transition within the construction sector. By analysing various digital technologies, the chapter demonstrates their potential to enhance the accuracy of life cycle assessments, facilitate stake-holder collaboration, and ultimately contribute to a more sustainable and resilient industry.

In Chap. 18, the concept of Material and Building Passports (MPs and BPs) is examined as a pivotal tool for enhancing circularity. The chapter discusses the evolution and application of these passports, emphasising their role in optimising

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building processes and materials. It also addresses the challenges and barriers to their widespread adoption, suggesting future research directions to refine their use.

The final chapter, Chap. 19, assesses the incorporation of circularity principles within internationally recognised sustainability assessment methods. Through a critical examination of methods such as BREEAM, DGNB, LEED, Level(s), and SBTool, this chapter reveals varying degrees of integration and highlights the complexities involved in aligning circularity with existing sustainability frameworks.

Together, these chapters offer a holistic view of the current landscape of circularity tools and frameworks, providing valuable insights for practitioners, researchers, and policymakers striving to implement CE principles in the construction sector.

Chapter 15
Circularity Tools and Frameworks for Existing Buildings

Haitham Abu-Ghaida and Leonardo Rosado

Abstract As the world embraces sustainable practices, the concept of circularity has become increasingly important, especially in the context of existing buildings. This chapter comprehensively analyses circularity tools and methods, focusing on their application in the built environment. By examining a variety of tools—both quantitative and qualitative—we explore their methodologies, information requirements, and levels of detail. This structured approach systematically evaluates products, materials, and systems in terms of their potential to support a closed-loop materials flow. Our analysis highlights the necessity of continuously updating and refining these tools to incorporate the latest data, trends, and technologies, guiding the construction and urban development sectors toward a more sustainable future. The chapter is a valuable resource for practitioners, researchers, and policymakers seeking to enhance the sustainability of existing buildings.

Keywords Circularity tools · Circular economy · Existing buildings · Built environment

15.1 Challenges and Opportunities for Circularity Tools in Existing Buildings

The concept of circularity is gaining traction as the world shifts towards sustainable practices [1]. Circularity tools and methods help guide industries towards more efficient and sustainable practices [2]. This chapter delves into a structured analysis of

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these tools, focusing on existing buildings for the benefit of practitioners, researchers, and policymakers.

The global emphasis on sustainability and the circular economy has necessitated developing and refining sophisticated tools and methodologies tailored to assess circularity within the built environment [3]. Various tools have been developed, each underpinned by distinct methodologies, ranging from quantitative analyses to qualitative evaluations. These tools collectively provide an intricate framework that facilitates the systematic evaluation of the potential of products, materials, or systems to adhere to a closed-loop materials flow paradigm, thereby aligning with the foundational tenets of the circular economy.

15.2 Method for a Structured Analysis of Tools, Methods, and Models for Existing Buildings

In the pursuit of a comprehensive understanding of building circularity assessment for existing buildings, a literature review was undertaken, encompassing an array of tools, standards, and methods available in this domain. The rationale for this methodological approach was to discern the nuances and intricacies of each tool. To facilitate a structured analysis and comparison, the tools, methods, and models were categorised based on specific criteria, as shown in the subsequent sections. Furthermore, a distinction was made between the types of methods and tools related to their purpose. The first two types relate mainly to obtaining information to generate data that allows the modelling of circular economy in existing buildings in terms of flows and stocks, while the other two types focus on tools and methods that support the implementation and analyses of circular economy strategies for the most significant life cycle stages of the buildings: refurbishment/maintenance and end-of-life.

15.2.1 Type of Approach

The categorisation of circularity tools is fundamentally rooted in the method of approach. Two prominent methods arise from the literature: quantitative and qualitative.

Quantitative tools utilise mathematical and statistical analyses to generate precise data-driven insights. Such tools often require robust datasets and offer replicable results, which makes them essential for rigorous scientific inquiries [4].

Qualitative tools are grounded in descriptive analyses, often relying on expert opinions, observations, or anecdotal evidence. These tools provide rich contextual insights, allowing for a deeper understanding of specific scenarios, behaviours, or patterns that might not be evident in purely numerical data [5].

15.2.2 Type of Circularity Strategy

At its core, the circular economy champions the principle of extending the value of resources and minimising waste. A widely accepted conceptual framework that elucidates this is the 9R model [6]. This model delineates nine strategic actions or pathways, providing a comprehensive approach to resource optimisation. These strategies include Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, and Recover. Each of these strategies presents unique opportunities and challenges. The aim of the circular economy, as manifested in these nine strategies, is to keep resources in use for as long as possible, derive maximum value from them, and then recover and regenerate materials at the end of their service life.

15.2.3 Information Requirements

In circularity assessment tools, the granularity and comprehensiveness of required data are paramount factors influencing their accuracy, applicability, and ease of use. Depending on the specific tool and its intended application, the extent of information required can vary significantly. Two primary categories emerge from the literature based on the depth of data required:

High Data Input. Tools classified under the "High Data Input" category necessitate a robust collection of detailed data, often capturing the intricate facets of a product's or material's lifecycle. These tools demand quantitative and qualitative metrics, capturing everything from raw material extraction, design, manufacturing processes, use-phase, and end-of-life management. Such depth allows for a holistic understanding, yielding detailed insights into potential improvement and resource optimisation. The primary drawback is the resource-intensive nature of data collection and analysis. Furthermore, the accuracy of results is contingent upon the precision and reliability of the input data, making the data collection process critical. Examples of tools or applications necessitating high data input include life cycle assessments (LCAs) and detailed material flow analyses (MFAs).

Low Data Input. In contrast, "Low Data Input" tools are designed to function effectively with minimalistic data sets. Their primary advantage lies in their ability to provide swift, albeit high-level, assessments. Such tools can be particularly beneficial in preliminary evaluations or when extensive data is unattainable or yet to be gathered. They are user-friendly, accessible, and ideal for stakeholders seeking quick insights or making rapid decisions without delving into the intricacies. The trade-off, however, is the potential need for more depth in analysis. Given their reliance on limited data, oversimplification is risky and might not capture the full spectrum of circularity considerations. Screening LCAs and basic eco-footprint calculators often fall under this category, providing stakeholders with a bird's-eye view of a product or process's environmental impact.

15.2.4 Level of Detail

Circularity assessment tools vary in their data input requirements and in the scope and granularity of their analysis. This spectrum of detail is crucial because it dictates the applicability and relevance of the tool to different stakeholders—from policymakers and industry leaders to product designers and manufacturers. Two predominant levels of detail emerge from the literature:

Macro-level. Tools and methods operating at the macro level provide overarching insights encompassing broader systems, sectors, or entire industries. Macro-level assessments often encapsulate regional, national, or even global perspectives, aiming to identify trends, benchmarks, and broad-scale challenges and opportunities. By delivering a panoramic view, these tools are essential for setting industry standards, formulating policies, and guiding large-scale sustainability initiatives. They help stakeholders understand systemic patterns and deviations. Due to their broad scope, macro-level tools might not offer the granular insights necessary for on-the-ground implementation or nuanced product-level decisions. There is a potential risk of missing localised challenges or opportunities. Examples of macro-level analyses include economy-wide Material Flow Analysis or national Circular Economy Index assessments.

Micro-level. On the other end of the spectrum lie micro-level tools, which zoom in on intricate details, focusing on individual products, specific components, or distinct materials. These tools delve deep into the nuances of a product or material, from its design intricacies to its end-of-life implications. Micro-level tools provide stakeholders with actionable insights for tangible changes. They can pinpoint inefficiency, waste, or environmental impact areas, enabling precise interventions. They benefit product designers, manufacturers, and businesses aiming for product-level improvements. While they offer detailed insights, their limited scope may not capture systemic or industry-wide challenges. Furthermore, the depth of analysis often requires comprehensive data, which might be resource-intensive. LCA for specific products or Detailed Component Analyses are classic examples of micro-level tools.

15.2.5 Connected Circularity Indicators

Circularity indicators are quantitative or qualitative metrics that provide insights into the performance and potential of a product, process, or system to adhere to circular economy principles. These indicators are pivotal, bridging the gap between abstract circularity concepts and tangible, measurable outcomes. Their scope and relevance can vary based on the tool or the specific objective of the assessment.

15.2.6 Case Studies

While comprehensive in their design, the theoretical frameworks and methodologies of circularity assessment tools gain true resonance when applied in real-world contexts. By analysing actual applications of these tools in diverse sectors and settings, one can garner a deeper appreciation of their operational nuances, potential impacts, and areas of refinement.

15.3 Tools for Material Flow or on a Material Level

15.3.1 Material Circularity Indicator (MCI)

Description: The Material Circularity Indicator (MCI) is a quantitative assessment tool used to evaluate the circularity of a system, product, or process. It is closely related to the material flow in a circular economy, which aims to create a restorative and regenerative industrial system. It was developed by the Ellen MacArthur Foundation in 2015 [7].

Type of approach: Quantitative.

The MCI is a quantitative measure that evaluates the extent to which a linear flow has been minimised and a restorative flow maximised for a product's component materials. It also considers the duration and intensity of a product's use compared to a similar average product.

Circularity strategy: It encompasses various strategies from the 9R model, such as reuse, refurbishment, and recycling. The MCI measures how restorative and regenerative the material flows of a product or company are.

Information requirement: High Data Input.

The MCI is constructed from three main product characteristics:

- The mass (m) of virgin raw material used in manufacture.
- The mass (w) of unrecoverable waste attributed to the product.
- A utility factor (u) that accounts for the length and intensity of the product's use.
- The associated material flows for technical materials are diagrammatically, and the MCI can be calculated using detailed knowledge of a product's parts and materials. The methodology may also use generic industry data or best approximations when specific product data is unavailable.

Level of detail: Micro-level.
The MCI focuses on the intricate details of individual products, specific components, or distinct materials. It delves deep into a product's or material's nuances,

from design intricacies to end-of-life implications. This micro-level analysis provides stakeholders with actionable insights for tangible changes, pinpointing exact areas of inefficiency, waste, or environmental impact.

Connected Circularity Indicators:

Examples include measures of material scarcity, which impacts the value of recovering the materials, and measures of toxicity, which affects the risks and costs of manufacture, reverse logistics, and public safety liabilities. It can also include measures of energy, water, and greenhouse gas impacts of a given product, service, or system. For instance, increasing the circularity of a product would decrease the energy used for raw material production and product manufacture, leading to reduced greenhouse gas emissions.

Case Studies:

A study on the circularity of construction products available in the German environmental database ÖKOBAUDAT [8] adapted MCI to analyse the circularity of construction products, showing that circular material flows are most likely to be applied to metals [9]. Another study [10] of plastic pallet manufacturers (PPM) implemented the Nano Level MCI to assess the production process, resulting in an average index of 0.79, indicating that the system in PPM is quite circular.

15.4 Tools for Material Stocks Modelling

15.4.1 Dynamic Material Inputs, Stocks and Outputs Model (MISO)

Description: This modelling approach is used to study stock dynamics through time and identify historical patterns of built environment development stocks.

Type of approach: Quantitative.

The model aims to extend the economy-wide Material Flow Accounting framework by tracing the accumulation of processed building stock materials as in-use stocks of manufactured capital and quantifying all processing, construction, and end-of-life materials subsequently available for recycling [11].

Circularity strategy: Raw material demand and potential for recycling.

Data on inflows of materials is based on existing statistics at the country level, while data on outflows is estimated based on lifetimes for products and infrastructure [12].

Information requirement: Detailed data input.

Economy-Wide Material Flow data; primary building stock materials; parameters on losses and wastes occurring in processing, re-manufacturing and construction; lifetime distributions; and recycling and downcycling rates; Cohorts of in-use stocks; end-of-life waste; recycled and downcycled secondary material flows.

Level of detail: Macro-level.

Based on mass-balance principles with inflows, outflows, and stock data, it is used at global and national levels with resolution at the materials level [13].

Connected Circularity Indicators: Economy-Wide MFA indicators with the addition of annual flows of primary and secondary processed materials, processed materials by use, in-use stocks, and end-of-life waste from stocks.

Case Studies:

A study by Wiedenhofer et al. (2019) developed and applied the MISO model to study the world's stock dynamics between 1900 and 2050 [11].

15.4.2 High-Resolution Maps of Material Stocks in Buildings and Infrastructure

Description: A stock-driven method to derive materials from stock maps.

Type of approach: Quantitative.

The purpose of the model is to combine EO raster data that characterise built-up structures, infrastructure data from crowd-sourced OSM vector data, and tabular data on Material Intensity factors to provide high-spatial resolution for an extensive spatial coverage for stocks of materials accumulated in the built environment [14].

Circularity strategy: Potential for recycling.

Data on stocks of materials based on material intensity for building and infrastructure archetypes [14].

Information requirement: High data input.

Advanced Earth observation (EO) products derived from optical Copernicus Sentinel-2 (S2) and radar Copernicus Sentinel-1 (S1) sensors; crowd-sourced data (Open Street Map, OSM); Comprehensive database of MI factors of building types and infrastructures, distinguishing different types of materials.

Level of detail: Meso and Macro-level.

10-m spatial resolution for seven material types at the country level.

Connected Circularity Indicators: Total material stocks.

Case Studies:

A study by Haberl and colleagues (2021) developed and applied the model to quantify the stocks of Germany and Austria.

15.4.3 Material Stock Estimation Using 4d-GIS

Description: This estimation method is a bottom-up approach to studying material stock dynamics through time and space for buildings, roadways, and railways [15].

Type of approach: Quantitative.

The model's purpose is to incorporate a four-dimensional geographical information system (GIS) at an urban scale into material flow analysis (MFA) and material stock analysis (MSA). This is done by quantifying the number of buildings and infrastructure in stock and multiplying the number of each specific product by its material intensity [12].

Circularity strategy: Potential for recycling.

Quantifying urban material stocks (MS) and unveiling the input history of construction materials could provide a new primary dataset for urban area assessment regarding urban morphology change. Such datasets can provide indicators based on MFA and MSA to measure progress toward a sustainable material-cycle society.

Information requirement: High data input.

Spatial data that contains information on the geo-localisation of buildings and infrastructures and their attributes such as type of buildings and infrastructure or year of construction. Material stock intensity data that informs on the material composition of buildings and infrastructures should be specific to each building and infrastructure.

Level of detail: Micro to Macro-level.

The description of each building and infrastructure with archetypes for building cohorts allows for detailed information about material composition at multiple levels due to the aggregation possibilities. A very data-intensive method that can provide information for materials and components if data to generate building passports for archetypes is available.

Connected Circularity Indicators: Economy-Wide MFA indicators with the addition of stocks and demolition through time.

Case Studies:

A study by Takinawa and Hashimoto (2010) developed and applied the model to study the stock dynamics of Salford in the UK and Wakayama city centre in Japan [15].

15.5 Tools for Adaptability and Refurbishment

15.5.1 Transformation Capacity (TC)

Description: The TC introduces its concept based on the high disassembly potential of structures, aiming to be an integral part of building/systems design [16]. It is seen as a part of an integrated life cycle design, which involves synchronising design for disassembly (DfD) aspects throughout various decision-making loops.

Type of Approach: Both Quantitative and Qualitative.

Circularity Strategy: Rethink.

The central assumption in this research is that a high TC of building structures relies on their high disassembly potential. TC indicates the building/system's overall flexibility.

Information Requirement: High data input.

A knowledge model was developed to assess the TC of building structures based on their disassembly potential. This model uses eight aspects of deconstruction and their sub-aspects. Each aspect's influence on TC is built into the model by defining weighting factors for each relation between the model variables. The model is based on fuzzy input data representing linguistic variables and has been developed using fuzzy logic.

Level of Detail: Micro-level.

The TC focuses on the disassembly potential of structures, which indicates the building/system's flexibility and environmental efficiency. High TC means high flexibility and low environmental impact.

Connected Circularity Indicators: The research hypothesis suggests that a higher TC results in a lower environmental impact. This is because a high transformation ability means buildings can adapt to new requirements, and their components and materials can be replaced, reused, reconfigured, and recycled. The aspects are arranged so that each aspect, resulting in the demolition of components, has values between 0.1 and 0.3. Aspects indicating partial demolition and reconfiguration are graded between 0.3 and 0.6, while those indicating disassembly with potential reuse, reconfiguration, and recycling have values between 0.6 and 0.9.

Case Studies:

A study by Androsevic and colleagues (2019) used this method to assess the potential for reusing wooden facade systems and waste creation [17]. A recent study [18] combined a simplified version of the TC indicator with LCA to assess the environmental benefits of a single-family house designed with DfD criteria and found that DfD criteria could lower greenhouse gas emissions of the building by up to 45% in the best-case scenario compared to Business as Usual.

15.5.2 ISO 20887:2020 - Sustainability in Buildings and Civil Engineering Works—Design for Disassembly and Adaptability—Principles, Requirements, and Guidance

Description: The ISO 20887:2020 [19] standard provides guidelines for designing constructed assets that can adapt to changing requirements or be disassembled for reuse or recycling. This involves considering the various layers and constituent materials, such as elements and components. It acknowledges that it might only sometimes be practical to consider that an entire building or civil engineering work should be disassembled and reused. For instance, some components, such as a ventilation system, might become obsolete by disassembly and may not be desirable for reuse.

Type of Approach: Qualitative.

Circularity Strategy: Rethink.

The primary goal of DfD/A is to design assets that can adapt to changing needs or be disassembled for reuse or recycling. This involves considering the various layers and materials, such as elements and components.

Information Requirement: High data input.

Below are the variables considered as needed input information.

- Versatility: Percentage of multi-use space without significant changes.
- Convertibility: Percentage of space designed for easy conversion.
- Expandability: Potential for adding floors or space without significant structural changes.
- Ease of Access: A rating scale for accessibility of components and services.
- Independence: A rating scale for design options' independence.
- Reversible Connections: Assessment of connection reversibility.
- Avoidance of Treatments: Determine if materials are recyclable or reusable without finishes.
- Supporting Re-use: Metrics on reclaimed and recycled content and product reusability.

- Simplicity: Count of parts per element and standardisation of materials.
- Standardisation: Level of uniformity in dimensions, components, and connections.
- Safety of Disassembly: Checklist on durability, accessibility, and connection types.
- Durability: Metrics on maintenance costs and product service life.

Level of Detail: Micro-level to Macro-level.

The guidelines provided in the standard can be applied at various levels, from individual components to entire buildings or civil engineering works. The focus is ensuring the design can accommodate future uses and material recovery or reuse.

Connected Circularity Indicators: The standard is connected to other sustainability indicators and guidelines, such as ISO 15392, which provides general principles for sustainability in buildings and civil engineering works, and ISO 15686–1, which focuses on service life planning.

Case Studies:

Sandin (2022) applied the standard to a timber building in Sweden. The study assessed the feasibility and data requirements of applying the ISO 20887 [20]. The study found that several indicators lacked clarity and/or were too subjective.

15.5.3 Circular Building Assessment Prototype (CBA)

Description: The CBA is a methodology that compares and assesses product and material resource flows during the lifetime of a built asset and beyond. The prototype was developed as part of the Buildings as Material Banks (BAMB) project [21].

Type of Approach: Both Quantitative and Qualitative.

Circularity Strategy: Rethink and Reuse.

The CBA emphasises reusing materials from previous constructions, designing for future reuse through reversible building design, and the potential for transformation.

Information Requirement: High Data Input.

The platform allows users to upload files generated from BIM authoring software, which the platform then uses to extract relevant data for the assessment. Where there are data gaps, web services are developed to pre-populate information.

Level of Detail: Nano-level to Micro-level.

The CBA can be applied at various levels, from individual components to entire buildings, ensuring that the design can accommodate future uses and material recovery or reuse.

Connected Circularity Indicators:

The CBA is connected to other guidelines, such as ISO 16739 (Industry Foundation Classes, IFC) [22] and COBie (Construction Operations Building Information Exchange) [23]. The BAMB Information requirements provide a placeholder within the BIM model for data to be stored against them, enabling the export to IFC and COBie or a tailored implementation referred to as 'BAMBie' that details more on the material level.

Case Studies:

Durmisevic and colleagues (2021) applied this tool to a Heerlen, Netherlands building to inform stakeholders about the potential to reuse different building systems [24].

15.5.4 Building Circularity Index (BCI)

Description: The building circularity index was developed by [25] in 2016, building on the MCI framework and aggregating material circularity results in systems and the building. It was further developed by [26, 27].

Type of approach: Quantitative and qualitative.

The BCI is a quantitative measure that evaluates the circularity of buildings by considering several factors related to material usage, product utility, reversibility, and waste generation. The BCI incorporates qualitative assessments of the reversibility of connections, which are then translated into numerical values using fuzzy number logic, thus integrating quantitative and qualitative aspects.

Circularity strategy: Reuse, Recover and Recycling.

The BCI considers the fraction of reused (Fu,j) and recycled (Fr,j) material in its formulation. The amount of Virgin Material for a product j, represented as Vj, is calculated as the total mass of the product Mj minus the reused and recycled material fractions.

Information requirement: High Data Input.

The BCI considers the following parameters:

- Virgin Material (Vj): Calculated using the formula Vj = Mj (1 - Fr,j - Fu,j).
- Product Utility (Xj): Computed by multiplying the lifetime ratio (Lj/Lav,j), which is the product lifetime Lj over the average lifetime of similar products Lav,j, and the intensity ratio (Uj/Uav,j), which is the intensity of use per year Uj over the market average Uav,j. Due to data constraints, all product utilities were set to 1 in the document.

- Unrecoverable Waste (Wj): Computed by summing the waste from the linear flow W0, j and the recovering process WF,j. The document assumes WF,j to be 0, indicating a perfect recovering process.
- Reversibility: the ability to reverse connections is a measure based on connection type, accessibility, form containment, and crossings.

Level of detail: Micro-level.

The BCI focuses on individual products within a building, such as doors, windows, tiles, furnishings, etc. It incorporates design factors to weigh each product's impact on the entire building's environmental assessment.

Connected Circularity Indicators: Detectability, greenhouse gas emissions, and embodied energy.

Case Studies:

Cottafava and Ritzen (2021) used this method in seven case studies of several buildings of different typologies located in different EU countries representing different climate zones in the EU. The method was combined with a simplified screening LCA to compare circularity scores to environmental impacts [27].

15.6 Tools for End-Of-Life (EoL)

15.6.1 Urban Mining Index (UMI)

Description: The UMI is a quantitative tool designed to measure the potential for urban mining in each area [28]. Urban mining refers to the process of reclaiming raw materials from products, buildings, and waste. The UMI evaluates the potential for extracting valuable materials from urban areas, considering factors such as the concentration of valuable materials, accessibility, and extraction technologies.

Type of Approach: Quantitative.

Circularity Strategy: Recover and Recycle.

The UMI emphasises the recovery and recycling of materials from urban environments. By identifying areas with high concentrations of valuable materials, the UMI promotes the efficient extraction and reuse of these resources, reducing the need for virgin material extraction.

Information Requirement: High Data Input.

The UMI parameters are the following:

- Materiality & Construction: UMI evaluates the material composition and construction methods to determine the potential for selective dismantling.

- Circular Material Metrics: It assesses the use of secondary or renewable resources and their future recycling potential.
- Circular Quality Levels: UMI differentiates materials based on their potential for closed-loop (maintaining quality) versus open-loop (diminishing quality) recycling.
- Economic Viability: UMI considers the feasibility of selective dismantling, which impacts the building's circular potential.
- End-of-Life Scenarios: Assessing two scenarios: high-quality after-use and typical after-use.

Level of Detail: Macro-level.

The UMI operates at a macro level, providing insights into the potential for urban mining across entire cities or regions. This broad perspective allows policymakers and industry leaders to identify areas with the highest potential for urban mining and prioritise their efforts accordingly.

Connected Circularity Indicators: The UMI is connected to various sustainability indicators, including resource efficiency, waste reduction, and carbon footprint reduction. The UMI contributes to more sustainable resource use and reduced environmental impacts by promoting the recovery and recycling of materials from urban areas.

Case studies: This framework was applied to The Korbach Town Hall, a historic building redesigned. Part of the overall construction project was deconstructing the town hall extension from the 1970s. The study [29] found that 66% of materials would be downcycled, and at the end of life, 23% can be recycled, and only 1% can be reused.

15.6.2 BIM-Based System for Demolition and Renovation Waste Estimation and Planning

Description: Cheng and Ma (2013) developed a tool that leverages the capabilities of BIM [30]. This system can extract detailed material and volume information from building models, offering an innovative solution to the current shortfall in waste estimation tools. The system facilitates accurate waste predictions, optimises recycling and reuse strategies, estimates truck logistics, and calculates waste disposal fees.

Type of approach: Quantitative.

This tool uses information from a BIM model to estimate waste generated at the end of the life of a building.

Circularity Strategy: Recycle.

Information requirements: Low data input.

The tool utilises default metrics for common construction material types. It only requires the total volume of elements within the building.

Level of detail: Macro-level.

Connected Circularity Indicators: Waste generation.

Case studies: The tool is applied on a 47-floor residential building typical in Hong Kong. The floors and the beams are responsible for most of the waste generated from the EoL of the building [30].

15.6.3 Circular Construction Evaluation Framework (CCEF)

Description: CCEF [31] was developed in 2021 and is used to assess and quantify the circularity credentials of construction projects, focusing on designing for the disassembly and reuse of building elements and components.

Type of approach: Qualitative.

The assessment is done based on a questionnaire about the construction system.

Circularity Strategy: Reuse and recover.

Information requirements: Low data input.

The CCEF parameters needed are:

- Disassembly plan
- Disassembly sequencing
- Clarity of plans
- Adaptability of design (5 aspects)
- Health and safety (2 aspects)
- Material information (durability, inventory, connections, reliability, and re-usability)

Level of detail: Macro-level.

Connected Circularity Indicators: LCA-related indicators.

Case Studies:

Dams and colleagues (2021) applied the method to four example case study buildings. Buildings made of timber showed the highest circularity score [31].

15.7 Summary of Reviewed Tools and Methods

The array of tools, methods, and models explored throughout this chapter (Table 15.1) highlights the diverse approaches to embedding circularity in existing buildings. The TC method emphasises the importance of disassembly potential in building structures, offering insights into the adaptability and flexibility necessary for circular design. In contrast, the UMI method quantifies the potential for reclaiming raw materials from urban infrastructures, providing a concrete measure of urban mining feasibility.

These tools, varying from quantitative methods demanding high data input, such as the MCI, to more qualitative assessments, underscore the multifaceted nature of sustainability challenges. High data input tools offer precision and may present data collection and interpretation challenges. On the other hand, qualitative tools afford adaptability and are invaluable in situations where rapid assessments are crucial or data is incomplete.

Stakeholders in the circular economy are encouraged to align the selection of these tools with the specific requirements of their projects. Policymakers and industry leaders need to be aware of the strengths and limitations of each tool, ensuring that the chosen methods align with their sustainability goals.

15.8 Conclusion

The future direction of circularity within the built environment should bridge the gap between micro-level detailed analyses and macro-level overviews. This calls for integrated platforms that can provide scalable insights. Furthermore, as circularity is subject to continuous evolution, these tools must be regularly updated and refined to incorporate the latest data, trends, and technologies.

The practical application of these tools should become a standard part of procedures within the construction and urban development sectors. Educational initiatives can further support practitioners in utilising these tools effectively, fostering a sustainability-driven industry culture.

In summary, the transition from theoretical frameworks to actionable tools is crucial for the shift towards a more sustainable future. These tools and methods' collective application and ongoing enhancement are essential for creating a resilient, adaptable, and circular built environment. This will ensure that sustainability is not just a transient concern but a fundamental aspect of global development strategies.

Table 15.1 Summary of the reviewed circularity tools, methods, and frameworks

Tool	Description	Type of Approach	Circularity Strategy	Information Requirement	Level of Detail	Case Studies
Material Circularity Indicator (MCI)	Quantitative tool evaluating material flow circularity	Quantitative	Reuse, Refurbishment, Recycling	High Data Input	Micro-level	Construction products are in the German database; Plastic Pallet Manufacturer
Dynamic Material Inputs, Stocks and Outputs model (MISO)	Quantitative model for studying stock dynamics and recycling potential	Quantitative	Raw material demand and potential for recycling	Detailed data input	Macro-level	Stock dynamics of the world between 1900 and 2050
High-Resolution Maps of Material Stocks in Buildings and Infrastructure	Spatially resolved material stock maps using earth observation data	Quantitative	Potential for recycling	High data input	Meso and Macro-level	Material stocks of Germany and Austria
Material stock estimation using 4d-GIS	GIS-based method for quantifying material stock dynamics	Quantitative	Potential for recycling	High data input	Micro to Macro-level	Stock dynamics of Salford, UK and Wakayama, Japan
Transformation Capacity (TC)	Assesses the adaptability and disassembly potential of building structures	Both Quantitative and Qualitative	Rethink	High	Micro-level	Reuse potential and waste creation of wooden facade systems
ISO 20887:2020 - Sustainability in buildings and civil engineering works	Guidelines for design for disassembly and adaptability in buildings	Qualitative	Rethink	High	Micro-level to Macro-level	Timber building in Sweden

(continued)

Table 15.1 (continued)

Tool	Description	Type of Approach	Circularity Strategy	Information Requirement	Level of Detail	Case Studies
Circular Building Assessment Prototype (CBA)	Assesses product and material resource flows during a built asset's lifetime	Both Quantitative and Qualitative	Rethink and Reuse	High Data Input	Nano-level to Micro-level	Building in Heerlen, The Netherlands
Building Circularity Index (BCI)	Evaluate the circularity of buildings, focusing on material usage and waste	Quantitative and qualitative	Reuse, Recover and Recycling	Detailed Data Input	Micro-level	Buildings in various EU countries
Urban Mining Index (UMI)	Measures the potential for urban mining in urban areas	Quantitative	Recover and Recycle	High Data Input	Macro-level	Korbach Town Hall deconstruction
BIM-based system for demolition and renovation waste estimation and planning	Estimates demolition and renovation waste using BIM technology	Quantitative	Recycle	Low data input	Macro-level	47-floor residential building in Hong Kong
Circular Construction Evaluation Framework (CCEF)	Assesses the circularity credentials of construction projects	Qualitative	Reuse, Recover	Low data input	Macro-level	four example case studies buildings

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Chapter 16
Circularity Tools and Frameworks for New Buildings

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Abstract The assessment of circularity in new building projects necessitates consideration of diverse factors such as material choice, design strategies, construction methods, operational efficiency, and end-of-life practices. Various tools and methodologies have been developed to aid stakeholders in the construction industry in evaluating these aspects and making informed decisions. With the dynamic evolution of the circular economy, understanding current circular practices is crucial for identifying areas needing enhancement. However, the absence of a tandardized approach poses a challenge, with existing methods often either too broad or narrowly focused on specific circular elements. This limits the comprehensive evaluation of system performance. Addressing these challenges requires practical tools, particularly for early

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design stages, that integrate quantitative methods to ensure circularity and environmental performance goals are met efficiently. This chapter reviews existing circularity assessment parameters, discusses aggregation methods for criteria and indicators, and evaluates available tools to guide researchers, practitioners, and policymakers in advancing circular practices in construction.

Keywords Building circularity · Circularity assessment · Circular economy · Construction industry

16.1 Introduction

The efficient circularity assessment of new buildings requires a multitude of factors that must be considered, including material selection, design strategies, construction techniques, operational efficiency, and end-of-life management. Consequently, a range of tools and methodologies have been developed to evaluate these aspects and support decision-making processes for stakeholders involved in the construction industry (CI).

With the dynamic evolution of the circular economy (CE) within the sector, it is imperative to acquire a comprehensive understanding of the circular practices that have been introduced. This understanding is crucial for distinguishing the current state of implementation and identifying areas that require further application or improvement. Numerous review articles are available that identified existing tools and methods for circularity assessment in CI [10, 12, 18, 27, 30, 60, 70]. The current challenge of circularity assessment is the lack of a standardised approach. Previous assessment methods either focused on circularity as a general term or prioritised one specific circular element. A limited scope of circularity indicators restricts the comprehensive evaluation of the system's performance. Consequently, using individual indicators as the only means to assess the circular building design and disassembly potential remains challenging, along with quantitative support being the primary method.

While the theoretical foundations of circularity are well-established, which was also handled in various sections in this book, the CI requires more practical tools for assessing circularity. Particularly in the early design phase, there is a demand for quantitative methods and tools that facilitate circular designs, mitigating the risk of rework in later phases due to issues related to circularity and environmental performance. However, the main challenge remains in the availability of information for circular assessments within the current design workflow, where uncertainty and incompleteness prevail, especially in the BIM approach. To effectively guide the design workflow, there is a need for more automated circularity assessment tools capable of directly evaluating circularity aspects. Despite the development of frameworks, there is a perceived lack of supportive policies to improve the reuse and recycling in CI.

This chapter addresses the challenges and needs of circular assessment methods for new building projects. Readers may find other relevant details about the criteria, indicators, and implementation practices of such tools in the different chapters of the report. However, this chapter comprehensively reviews the circularity assessment parameters and their possible variations on indicators and factors, and then presents quantitative and qualitative aggregation methods for the criteria and indicators to develop guidelines, indexes, and rating methods. Finally, the available circularity assessment tools are evaluated as complete assessment methods. By examining the existing literature and drawing insights from case studies, this study intends to shed light on the diverse approaches researchers, practitioners, and policymakers employ in this rapidly evolving field.

16.2 Circularity Assessment Parameters: The Variation of Criteria and Indicators

The identification and use of criteria and indicators are key activities in circularity assessment. These activities have been the focus of much research in the field, and they are essential for developing effective circularity assessment methods. This subsection briefly overviews the criteria and indicators, typically the focal point of all the tools used in circularity assessment methods. It highlights the thematic and conceptual similarities and differences between the different criteria and indicators, which will help readers understand their relationships and key roles in the circularity assessment paradigm. For more detailed information, please refer to the dedicated chapters on the criteria and indicators of this book.

Circularity assessment is performed through the use of various circularity indicators or a specific metric that utilises single or aggregated scores [26]. However, the lack of consensus on the definition creates confusion in distinguishing a circularity indicator from other circularity metrics (e.g., index, framework). The lack of standardisation yielded the interchangeable use of multiple circular terminology, often hindering the result interpretation. The definition given by the Organisation for Economic Co-operation and Development (OECD) describes an indicator as "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor" [74].

The use of generic circularity indicators is restricted by the unique attributes of CI. Unlike most products in the manufacturing industry, buildings have longer service lives, incorporate diverse materials, engage multiple stakeholders, and are highly customised and context dependent. These distinctive characteristics complicate the straightforward implementation of standardised circularity indicators in the construction sector [61]. A set of reliable indicators is vital when assessing the progress towards the CE [34]. This section reviews only those circularity metrics focusing on a single circularity aspect to be classified as a circularity indicator.

Numerous studies have reviewed existing circularity indicators [85]. reviewed a set of 55 circularity indicators and classified them into ten different categories, including CE implementation level (e.g., micro, meso, macro), loops (e.g., maintain, reuse/remain, recycle), performance (e.g., intrinsic, impacts), prospective (e.g., actual, potential), usages (e.g., improvement, benchmarking, communication), transversely (e.g., generic, sector-specific), dimension (e.g., single, multiple), units (e.g., quantitative, qualitative), format (e.g., web-based tool, Excel), and sources (e.g., academic, companies, agencies) categories. However, most of the reviewed indicators were adapted from existing methods in other sectors, specifically for the construction sector, with the exception of the Building Circularity Index (BCI).

Khadim [60] analysed another set of 24 specific circularity indicators with 35 variations with a wide scale of application (e.g., new and existing buildings, type of buildings, and scale of measurement). [77] reviewed common building construction and demolition waste (BCDW) indicators and classified them into four categories: process, government initiatives, market, investment, and platforms,industrial symbiosis; and sharing economy. Likewise, [55] discussed existing trends, challenges, and perspectives of CE in CI by reviewing existing indicators and their dimensions (e.g., environmental, economic, management/behaviour, technological, social, innovation, and policy). The existing circularity indicators reviewed in the literature are presented in Table 16.1. It is worth mentioning that not all indicators are thoroughly reviewed in the text.

16.3 Development and Design of Circularity Indicators

The majority of existing circularity indicators employ quantitative measures, given the fundamental purpose of a circularity indicator, which lies in the objective assessment of critical aspects and dimensions of CE in built environments. However, there are instances of adopting qualitative and semi-qualitative approaches in indicator development. For example, the measurement scale developed by [73] is a qualitative assessment scale that adopts selected indicators for the construction industry. Other examples of a semi-qualitative approach include C2C by Antwi-Afari et al. (2022) and the methodology described by [1]. Development of a new indicator can be challenging; therefore, adopting them from existing building assessment tools (e.g., BREEM, LEVEL(s), LCA, LCCA, MCI, BCI) remains a more popular approach rather than creating new indicators from scratch [57, 60]. The design of circular indicators can be reviewed on the examples of the most commonly used indicators. Indicators can be quantified or qualified based on observations, measurements, calculations, or a combination of complex methods. For example, the rate of virgin materials over reused materials in secondary materials used to construct new buildings is a simple or less complex indicator,it is simply a ratio.

The Material Circularity Indicator (MCI) is another example of a more complex indicator developed by the [37] to quantify the level of circularity for construction materials. It assesses the degree to which a product minimises linear resource consumption and maximises materials restoration within its components. Moreover, it evaluates the product's duration and intensity of use in comparison to an average

Table 16.1 Summary of the circularity metrics of the reviewed literature

The existing circularity indicators	References
Building Circularity Indicator (BCI)	[98]
Building Circularity Indicator (Disassembly Reconsidered) (BCIDR)	[96]
BIM-Based Building Circularity Assessment (BBCA)	[103]
Modified Alba Concept (For Foundations) (MAC)	[95]
Alba Concept BCI (ACBCI)	[8]
Modified Building Circularity Indicator (MBCI)	[19]
Predictive Building Circularity Indicator (PBCI)	[27]
Circularity Indicator for Pedestrian Bridges (CIPB)	[9]
ARCH Circular Environmental Indicator Framework (ARCHCEIF)	[42]
MADASTER Circularity Indicator (MAD-CI)	[67]
FLEX 4.0	[46]
Material Circularity Indicator (MCI)	[37]
Circular Economy Measurement Scale (CEMS)	[73]
Circular Economy Scale (CES)	[73])
Circular Business Model (CBM) Based Circularity Indicator (CBMCI)	[31]
Integrated Energy Performance and Circularity (IEPC)	[89]
BIM-based Whole-life Performance Estimator (BBWPE)	[6]
Bridge Circularity Assessment Framework (BCAF)	[25]
Synthetic Economic Environmental Indicator (SEEI)	[44]
Gypsum End of Life Measurement Indicator (GEOLMI)	[59]
RIPAT 1.0	[93]
Framework for Circular Buildings (FCB)	[63]
Platform CB’ 23 (PCB)	[21]
Circularity Calculator (CC)	[57]
Circular Building Assessment Prototype (CBAP)	[16]
C-CALC	[22]
Circulytics	[38]
Circular Assessment Criteria for Envelope (CACE)	[40]
Circular Construction Evaluation Framework (CCEF)	[29]
Material Reutilization Part (C2C)	[66]
Circle Assessment (CA)	[24]
Circularity Assessment Tool (CAT)	[80]
Circular Benefits Tool (CBT)	[4]
Circular Economy Company Assessment Criteria (CECAC)	[97]
Circular Economy Index (CEI)	[3]

(continued)

Table 16.1 (continued)

The existing circularity indicators	References
Circular Economy Indicators for India (CEII)	[90]
Circular Economy Indicator Prototype (CEIP)	[100]
Circular Economy Monitoring Framework (CEMF)	[36]
Circular Economy Performance Indicator (CEPI)	[56]
Circular Economy Toolkit (CET)	[3]
Circular Economy Toolbox US (CETUS)	[92]
Circular Economic Value (CEV)	[41]
Circularity Index (CI)	[56]
Circular Impacts Project EU (CIPEU)	[36]
Circularity Material Cycles (CIRC)	[79]
Closed Loop Calculator (CLC)	[43]
Circularity Pathfinder (CP)	[84]
Circularity Potential Indicator (CPI)	[3]
Super-efficiency Data Envelopment Analysis Model (DEA)	[103]
Evaluation of CE Development in Cities (ECEDC)	[17]
Evaluation Indicator System of Circular Economy (EISCE)	[3]
Indicators for Material input for CE in Europe (IMCEE)	[35]
End-of-Life Recycling Rates (EoL-RRs)	[37]
Environmental Protection Indicators (EPICE) in a context of CE	[75]
Evaluation of Regional Circular Economy (ERCE)	[22]
Eco-efficient Value Ratio (EVR)	[56]
Economy-Wide Material Flow Analysis (EWMFA)	[53]
Five Category Index Method (FCIM)	[65]
Hybrid LCA Model (HLCAM)	[45]
Indicators for Consumption for CE in Europe (ICCEE)	[35]
Circularity Indicator Project (ICT)	[99]
Indicators for Eco-design for CE in Europe (IECEE)	[35]
Indicators of Economic Circularity in France (IECF)	[68]
Integrative Evaluation on the Development of CE (IEDCE)	[83]
Input–Output Balance Sheet (IOBS)	[3]
Indicators for Production for CE in Europe (IPCEE)	[35]
Industrial Park Circular Economy Indicator System (IPCEIS)	Geng (2012)
Measuring Regional CE–Eco-Innovation (MRCEEI)	Smol (2017)
National Circular Economy Indicator System (NCEIS)	Geng (2012)
Product-Level Circularity Metric (PCM)	[3]
Regional Circular Economy Development Index (RCEDI)	[51]

(continued)

Table 16.1 (continued)

The existing circularity indicators	References
Resource Duration Indicator (RDI)	[3]
EU Resource Efficiency Scoreboard (RES)	[34]
Recycling Indices (RIs) for the CE	[37]
Resource Productivity (RP)	Wen and Meng (2015)
Reuse Potential Indicator (RPI)	[3]
Recycling Rates (RRs)	[37]
Sustainable Circular Index (SCI)	[15]
Value-based Resource Efficiency (VRE)	[100]
Zero Waste Index (ZWI)	[15]
Whole building circularity indicator (WBCI)	[61]
Product Circularity Index (PCI),	[94]
Element Circularity Index (ECI)	[94]
Critical Success Factors (CSFs)	[76] [62]
Reuse Potential Indicator (RPI)	[10, 78]
Whole-Life Performance Estimator (WLPE)	[6]
Circular Economy Performance Indicator (CPI)	[56]
Global Resource Indicator (GRI)	[2]
Deconstruction, and Resilience (3DR)	[75]
System Circularity Indicator (SCI)	[11]
The Circular Construction Evaluation Framework (CCEF)	[29]
The Disassembly and Deconstruction Analytics System (D-DAS)	[5]

product within the same industry. The MCI is primarily composed of three key product characteristics: the amount (V) of used virgin raw materials, the amount (W) of unrecoverable waste attributed to the product, and the utility factor (X) that accounts for the lifetime of the product. MCI is determined by considering the proportion of material input (virgin or non-virgin), the material output (either energy recovery or landfill disposal), and the technical lifecycle of a product. These factors collectively represent the theoretical circular capacity of each product. To calculate the MCI for each product, a Bill of Materials (BoM) is utilised as input. The MCI represents 50% of the circular potential of products [11]. From this perspective, the MCI is not just a simple indicator but a more complex assessment method for measuring material circularity. In the fourth section, the focus is driven to the specifics of the MCI and its integration with other components to form the Building Circularity Indicator (BCI), providing a complete methodology for circularity assessment.

16.4 Development of Circularity Indices: Aggregation of Indicators

Generally, criteria and indicators are quantitative or qualitative measures created from a collection of observed facts that might reflect relative positions in a certain area [23]. They can show the change in direction across time and between various units when it is reviewed regularly. They can also be useful in establishing policy priorities, benchmarking, and performance monitoring. When separate indicators are combined into a single index (sometimes called ranking, method, or tool) based on an underlying model, the resulting indicator is generally referred to as an "index" or aggregated indicator [86]. Ideally, the index should measure multidimensional aspects such as competitiveness, industrialisation, sustainability, single market integration, and knowledge-based society, which a single indicator cannot adequately represent. Table 16.2 presents a list of pros and cons of indices, which was originally evaluated by the Joint Research Centre-European Commission in 2008.

An index quality and the validity of the information it delivers largely depend on the framework and data used rather than only the methodology employed in its creation [52]. Despite the employment of cutting-edge methodology in its creation, an index built on a weak theoretical foundation or soft data with significant measurement errors may produce policy statements that are open to debate. The experience demonstrates that disagreements regarding the best way to create weights are difficult to settle. Science may considerably contribute to ensuring that the processes of aggregation are as sound and transparent as feasible, although it cannot give an objective approach for creating the only true index to summarise a complex system. Therefore, in this part, a generic index generation framework is given to guide aggregators like a checklist for constructing an index (See Fig. 16.1).

Building an index begins with a strong theoretical framework step. The framework should explicitly identify the phenomenon to be assessed and its constituent parts, choosing distinct indicators and weights (see the previous section) that reflect the

Table 16.2 Pros and Cons of Aggregated Indicators (Indices) (Adapted from [86], OECD 2008)

Pros	Cons
Indices can be used to summarise complicated or multifaceted problems	Indices that are poorly constructed or evaluated may lead to false or incomplete understandings
They can simplify classification based on challenging criteria	The judgement required to form indices can introduce subjectivity
They facilitate the interpretation of trends across a variety of distinct metrics	Indicators necessitate data, which is sometimes unavailable or inaccessible, making its acquisition time-consuming or resulting in inaccurate calculations
They help fit more data into the allotted space or streamline a list of indicators	If the construction process is not transparent, it may obscure serious flaws in some dimensions and make it more difficult to identify appropriate corrective action

Fig. 16.1 A generic framework for index generation steps (*Source* own elaboration)

relative weights of these components and the dimensions of the final composite. The ideal approach would be to base this procedure on what is desirable to measure rather than on which indicators are readily available.

Within the data selection step, the quality of the underlying variables significantly impacts both the indices' strengths and flaws. Variables should ideally be chosen based on their applicability, analytical quality, timeliness, and accessibility. With advancements in data selection and indicator development, aggregated indicators' quality and accuracy should also advance. Missing data frequently hampers the creation of reliable indices. Both random and non-random data loss is possible. In this situation, a step for imputation of missing data should be managed. Variance estimations should consider the uncertainty in the imputed data. Because of this, the analysis can now account for the impacts of imputation. Single imputation, however, is notorious for underestimating variance because it only fully accounts for imputation uncertainty. The multiple imputation approach, which offers numerous values for each missing value, can better capture the uncertainty brought on by imputed data.

More decision-makers need to create aggregated indicators than ever before. In most cases, the choice of a single indicator is made randomly, with little thought given to how that signal may interact with other indicators. Therefore, the data set's applicability may be evaluated by applying multivariate analysis (MVA), which also helps to understand how the methodological decisions will impact the results. The most common MVA methods are Multiple Linear Regression Analysis, Principal Components and Factor Analysis, Cronbach Coefficient Alpha, and Cluster Analysis, which are briefly explained in Table 16.3.

Table 16.3 Multivariate analysis techniques for aggregating indicators (OECD, 2008)

Analysis Name	Mathematical Formulation	Advantage	Disadvantage
Multiple Linear Regression	$\hat{Y} = a + b_1 X_1 + \cdots + b_n X_n$ where $\hat{Y}$ is the indicator, a is a constant, and b_1 to b_n are the regression coefficients (weights) of the associated sub-indicators $X_1, X_2 \ldots, X_n$	Managing many diverse variables	For other ranges, the output uncertainty might not hold
Principal Components & Factor Analysis	$Z_j = \sum_{i=1}^{p} a_{ij} X_i, j = 1,2, \ldots, p$ takes p variables $X_1, X_2 \ldots, X_p$ and finds linear combinations of these to produce principal components $Z_1, Z_2 \ldots, Z_p$ that are uncorrelated	One important feature in evaluating various statistical aspects of the data is the absence of correlation	Not usually efficient since many original variables are reduced to a small number of modified variables
Cronbach Coefficient Alpha	$\alpha = \frac{p.\bar{r}}{1+(p-1).\bar{r}}$ number p of indicators and the average inter-correlation $\bar{r}$ among the indicators	The strength of correlations between groups of sub-indicators can be evaluated by researchers by using a coefficient of dependability, also known as consistency	Results can be positively or negatively impacted by sample size, and low-reliability scores are usually associated with fewer items
K-means Clustering Analysis	$J = \sum_{j=1}^{K} \sum_{n \in S_j} \left\| x_n - \mu_j \right\|^2$ n examples to one of k clusters, where n is the sample size and k	Presenting an alternate technique for grouping nations and illuminating the composition of the data set	Only descriptive; might not be transparent if methodological choices made during the investigation are not well supported and given adequate context

16.4.1 Common Weighting and Aggregation Methods

The sub-indicators that are measured in various units must be converted to the same unit before an index can be calculated. Choosing the appropriate weights is the more challenging issue [105]. Six possible approaches to calculating an indicator are represented by equations in Table 16.4 [87]. These vary from the most straightforward (Method 1) to the most intricate (Method 6). There are additional ways to calculate a composite indicator. Each method has several variations. Each of the given methods is briefly explained in this part.

Table 16.4 Methods for calculating indices for country c (Adapted from [87])

	Method	Equation
1	Total ranking of countries	$CI_c^t = \sum_{i=1}^{N} Rank_{ic}^t$
2	The sum of the indicators above and below the mean for each indicator	$CI_c^t = \sum_{i=1}^{N} sgn\left[\frac{x_{ic}^t}{x_{EU_i}^t} - (1+p)\right]$
3	Ratio or percentage of variance from the average	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t}{x_{EU_i}^t}$
4	Variation in the annual percentage	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{ic}^{t-1}}{x_{ic}^t}$
5	Standardised values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{EU_i}^t}{\sigma_{EU_i}^t}$
6	Re-scaled values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - min(x_i^t)}{range(x_i^t)}$

$^* x_{ic}^t$ is the value of indicator i for country c at time t. $w_i w_i$ is the weight given to indicator i in the composite index. In Method 2, p = an arbitrarily chosen threshold above and below the mean

The first method is the simplest aggregation technique among the methods given in Table 16.4. For each sub-indicator, the variables (e.g., countries) are ranked, and the rankings are then added up. Therefore, ordinal levels are the foundation of this method. Its simplicity and independence from outliers is its merits. Its drawback is that absolute-level information is lost. Method 2 solely uses data at the nominal level for each indicator. It only calculates the difference between the number of indicators above and below a mean-cantered threshold. The simplicity of the procedure and the fact that it is unaffected by outliers are its benefits. This method's drawback is that interval-level information is lost. Method 3 averages the ratios (or percentages) close to each indicator's mean. It has the benefit of allowing for the calculation of changes in the composite indicator over time. However, there is a significant drawback to this approach. In the presence of outliers, it is less resilient. Method 4 substitutes the sub-indicator values for the differences between the current year and the prior year and divides those values by the value from the prior year. Method 5 has been frequently employed in various indexes, such as the environmental sustainability index. The index is calculated using the standardised scores for each indicator, which are calculated as the difference between each indicator's score for each variable and the mean divided by the standard error. Compared to Method 3, this approach is more resilient when handling outliers, but it does not provide a complete solution. This is since each indication will have a different range between the least and maximum observed standardised scores. An indicator in the variables with extreme values is given more weight by the approach. In contrast to Method 5, Method 6 employs rescaled values for the constituent indicators. As a result, the standardised scores for each indicator have the same range. Due to this, this technique is more resilient in the presence of outliers.

Some weighting and aggregation techniques are generated from statistical models like Data Envelopment Analysis (DEA) and Unobserved Components Models

(UCM) or from participatory techniques like Budget Allocation Procedures (BAP), Analytic Hierarchy Processes (AHP), and Conjoint Analysis (CA) [32, 104].

Since the indicators in a data set frequently have distinct measurement units, normalisation is necessary before any data aggregation as part of the one-step-ahead framework technique. The following section presents the normalisation techniques in the context of nine different formulations.

16.4.2 Common Normalisation Methods

Normalisation is necessary before any data aggregation since the indicators in a data set frequently have distinct measurement units [81]. There are numerous normalisation techniques, which are summarised in Table 16.5. However, choosing an appropriate method is not simple and requires specific consideration for potential scale adjustments, transformations, or severely skewed indications. The data qualities and the goals of the composite indicator should both be considered when choosing the normalisation approach. To evaluate their effect on the results, robustness tests may be required [69].

According to WBCSD (2018), a circularity assessment method built on a well-liked current tool is more likely to be adopted than to produce something entirely new. As a result, many indicators are created using already available technologies. However, a small number of authors created their framework by defining a wide variety of circular KPIs and employing varied research approaches, according to [60]. In the highlight of these implications, a circularity index generation methodology for a new building process is presented as a conceptual framework design for circularity assessment mainly due to the indicated steps in this field. The following part provides some selected case studies of the developed tools by focusing on their methodologies.

16.5 Examples of the Circularity Indices for New Building Assessments and Their Methodologies

This section includes MCI and BCI-based tools as well as the Circular Construction Evaluation Framework (CCEF) and Disassembly and Deconstruction Analytics System (D-DAS). The selection of indicators, their derivatives, and specific frameworks was based on their widespread use within the field, considering their value in evaluating the circularity of building materials and construction processes. Each of these chosen metrics or frameworks offers a quantifiable means to assess the efficiency of resource management, reuse, and recycling within the construction industry. The major challenge in CE lies in standardising these indicators, prompting the combination of the most prevalent ones into a cohesive framework. This approach

Table 16.5 Generic normalisation methods analysing country c (Adapted from [87])

	Method	Equation
1	Ranking	I^t_{qc}=$Rankx^t_{qc}$
2	Standardisation (or z-score)	$I^t_{qc}=\frac{x^t_{qc}-x^t_{qc-\tau}}{\sigma^t_{qc-\tau}}$
3	Min–Max	$I^t_{qc} = \frac{x^t_{qc}-min_c(x^{t0}_q)}{max_c(x^{t0}_q)-min_c(x^{t0}_q)}$
4	Distance to a reference country	$I^t_{qc} = \frac{x^t_{qc}}{x^{t0}_{qc-\tau}}$ or $I^t_{qc} = \frac{x^t_{qc}-x^{t0}_{qc-\tau}}{x^{t0}_{qc-\tau}}$
5	Categorical scales	e.g. $I^t_{qc} =$ $\{0 if x^t_{qc} < p^{15} 20 if p^{15} \le x^t_{qc} < p^{25} 40 if p^{25} < x^t_{qc} < p^{95} 100 if p^{95} \le x^t_{qc}$
6	Indicators above or below the mean	$I^t_{qc} = \{1 if w > (1+p) 0 if (1-p) \le w \le (1+p) - 1 if w$, where $w = \frac{x^t_{qc}}{x^{t0}_{qc-\tau}}$
7	Cyclical indicator (OECD)	$I^t_{qc} = \frac{x^t_{qc}-E_t(x^t_{qc})}{E_t(\lvert x^t_{qc}-E_t(x^t_{qc})\rvert)}$
8	Balance of opinions (EC)	$I^t_{qc} = \frac{100}{N_e}\sum_e^{N_e} sgn_e(x^t_{qc} - x^{t-1}_{qc})$
9	Percentage of annual differences over consecutive years	$I^t_{qc} = \frac{x^t_{qc}-x^{t-1}_{qc}}{x^t_{qc}}$

*x^t_{qc} is the value of indicator q for country c at time t. $\underline{C}$ is the reference country. The operator sgn gives the *sgn* of the argument (i.e. + 1 if the argument is positive and -1 if the argument is negative). N_e is the total number of experts surveyed. p^i is the i-th percentile of the distribution of the indicator x^t_{qc} and an arbitrary threshold around the mean

provides a unified means of evaluating circularity in the context of construction practices.

16.5.1 Material Circularity Indicator (MCI)

The first example is the indexing method details of the MCI, which is already discussed in the previous parts for indicator selections and developments. The MCI value ranges from 0 to 1, with a higher number indicating a higher level of circularity. The MCI is a multidimensional assessment that considers several factors. Firstly, the MCI primary input is the comprehensive analysis of the proportion of resources derived from both virgin and recycled materials, as well as components that have been repurposed from previous usage.

Secondly, the MCI also considers utility derived during the product's usage phase. This evaluation involves a comparative assessment of the duration and intensity of product use in relation to industry norms for similar product types. Along with the product durability assessment, the analysis extends to account for scenarios involving repair, maintenance, and shared consumption business models. Thus, the MCI can assess if the product has the potential to exceed its planned durability, prolonging its use in the industry.

The subsequent focus of the MCI is the post-usage phase, with a critical examination of the material destination after being used. This involves quantifying materials designated for landfill disposal or energy recovery and those designated for recycling. Moreover, the MCI identifies components with the potential to reuse, reducing waste generation and optimising resource use. Moreover, the MCI also evaluates the efficacy of recycling processes. This assessment considers the efficiency of recycling protocols in generating and recycling input materials at the product's end-of-life stage, profoundly influencing product circularity and minimising resource consumption and environmental impact. Finally, the detailed bill of materials is essential for the MCI itemising and quantifying data for all components and materials. Additionally, the MCI can incorporate optional risk and impact indicators for products (e.g., material price variation, material supply chain risk, material scarcity and toxicity, energy usage, and CO_2 emissions) to provide further insights related to the business concerning the product [37].

Mathematically, the MCI for a product can be defined through the Linear Flow Index (LFI) of the product, along with the factor F(X), which is constructed as a function F of the utility X. This utility factor determines the impact of the product's utility on its MCI [37]. There are multiple case studies that utilised the MCI for the circulatory assessment [60, 82]. However, MCI has a few limitations. Firstly, it focuses solely on the materials that ultimately become finished products, neglecting any losses that may occur during extraction, transportation, and manufacturing processes. Secondly, the MCI tends to overestimate the quality of recovered products, assuming they are equivalent to newly produced ones. Thirdly, it fails to consider the significance of biological materials in the transition from a linear to a circular economy [60].

Moreover, Jiang (2022) argues that the MCI excessively relies on the mass of the product, which may not accurately reflect the value of a specific material. This has raised a debate about the practice of simply summing up the MCIs of individual materials to calculate the MCI of a product, as it may overestimate its circular value due to challenges in separating materials for recovery at the end of life in many instances. [57] modified the MCI to overcome these limitations by employing economic value (E) as the unit of measurement and introducing a new indicator known as residual value (R).

16.5.2 Building Circularity Indicator (BCI)-Based Tools

The first version of the Building Circularity Indicator (BCI) model was introduced by [98] to measure the extent to which the linear flows have been minimised and restorative flows maximised for four levels of detail in a building: Material, Product, System, and Building. The model implies a bottom-up approach to calculate the indicators at the four levels, scaling up from the Material Circularity Indicator (MCI), which was first introduced by the Ellen McArthur Foundation (2015), consecutively to the Product Circularity Indicator (PCI), then the System Circularity Indicator (SCI) up to the overall Building Circularity Indicator (BCI). The general idea behind the BCI is to look at the input, usage, and output. This model should also be used to communicate between chain partners in the construction process.

The research methodology followed in this model is built upon an extensive list of KPIs obtained from expert semi-structured interviews, then a subjective prioritisation by the author to shorten the list, providing a set of the most important circularity indicators that later is validated by an expert panel. The previous process resulted in a conceptual framework that was translated into an assessment methodology and eventually tested and validated on a case study using Excel functionality.

The final set of KPIs is categorised into three groups of indicators:

1. Technical requirements: these consider the type of input and output, the technical lifetime, and the disassembly factors for only technical cycles
2. Preconditions: these involve aspects of material health, GHG emissions, renewable energy use, and environmental impact.
3. Drivers: these encompass material scarcity, potential financial value, and future reuse possibilities

The circularity indicators only include the technical requirement of materials that should be considered. The preconditions and drivers are designed to give principals (organisations) the possibility to incorporate their interests even better. The preconditions may provide additional information to evaluate if the changing level of material circularity affects other impacts or interests of principals and their stakeholders (e.g., energy and water). Drivers could not be seen as real indicators but more as a value proposition.

The distinction between the indicators at different hierarchical building compositions of material, component, system, and full building scales of assessment allows us to identify the relevant criteria and indicators to the materials and products separately, but also the interconnections and physical interfaces at the assembly in a building. At a material level (MCI), the material input and output and the utility of a product, depending on its technical lifetime, are evaluated. At the product level (PCI), the interfaces and connections between products and materials are considered based on the Design for Disassembly (DfD) principles and possibilities, including aspects of functional, technical, and physical deconstruction. At the system level, the SCI assesses the circularity of products in a system together based on their weight of sales revenues and makes the separation of a system based on the shearing layers to compare systems with each other and the different lifetimes of each system. Finally, at a building level, the BCI assesses the separate systems as a whole with a factor for the level of importance of each system.

The overall aspects considered in the circularity calculation methodology, technically, only consist of two components: (1) the material specifications and (2) the design for disassembly (functional, technical, and physical). The BCI by Verberne formed the first circularity assessment tool for a whole building level and introduced an important base for later building circularity models, which built upon it and addressed some of its limitations. For example, [96] refined the BCI by addressing certain limitations related to design for disassembly (DfD) and the weighting of factors. [95] expanded the BCI by introducing circularity criteria for foundations. [103] proposed an automated framework using BIM that further developed Verberne's original BCI. [61] enhanced the model by incorporating adaptability factors.

Cradle to Cradle Certified is among the prevalent models for assessing circularity in building projects, evaluating products based on criteria such as material health, reutilisation, renewable energy, water stewardship, and social equity [28]. BREEAM, primarily focused on environmental assessment, incorporates principles of the circular economy related to materials use and life cycle impacts (Building Research Establishment (BRE), n.d.). LEED, developed by the U.S. Green Building Council, promotes sustainable practices in design, construction, and operation, emphasising materials and resources aligned with circular economy principles [91]. The Ellen MacArthur Foundation's Circulytics measures circular economy performance across business dimensions [39]. Malaysia's Green Building Index (GBI) rates buildings based on sustainable material use and life cycle impacts, aligning with circular economy principles (Green Building Index Malaysia, n.d.).

Despite their importance in advancing sustainability in construction, these models face significant challenges. They often require substantial resources for data collection, analysis, and verification, which can be daunting for smaller organisations or projects with limited capabilities. Moreover, their focus tends to be on inputs like material selection and energy efficiency, rather than on assessing outputs such as actual circularity achieved or the effectiveness of recycling and reuse processes [71]. This gap between input-focused assessments and real-world circular outcomes can hinder their ability to comprehensively achieve sustainability goals. Furthermore, while these models address lifecycle impacts to some extent, they may not fully encompass critical stages such as end-of-life scenarios or the management of materials post-demolition or renovation [14]. Certification costs also pose barriers, as the expenses associated with assessments and audits can be prohibitive, especially for projects in developing regions [101]. Additionally, the adaptability of these models to diverse regional contexts and regulatory frameworks varies, potentially limiting their global applicability. Balancing complexity with practical application remains an ongoing challenge, requiring continuous refinement to ensure these models effectively support sustainable and circular practices across different scales and contexts within the building sector.

In contrast, modern BCI-based tools offer robust features that distinguish them from traditional building circularity models. These tools integrate comprehensive circular economy principles throughout the building lifecycle, encompassing not only material health and energy efficiency but also critical aspects like end-of-life recycling and reuse. They adopt a holistic assessment approach that balances inputs such as material selection with outputs like actual circularity achieved and the recyclability of materials post-use, providing a more accurate measure of sustainable practices [88]. Utilising advanced data analytics and digital technologies, these tools streamline data collection, analysis, and reporting, making sustainability assessments more efficient and accessible across diverse projects. Customisable criteria tailored to regional contexts enhance their global relevance and applicability, fostering transparency and stakeholder engagement. Furthermore, modern tools emphasise performance-based metrics, enabling continuous improvement and benchmarking against sustainability goals. Innovations such as digital twin simulations optimise building performance and resource efficiency. These advancements collectively enhance the capacity of modern building circularity indicator-based tools to drive sustainable and resilient building practices in today's dynamic environment.

16.5.3 HOUSEFUL's Building Circularity Methodology (BCM)

The Horizon 2020 HOUSEFUL project on "Innovative circular solutions and services for new business opportunities in the EU housing sector" (2018–2022) recently reported a methodology to evaluate circularity degree in the sector of housing to be implemented at the earlier stages (new and retrofitted) of building design, as an originally circularity measure via a global circularity indicator, the BCS, Building Circularity Score [49]. The HOUSEFUL approach, using a composed circularity indicator, is fundamental on the degree of circularity based on six pillars—.e., energy, water, and material balances,social and environmental impacts; and life cycle cost reduction. Being the proposed indicator under a life-cycle-based methodological approach, it is aligned with common and existing methods of building sustainability, such as the CEN Technical Committee 350 (CEN TC 350) and the European Union (EU) LEVEL(s); including potential for improvements regarding water and energy circularity per life cycle stage. The six pillars encompass a set of meaningful Key Performance Indicators (KPIs) and weighting factors (energy and water consumption, materials usage, social added value, and life cycle economic value), which are extensively implemented in the sustainable construction sector to result in a single circularity KPI, the so-called BCS [49]. The methodology was applied in the HOUSEFUL demo buildings and related projects, being tested and validated in practice with real data and in different scenarios by comparing different buildings—i.e., location, use, measures, etc. (González et al., n.d.).

The Building Circularity Methodology (BCM) was proposed as a multidimensional model to assess and evaluate the circularity degree in residential and/or tertiary buildings (housing sector), highlighting its implementation in the EU countries under a Circular Economy (CE) perspective. This methodology and the BSC constitute a consistent and reliable output aimed at applying market-usable and innovative solutions accessible to data on current circularity degrees. Thus, it would be useful to inform existing policies and strategies on circularity in the urban built environment and to provide recommendations to the construction sector stakeholders—e.g., designers, manufacturers, promoters, decision-policy, lawmakers, and end-users. Moreover, the HOUSEFUL approach and indicator, which is based on easy and objective metrics, would bring green funding opportunities under the umbrella of administrations and other public bodies and tenders and novel project calls towards the implementation, achievement and promotion of CE principles in the urban built environment. The BSC would be automatically calculated by providing input data on the HOUSEFUL web-based Circularity Tool (CT), as a Software-as-a-Service (SaaS) tool facilitating decision-making and future planning and the design at the construction phase [49].

As highlighted above, the HOUSEFUL's Building Circularity methodology was developed by considering the CE principles of recyclability, reusability and waste management related to materials and buildings on energy and water life cycles, and economic and social performance, as well as circular solutions feasibility. Moreover, new and existing methodologies on CE pillars were considered—e.g., Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and Social Life Cycle Assessment (S-LCA). Additionally, the HOUSEFUL approach is also well-matched with sustainable building certifications—e.g., LEED, BREAM, WELL [49]. The comprehensive circularity calculation, at building level characterisation and its indicators, complements the BCS by the above-mentioned six-pillar consideration. Thus, circularity degree valuation at the lifecycle stage level would provide and identify solid knowledge on improvements and solutions among different CE aspects (pillars), thus improving and unifying building circularity [47].

16.5.4 Circular Construction Evaluation Framework (CCEF)

The Circular Construction Evaluation Framework (CCEF), proposed relatively recently by [29], aims at evaluating the degree of a project's circularity. It addresses both existing and new (proposed) design and construction projects and can be used by a variety of contributors and participants in a project's development (e.g., clients and other professionals in the sector). Its methodological approach consists of the quantification of the level of the examined project's circularity with regard to several relevant criteria.

The assessment takes place on a whole-building basis and at the level of building elements. The circularity credentials for each one of these levels are quantified by different criteria organised in broader groups. Specifically, when the whole building is considered, 14 criteria are employed, classified under four groups [29]:

- Recorded information design, data, and materials: 1. Disassembly plan included in design drawings and specifications, 2. Disassembly sequencing information, 3. Clarity and transferability of plans and specifications,
- Adaptability in design: 4. Versatility (in regular use, cosmetic change), 5. Convertibility (partition/space changes), 6. Expandability (vertical, without major foundation modification), 7. Expandability (horizontal, compatible foundations)
- Simplicity in design: 8. Parts per element, 9. Standardisation and modularity of elements (dimensions), 10. Standardisation and modularity of elements (component variation), 11. Standardisation and modularity of elements (connections), 12. Degree of element independence and classification of construction
- Health and safety: 13. Toxicity/synthetic chemicals, 14. Ease of access, construction, and disassembly

The respective structure at the assessment level of elements comprises 11 criteria that are classified into three groups and three criteria not belonging to a larger thematic area [29]:

- Durability: 1. Number of previous design lives/uses, 2. Length of previous design lives, 3. Predicted length of current design life
- Material inventory: 4. Suppliers and production, 5. Warranties, 6. Donor building(s), 7. Reclaimed and/or recycled content, 8. Involvement of reuse in cleaning or restoration work, 9. Life Cycle Analysis with end-of-life Scenario and Environmental Product Declaration
- Finishes/Treatment: 10. Synthetic/chemical/wet resins/adhesives? (yes/no response) 11. Chemical coatings, 12. Reversibility of connections, 13. Reusable (without restoration or modification), 14. Recyclable (no downgrading)

The rating in the context of each criterion ranges from 0 to 5, with higher scores indicating a higher degree of circularity. This scoring scale is also used for criteria of a qualitative nature (e.g., yes/no reply), so that quantitative final results are achieved. The evaluations at the element- and at the whole building level take place separately and result in two separate scores. Regarding the objectivity of the results, the authors formulating the framework point out the possibility of "an element of bias" [29], p. 6). The structure of the framework's computational implementation provides the possibility for weightings' determination and introduction (however, such development is unavoidably accompanied by a subjectivity factor).

As indicated by the aforementioned criteria, circularity aspects heavily considered within this framework are, among others, design for adaptability and disassembly, as well as materials' reuse. LCA/EPDs related issues, durability and reusability, toxic or synthetic substances creating health risks or preventing direct reuse of components, and several other parameters (simplicity, methods of construction), all seen under the light of a lifecycle approach also considering past and future design lives and uses, are also included in the performed assessments.

16.5.5 Disassembly and Deconstruction Analytics System (D-DAS)

The disassembly and deconstruction analytics system (D-DAS) is a framework enabling the integration of end-of-life performance evaluation/consideration into the buildings' design stage and process [5]. The system's main target evolves around the selection of materials, already in the building's design stage, that will contribute not only to efficient materials' use but also to the reduction of waste at the end-of-life with regard to the built environment. D-DAS uses and builds upon the capabilities of building information modelling (BIM). Allowing the consideration of various alternative solutions for the building design at various levels (materials selection, etc.) and providing the possibility for access to extensive information on the building as well as for complex computational processes, visualisation, and simulation, this system can serve as a decision support tool.

Four layers of D-DAS architecture work together as a single system. The data, based on which the calculations are made, are related to building design (parametric building models, materials, etc.), to the building materials' specification (materials' properties and status), as well as to deconstruction and demolition information (historical data). The system comprises five functional models and analytics: (i) Building Whole Life Performance Analytics, related to the calculation/estimation of the building's performance over time; (ii) Building Element Deconstruction Analytics, resulting in an evaluation of the building design with regard to whether and to which degree design for deconstruction is supported (the applied model is based on Deconstructibility Assessment Score [7], (iii) Deconstruction Arising Analytics, forming the basis for the Pre-Deconstruction Audit generation (iv) Design for Deconstruction Advisor, which identifies possible optimisation points in the design (building components- and materials wise) regarding the materials reuse and the reduction of waste, and provides alternative solutions; (v) Deconstruction Visualisation, providing the plan of the deconstruction process, as well as its visualisation (along with the disassembly process). Each one of these entities supports a different functionality. According to [5], D-DAS can be implemented either as a plug-in for an existing BIM or as a standalone application (visualisation and simulation tools-based).

The implementation of D-DAS presented by [5] is a plug-in to Autodesk Revit, including the functional modules (i), (ii), and (iii). It was validated through the examination of three alternative scenarios for a building. However, important assumptions and simplifications were adopted in this process [13], creating the need for further testing and validation of the system.

16.6 Insights for Future Work and Further Improvements

This section offers valuable insights into the challenges faced by the construction industry in developing circularity assessment tools. To promote more sustainable construction practices and advance the field of circularity assessment, we need to identify several areas for future improvements.

- **Standardisation of Circularity Assessment**: The critical review in this section highlights that one of the main challenges is the lack of a standardised approach to circularity assessment. Therefore, future research should focus on developing sector-wide standards and guidelines for assessing circularity in construction projects. This would streamline the evaluation process and make it easier to compare different projects.
- **Development of Automated Tools**: As mentioned, there is a need for more automated circularity assessment tools, especially in the early design phase. Researchers and software developers should work together to create user-friendly software that integrates circularity assessment seamlessly into Building Information Modelling (BIM) workflows. This will help architects and designers make informed decisions from the outset, reducing the risk of rework in later project phases.
- **Enhanced Data Availability**: The circular economy addresses the importance of data sharing and availability within the current design workflow, where uncertainty and incompleteness prevail, and is addressed in this review as a significant challenge. Future research should explore ways to improve data collection and sharing, possibly through collaborative platforms and databases specifically tailored for circularity assessment in construction.
- **Policy Support**: The section also mentions a perceived lack of supportive policies to improve reuse and recycling in the construction industry. Advocacy for and development of policies that incentivise circular construction practices, such as tax incentives or procurement regulations, can significantly accelerate the adoption of circularity principles.
- **Circularity Indicator Classification and Standardisation**: There is a confusion arising from the interchangeable use of circular terminology. Future work should focus on classifying and standardising circularity indicators, indices, and frameworks to provide a clear and consistent language for circularity assessment in the construction sector.
- **Innovative Circularity Indicators**: Researchers should explore and develop new circularity indicators tailored to the construction industry's unique attributes. These indicators should consider factors such as building service life, diverse materials, stakeholder involvement, and customisation.
- **Interdisciplinary Collaboration**: Circular construction is a complex field that requires expertise in materials science, architecture, engineering, policy, and economics. Encouraging interdisciplinary collaboration among these experts can help foster a holistic approach towards assessing circularity and promoting innovation.

- **Qualitative and Semi-Qualitative Approaches**: While quantitative indicators are essential, it is equally crucial to explore qualitative and semi-qualitative approaches for circularity assessment. These approaches may offer a better understanding of the social and environmental dimensions of circular construction.
- **Education and Training**: To promote the adoption of circularity in the construction industry, it is vital to develop training programmes and educational resources for professionals and stakeholders. Building a skilled workforce that understands the principles and benefits of circularity is essential.
- **Longitudinal Studies**: Longitudinal studies that track the impact of circular construction practices over time can provide valuable insights into their effectiveness. Monitoring the performance and environmental impact of circular buildings throughout their lifecycle and integrating them into existing assessment tools can be a useful strategy.

In conclusion, the construction industry is undergoing a transformation towards circular economy principles. However, to further advance this shift, it is essential to address challenges like standardisation, data availability, policy support, and the development of innovative tools and indicators. With these improvements, the construction industry can become a more sustainable and circular sector, contributing to a greener future.

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Chapter 17
Driving the Built Environment Twin Transition: Synergising Circular Economy and Digital Tools

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Abstract This chapter offers a comprehensive analysis of the intersection between digitalisation and the circular economy (CE) within the construction sector. It underscores the transformative potential of integrating digital tools to advance circularity objectives across managerial, environmental, economic, and social dimensions. The

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chapter discusses fourteen digital tools and technologies, which play a pivotal role in CE by streamlining data integration and visualisation, enhancing the accuracy of Life Cycle Costing (LCC) and Life Cycle Analysis (LCA) assessments, and supporting the adoption of CE strategies. Moreover, it explores how digital tools can facilitate collaboration among stakeholders, fostering knowledge sharing and effective communication throughout the project lifecycle. Nevertheless, challenges such as the absence of standardised methods, data interoperability issues, and the need for well-defined system boundaries remain. The chapter highlights the critical role of digitalisation in advancing the transition towards CE in the construction sector, emphasising the necessity of overcoming technical and systemic obstacles to fully harness the potential of digital tools in implementing CE. This transition aligns with the broader ambitions of the European Green Deal and the EU Digital Strategy, aiming to create a more sustainable, efficient, and resilient construction industry. By addressing these challenges and leveraging digitalisation, the construction sector can make a significant contribution to a sustainable and circular economy, ultimately benefiting both the environment and society.

Keywords Digitalisation · Circular economy · Digital tools · Key enabling technologies · Twin transition

17.1 Introduction

17.1.1 The Twin Transition—Green and Digital

The European Green Deal initiated the green transition within its sustainable growth agenda, with the aim of reframing the challenge of climate change into a unique opportunity. As stated by the European Commission, this green transition is pivotal for two primary objectives: firstly, to mitigate the consequences of climate change and environmental degradation, and secondly, to strengthen the European Union's (EU) energy self-sufficiency. At the heart of the European Green Deal's roadmap lies the Circular Economy (CE), a critical policy area intended to champion the efficient use of resources and stimulate sustainable economic growth, with a particular focus on the seven most resource-intensive sectors, including construction and building [1].

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Simultaneously, Industry 4.0 presents another essential transition in line with its objectives, referring to the profound changes in the design, production, operation, and servicing of manufacturing systems and products, marking the world's fourth industrial revolution [2]. Known as digital transition, this transformation hinges on several innovative technological advancements:

- **Information and communication technology (ICT)** to digitalise and seamlessly integrate information across the product life cycle and various sources, including different actors and companies.
- **Cyber-physical systems**, encompassing sensors and robots, which support additive manufacturing.
- **Network communications** linking devices, products, systems, and individuals.
- **Simulation**, modelling and virtualisation techniques.
- **Data collection**, big data analysis, and cloud computing.
- **Support human workers**, incorporating robots, augmented reality, and intelligent tools.

The Industry 4.0-driven digital transition offers significant growth potential for Europe across two principal dimensions: firstly, through the adoption of innovative solutions by businesses and citizens, and secondly, by enhancing the accessibility and efficiency of both private and public services. As outlined in the EU's digital transition plan, this transformation opens up *new opportunities for businesses, encourage the development of trustworthy technology, foster an open and democratic society, enable a vibrant and sustainable economy, help fight climate change and achieve the green transition* [3].

Furthermore, following Industry 4.0, Industry 5.0 is a new technological revolution that aims to enhance the transformation of the industrial sector into intelligent spaces based on the Internet of Things and cognitive computing. It is human-centric, sustainable, and resilient and relies on putting artificial intelligence at the service of people, bringing machines and humans together. The main difference between these two concepts lies in the role technology plays in each. In Industry 4.0, it is humans who monopolise the generation of knowledge and intelligence, using technology only as a support mechanism. However, in Industry 5.0, machines take on a different role, becoming the ones who also generate knowledge and intelligence, using artificial intelligence to be at the service of people. The main benefits of industry 5.0 are [4]:

- Reduce cost due to resource efficiency
- Empowered workers remaining in control
- Improved safety and well-being
- Competitive edge in new markets
- Adapted training for evolving skills
- Competitive industry by attracting best talent
- A solution provider for people and for our planet

The EU aspires to become a sustainable and competitive economy. To realise this vision, it is imperative for the European construction industry to embrace the practices of Industry 4.0 and CE, given their profound impact on the economy [5], environment and social communities. These two paradigms hold the potential to revolutionise the construction sector, enabling more sustainable and efficient practices that support the dual green and digital transitions. This is particularly critical because the construction industry stands as one of the largest consumers of raw materials and energy while concurrently generating a significant volume of waste and emissions [6].

The concept of twin transition, encompassing green and digital shifts, has been presented by the EU as the cornerstone of the transformations that will define the EU's future. This twin transition, propelled by a top-down approach and holding a prominent place on the political agenda, signifies the transformation necessary to attain green and digital objectives. The synergy arising from the amalgamation of both transitions goes well beyond their individual impacts. Digitalisation can amplify the green transition, and it is indispensable in comprehending, evaluating, and comparing alternatives, thereby challenging the prevailing business-as-usual (BaU) approach and charting new paths towards a more sustainable, circular, and digital future, spanning the three core dimensions of sustainable development: social, economic and environmental.

Aligned with the European Green Deal and the EU Digital Strategy several research projects have been supported by the EU, namely the GREEN AT YOU project from the EntreComp Community, an initiative that focuses on addressing the challenges and opportunities associated with the green and digital transition in Europe, aiming to make green job opportunities more inclusive and accessible to people in vulnerable situations, supporting the European Commission's agenda for a cleaner environment, green economy, and digitalisation, aligning with this twin transition [7].

For a successful twin transition, the Strategic Foresight Report [8] has identified ten key areas of action, including:

1. Strengthening resilience and open strategic autonomy in critical sectors.
2. Stepping up green and digital diplomacy.
3. Strategically managing the supply of critical materials and commodities.
4. Strengthening economic and social cohesion.
5. Adapting education and training systems.
6. Mobilising additional future-proof investment into new technologies and infrastructures.
7. Developing monitoring frameworks.
8. Ensuring a future-proof regulatory framework for the Single Market.
9. Stepping up a global approach to standard-setting.
10. Promoting robust cybersecurity and secure data-sharing framework.

In the "Towards a Green and Digital Future" report [9], the key requirements for the twin transition are grouped into five thematic clusters:

1. **Social**, to ensure a just transition, increase societal engagement in the change, and ensure privacy and ethical technology use.

2. **Technological**, implementing innovation infrastructure, building a technology ecosystem, and ensuring data availability and security.
3. **Environmental**, avoiding rebound effects, and reducing the impact of green-digital technologies.
4. **Economic**, to create enabling markets, ensure diversity of market players, and equip labour with relevant skills.
5. **Political**, implementing adequate standards, ensuring policy coherence, and channelling investment into green-digital solutions.

This study underscores the significance of the buildings and construction sector in the green transition. Within an industry characterised by lower and relatively stagnant productivity compared to other manufacturing sectors and a shortage of skilled labour, the digitalisation and industrialisation of the construction process provide an opportunity to address both challenges. This can be achieved by reducing dependence on labour and increasing productivity.

17.1.2 Key Enabling Technologies (KETs)

Key enabling technologies (KETs) represent the catalyst for rapid and far-reaching technological advances that reshape our economy, ushering in new markets and stakeholders [10]. Aligned with the objective of addressing paramount societal concerns, including the environment, energy, mobility, health and well-being, food and nutrition, security, privacy, inclusion, and equality, the European Commission champions six KETs organised into three primary domains:

1. Production technologies:
   - Advanced manufacturing
   - Advanced materials
   - Life-science technologies
2. Digital technologies:
   - Micro/nano-electronics and photonics
   - Artificial intelligence
3. Cyber technologies
   - Security and connectivity

A subset of these KETs is intimately intertwined with digitalisation technologies within the construction sector, which will be expounded upon in subsequent sections.

The analytical report from the European Construction Sector Observatory [11] entitled "Digitalisation in the Construction Sector," presents an overview of the most pertinent digital technologies in the construction sector, categorised into three distinct areas:

- Data acquisition: sensors, Internet of Things (IoT), and 3D scanning.
- Automating processes: robotics, 3D printing and drones; and
- Digital information and analysis: Building Information Modelling (BIM), Virtual/Augmented Reality (VR and AR), Artificial Intelligence (AI), and Digital Twins (DT).

Governments have exhibited robust support for the digitalisation of the Architecture, Engineering, and Construction (AEC) industry, resulting in an encouraging acceleration. This momentum is underpinned by a confluence of factors, including political priorities and financial backing, the imperative to enhance productivity while reducing costs, and the market demand for digital technologies. Nevertheless, several main challenges must be overcome, notably the scarcity of skilled labour and awareness, as well as the expenses associated with equipment and software.

The most relevant digitalisation technologies in the construction sector are elaborated in the European Commission's report "Supporting Digitalisation of the Construction Sector and SMEs: Including Building Information Modelling" [12]. Key technologies outlined in this document encompass Building Information Modelling (BIM), Additive Manufacturing, Robotisation, Drones, 3D Scanning, Sensors, and IoT. Within this document, BIM is not merely regarded as a technology but as a comprehensive methodology that underpins and harmonises the entire suite of digital advancements.

17.2 Analysis of Existing Key Enabling Digital Technologies for the Construction Sector

Within the realm of circular built environments, digital technologies and transformations have emerged as vital enablers in closing, slowing, and narrowing material loops. Aligning circular and digital transitions is believed to bring multiple benefits to environment, economy and society. In this regard, numerous studies have explored the best practices for implementing CE in the construction sector through digitalisation, shedding light on several tools, innovative products, applications, and services that have demonstrated significant benefits. Together, they create a dynamic ecosystem of digital technologies that fuel socio-economic transformation [13]. This chapter specifically highlights 14 key enabling digital technologies that play a pivotal role as drivers for the digital CE within the built environment.

17.2.1 Building Information Modelling (BIM)

Building Information Modelling or Building Information Management (BIM) is a methodological approach that revolves around creating a parametric 3D virtual model, or multiple linked models, to consolidate information about a building. This process begins in the early stages, such as commissioning or conceptual design, and ideally extends throughout the entire life cycle of the structure. The BIM model starts by representing existing conditions (the existing building or site), serves as a tool during the design phase to centralise and coordinate various aspects like architecture, engineering, and landscaping, and continues to be a valuable resource during construction, offering support for construction management and design modifications. This evolving model, often referred to as an "as-built BIM model", remains relevant after being delivered to the client or facility management team, supporting use and maintenance activities. Ultimately, it is ideally employed in the end-of-life (EoL) phase, assisting with demolition or, preferably, dismantlement and waste management. Throughout the building's life cycle, the BIM model enables various analyses, such as energy efficiency, material usage, layout planning, and sun exposure, providing data for various alternative scenarios and informing decision-making [14].

The BIM methodological approach hinges on data exchange and digital information interoperability. This entails seamless data sharing among different stakeholders with minimal or no information loss. The concept of "Open BIM" in contrast to proprietary software and data formats, is championed by the international organisation BuildingSMART, which promotes data exchange [15]. BuildingSMART is an international organisation dedicated to advancing research and knowledge in developing interoperable, open, and international BIM standards. Industry Foundation Classes (IFC) stands out as the widely accepted standard governing how building information is communicated and shared among stakeholders and applications using a Common Data Environment (CDE). A CDE is a common digital space that hosts the relevant information for collaboration, exchange, and communication to deliver a project, and comprises two components: the Data Standard (what is the information required and how the information is structured for sharing and collaboration within a common data environment to deliver a project) and the Data Platform (the computer system or technology platform that the data and information is stored, shared and collaborated on in a CDE) [16].

The BIM model can be developed with various levels of detail or level of development (LoD). It starts at LoD 100 with only basic graphical data and may progress to LoD 500, which includes detailed graphical and non-graphical data and information, as follows:

- LOD 100, Conceptual Design: At this level, the focus is on the physical appearance and visual or conceptual design, accounting for approximately 20% of the total data.
- LOD 200, Approximate Geometry: This level involves basic or schematic representations with parameterised dimensional information, constituting about 40% of the total information.
- LOD 300, Precise Geometry: Here, the model includes specific functions in addition to geometric dimensions, making up roughly 60% of the total information.

- LOD 400, Fabrication: This level encompasses the parameters necessary for a particular model and is typically considered at the contracting or construction project level, representing around 80% of the total information.
- LOD 500, “As Built”: This level refers to a highly detailed model that closely replicates the actual building as constructed, comprising 100% of the total information.

The European standard ISO 19650-1 substitutes this LOD definition (more commonly used in the USA) by Level of Information (LoI) needed. In the UK the different levels of LoI are more granular and related with different project stages, according the exchange information requirements (EIR), that includes the technical aspects (such as details of software platforms, definitions of levels of detail etc.), management aspects (such as details of management processes to be adopted in connection with BIM on a project); and commercial aspects (such as details of BIM Model deliverables, timing of data exchange and definitions of information purpose) [17]. By using these different LoD levels, BIM models can cater to a range of project phases and requirements, from initial concepts to the faithful representation of the final built structure.

BIM models are often associated with various dimensions. The journey begins in a pre-BIM stage with a 3D model, and additional dimensions include the 4th dimension, time, introduced through project planning; the 5th dimension, cost, for estimating and cost control; the 6th dimension, sustainability, focusing on impacts and energy estimation; and the 7th dimension, utilisation, aligned with facility management (FM). The concept of nD extends to consider additional dimensions, with the eighth dimension potentially connected to circularity and EoL activities [18]. Presently, these dimensions are often referenced as BIM model functionalities or uses. Figure 17.1 illustrates the established BIM dimensions and their respective applications.

According to MacLeamy curve [19], incorporating BIM into the building design and construction process shifts the primary effort from the construction phase, where most effort traditionally occurs, to an earlier stage during design. This phase is critical because it offers the highest potential for influencing overall costs and functional

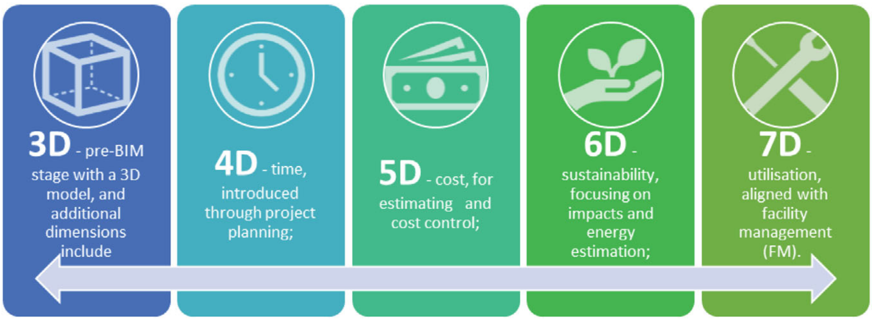

Fig. 17.1 3D to 7D dimensions of BIM

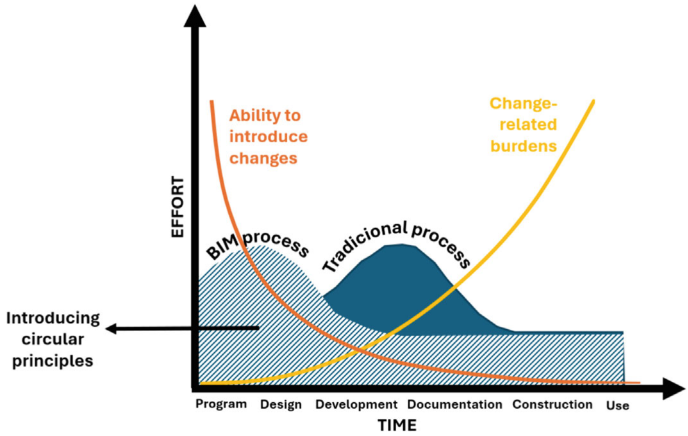

Fig. 17.2 Time versus effort along the building's life cycle: incorporating BIM use (based on MacLeamy curve) and adopting circular principles

capabilities while keeping the cost of potential future changes relatively low. Therefore, adopting BIM at an early design stage can leverage the adoption of circularity strategies such as design for adaptability and design for disassembly with minimal or no associated costs. This underscores the importance of embracing BIM in design and introducing circularity principles at an early stage when change-related burdens are relatively low, while maintaining the ability to introduce change in later lifecycle stages remains high, as depicted in Fig. 17.2.

17.2.2 Digital Twin

A digital twin (DT) represents a virtual model of a real-world product or building which consists of the actual geometry, structure and physical characteristics [20]. A DT can also be referred to as a 3D digital copy of a real-world physical asset [21].

During the construction phase, the BIM model (previously developed during design and preparation phases) should be constantly updated in a so-called "as-built BIM". After the conclusion of the works, the final BIM model becomes a digital twin, representing the physical asset and playing an important role in managing the real building.

DTs are distinguished by the smooth integration of the cyber and physical spaces as well as virtual data throughout a product or building lifecycle [22]. They find application in several areas such as product design, production planning and assembly [22]. In the built environment, having a DT of a real-world asset would allow tracking aspects like energy management, indoor comfort, and safety [23]. Besides enabling the monitoring of the current state, it facilitates predicting future state, allowing proactive measures for optimal operation [24]. Considering these capabilities, DTs are instrumental in assessing building performance and alternatives, supporting optimisation analysis, and enhancing reliability opportunities [25].

In the context of circularity, DTs are essential as they consist of information about the built-in materials of a building, which is relevant for implementing circularity practices [26]. When combined with Material Passports, DTs can help extend the lifetime of building elements through predictive maintenance [27] and facilitate the reuse of materials and elements at the end-of-life stage [28].

17.2.3 Additive Manufacturing (3D Printing)

Additive manufacturing, commonly referred to as 3D printing, has emerged as a transformative force in various industries, offering a multitude of benefits. Unlike conventional manufacturing methods that involve subtracting material from a larger piece to create parts and products, additive manufacturing stands out for its ability to reduce waste in production processes, promote decentralised manufacturing, and facilitate increased repair and remanufacturing. The primary value drivers of 3D printing encompass simplified manufacturing processes, swift prototyping, innovative design capabilities, product customisation, use of recycled materials, less waste generation, on-demand production, spare parts availability, and cost efficiency [29, 30].

The applications of additive manufacturing span diverse sectors. In the realm of manufacturing and industry, it is employed for rapid prototyping and has gradually expanded into full-scale production, thereby reducing lead times and development costs for prototypes [31]. In the medical field, 3D printing has revolutionised the production of medical devices, prosthetics, implants, and even the bioprinting of human tissue and organs [31]. The construction industry has also embraced additive manufacturing for tasks such as concrete printing and the fabrication of building components from metals and polymers. This enables resource optimisation, waste reduction, the creation of lightweight structures, and the use of recycled materials. Furthermore, additive manufacturing has made significant contributions to the automotive and aerospace sectors, exemplified by Boeing's use of 3D printing to produce over 50,000 units of more than 900 distinct parts [13]. Other industries benefiting from additive manufacturing include jewellery, where intricate and personalised designs are made possible, as well as the food industry, where advancements in 3D printing technology enable the creation of unique shapes and designs.

In the OECD Digital Economy Outlook, 3D printing is recognised as an application empowered by AI, big data, and simulations [32]. Digitalisation in additive manufacturing provides a range of advantages and plays a pivotal role in advancing circular construction practices as outlined by Antikainen, Uusitalo and Kivikytö-Reponen [33].

Firstly, digital additive manufacturing enables design optimisation through the use of advanced software tools, such as parametric modelling (e.g., BIM) and generative design algorithms. Architects and designers can create intricate, customised shapes that maximise material efficiency and minimise waste. Additive manufacturing techniques, like 3D printing, can then directly translate these optimised designs into physical structures.

Secondly, digitalisation promotes material efficiency by facilitating the precise layer-by-layer deposition of advanced materials and composites. This precision reduces waste during the construction process. Additionally, digitalisation allows for the analysis of material properties and performance, ensuring the selection of suitable materials for specific building components.

Another important role of digital additive manufacturing is on-demand manufacturing. This implies that building components are produced only when required, reducing the need for excess inventory and minimising waste. Furthermore, producing components in close proximity to the construction site reduces transportation costs and the carbon emissions associated with traditional supply chains.

Modularity and customisation are also encouraged through additive manufacturing and digitalisation. Modular building components can be easily assembled and disassembled, promoting the reusability and recyclability of materials. Digitalisation plays a vital role in designing and coordinating these modular systems, ensuring compatibility and efficient assembly.

Reduced energy consumption is another benefit of digitalisation and additive manufacturing. By optimising designs, reducing material waste, and enabling on-demand manufacturing, the overall energy required for construction can be minimised. Additionally, additive manufacturing techniques can incorporate energy-efficient features, such as complex geometries for natural ventilation or the integration of insulation materials [30].

17.2.4 Blockchain Technology (BCT)

Blockchain is a geographically dispersed and shared database, known as a distributed ledger. It operates within a peer-to-peer network, employing a consensus mechanism to maintain the integrity and accuracy of data, allowing for replication across computer nodes (participants). Consequently, any information exchanged between participants remains confidential, transparent, and auditable [34].

As a decentralised and transparent system designed to accommodate a vast and continually expanding volume of data, BCT holds considerable potential for applications in the built environment. Specifically, it can facilitate sustainable development and accelerate the transition to a CE, support data-driven decision-making across all stages of a product's life cycle and address the productivity challenges typical of the construction sector. Consequently, over the past decade, it has garnered significant attention from scholars. Nonetheless, the full adoption and broader application of BCT concepts remain limited, with the majority of research existing in the conceptual domain, complemented by only a few pilot studies such as the life cycle of HVAC [35] and additive manufacturing [36].

Thus far, the academic consensus primarily revolves around two key points. Firstly, the potential applications of BCT offer numerous advantages, including the design of mechanisms to incentivise environmentally friendly behaviour, increasing system efficiency and transparency throughout the entire product life cycle, reducing capital and operational costs, and promoting sustainability performance monitoring and reporting within supply chain networks [37]. Secondly, the use of BCT as a standalone tool in a circular built environment is seldom recommended. Instead, it is often suggested in conjunction with other digital technologies, such as the IoT [38, 39], Big Data Analytics [39], BIM [40], Digital Twins (DT) [38], Material Passports [41, 42] and additive manufacturing [36]. One of the earliest concepts introduced involved the integration of IoT, big data analytics, and BCT to conduct life-cycle assessments in energy savings, ecosystem quality management, and waste management [39].

A limited number of studies utilising BCT as a standalone tool have concentrated on enhancing waste management systems. In these studies, BCT was employed to optimise the system and foster greater trust between citizens and waste management operators. Two frameworks were introduced for this purpose: the first was focused on the management of urban waste streams in its entirety [43], while the second was concentrated on construction waste exclusively [44]. Both systems have the potential to enable the tracking and verification of significant data sets, including but not limited to the volume of waste generated or treated and associated rewards. These data are generated by various stakeholders within waste management systems.

Other frameworks explore the integration of BCT with BIM [40] and with DT [38]. The first framework promotes the CE by encouraging collaboration between stakeholders, sharing information about building components and materials, and developing repositories of reusable BIM families while motivating designers to utilise them. The second framework integrates IoT, BIM, and DT throughout the various phases of a project's life cycle. During the design phase of the Decentralised DT Cycle, 3D BIM data and design parameters are stored on the BC, while 4D BIM and procurement data are retained during the construction phase, and 6D BIM and IoT data are maintained during the operational phase.

17.2.5 Scanning Technologies

Scanning technologies, commonly known as laser scanning or Light Detection and Ranging (LiDAR), are advanced systems designed to determine the distances to various points surrounding a laser scanner by measuring the time it takes for a light pulse to travel to and from an object [45]. These technologies primarily provide local coordinates, which are subsequently cross-referenced with known geographic coordinates of objects. Laser scanners can be either static (terrestrial, positioned on the ground) or mobile (portable, mounted on drones, aircraft, or vehicles) and are capable of collecting vast amounts of data, necessitating intensive pre-processing before further applications.

In the realm of the built environment, scanning technologies are predominantly employed for purposes such as inspection, site monitoring, and 3D reconstruction [46]. Their application contributes significantly to enhancing circularity within the built environment by facilitating the 3D reconstruction of objects and the creation of BIMs and City Information Models (CIMs). These models are enriched with valuable information, enabling them to support local governance and various smart city and CE initiatives [47].

The academic literature on laser scanning technologies, in the context of their support for the CE, varies in terms of the scanning area and the level of detail (LoD). For instance, LoD 1 entails representing a building with basic information such as its footprint area, height, and flat roof, while LoD 2 includes a more precise representation that accounts for roof slopes. As a general rule, the larger the scanning area, the lower the level of detail.

Laser scanning technology has been applied across a wide range of projects, from assessing the geometry for single buildings in Vienna [48] to scanning 1,361 buildings in Hong Kong [47]. It has also been employed for projecting mineral Construction and Demolition Waste (CDW) flows [49] and conducting life cycle assessments for entire cities in Luxembourg [50]. Recent advancements in this field include the development of a methodological framework for semi-automated reconstruction at higher levels of detail for existing buildings, aimed at creating CE passports [51]. Another notable initiative involves the reconstruction of building facades to facilitate energy-based simulations for retrofitting existing structures [52]. These applications highlight the versatility and significance of scanning technologies, not only in improving circularity but also in advancing sustainable practices in the built environment.

In addition to providing information about the geometry and surface materials, laser scanning is employed to facilitate circularity practices such as preservation, reuse, and recycling. However, for a comprehensive understanding of building elements' material composition, it becomes essential to delve beyond surface materials. Addressing this need, a study by Honic et al. [53] used Ground Penetrating Radar (GPR) to identify material types within walls and slabs, generating Material Passports (MPs) for a building. GPR, a near-surface geophysical tool, allows non-destructive characterisation of shallow subsurface targets by detecting changes in the electromagnetic properties of materials [54]. Its non-destructive nature has been extensively applied in archaeological studies over the past decades. In the context of CE and the built environment, GPR holds significant promise for detecting built-in materials without causing damage. This capability aligns with the circularity principles of preservation, reuse, and recycling, making GPR a valuable tool for sustainable practices in construction and material management.

17.2.6 Internet of Things (IoT)

The Internet of Things (IoT) can be described as a networked system of sensors and actuators integrated with a computing system, enabling internet connectivity among sensor-equipped devices for autonomous data collection and analysis [55]. This technology facilitates the monitoring and management of the health and activities of interconnected objects and machines.

In the context of CE, IoT has the potential to revolutionise various industries, including construction, services, manufacturing, logistics, and supply chains [55]. It facilitates stakeholder connection throughout the value chain by leveraging sensor-collected data [56]. By enabling autonomous data collection and analysis, IoT helps reduce waste, losses, and expenses, while also enhancing the tracking and traceability of materials throughout the supply chain [29], thus supporting the implementation of CE principles [56]. In urban environments, the concept of smart cities exemplifies how IoT contributes to CE improvement by enabling data gathering and interpretation for sustainable solutions, efficiency enhancement, pollution reduction, and promotion of eco-friendly consumption [57].

Reuter [58] highlights the transformative potential of IoT within CE by facilitating digitalisation and optimisation of systems through measurements and quantification tools. Moreover, IoT enables CE models to incorporate dynamic feedback control loops, connecting all system stakeholders and allowing for the assessment of the impact of actions taken by different actors throughout the lifecycle of physical products [56]. Real-time data and information provided by IoT can lead to the optimisation of products, goods, services, and policy formulation, resulting in a significant reduction in the environmental footprint of the CE systems.

The digitisation of the CE information through IoT brings about transformative changes in business models and the introduction of CE-based marketing strategies. This partnership aims to establish a business and consumption model rooted in social responsibility, reduced consumption, and efficient management of product life cycles, with a strong emphasis on reuse, recycling, and reduction. Transitioning from the traditional marketing mix to the green marketing mix is considered a profitable and sustainable management process and a key business strategy of the future [59]. As argued by McDaniel and Rylander [60], green marketing has become a crucial factor in the mission, vision, and values of companies. Furthermore, the implementation of the circular and digital economy model relies on the effective utilisation of the 4Ps (price, product, placement, and promotion), with IoT playing a significant role in this process. In this regard, IoT provides the necessary support for companies to achieve a CE with long-term effects. For instance, LCA is one area where IoT's impact is evident, as it is a widely used method for quantifying sustainability within organisations [59].

The transition to a CE with the assistance of IoT is significantly influenced by the supply–demand relationship. The market's responsiveness to consumer preferences is a driving force behind the digitisation of production and consumption processes. This integration has the potential to enhance productivity and sustainability in both local and global economies, as well as in various business models. IoT and the CE share a common focus on the entire product life cycle, demanding product designs that align with present and future market expectations while adhering to the 17 UN Sustainable Development Goals [59].

17.2.7 *Artificial Intelligence (AI)*

Artificial Intelligence (AI) is one of the main technologies that can accelerate the transition towards a CE [61]. McKinsey Global Institute [62] estimated that AI could potentially generate a staggering $13 trillion in global economic impact by 2030. The Ellen MacArthur Foundation [63] underscores the transformative power of AI in imbuing inanimate objects with intelligence. Its integration into design, infrastructure, and business models is driving the creation of regenerative systems. This 2019 report identifies several ways in which AI can expedite the transition to a CE:

- Enhancing Problem Solving: Advanced AI enables complex problem-solving in significantly less time, with algorithms trained and applied to real-life challenges throughout the development process.
- Unlocking CE opportunities: AI contributes to more efficient design and optimisation of business models and infrastructure, hastening the establishment of a CE.
- AI can potentially unlock three main CE opportunities: (1) Circular product, material, and component design; (2) Circular business model operations; and (3) Infrastructure optimisation to facilitate the circular flow of materials and products.

A substantial volume of data is generated at various stages of the product development lifecycle, from manufacturing to utilisation and EoL [64]. AI can play a pivotal role in analysing and further enhancing these processes. Furthermore, the integration of circular design tools and methods with AI can significantly enhance product circularity within a business context [65].

AI excels in the analysis of large datasets, saving time through high-performance computing. Despite its dynamic and complex nature with numerous parameters, AI applications in the construction sector offer substantial opportunities. Notable current and actively researched AI applications in construction include: safety measures, automated monitoring of structural health for buildings, bridges, and road pavements, detection of safety risks at construction sites, activity recognition at construction sites, modelling of energy demand for buildings, construction cost prediction, computer vision, intelligent optimisation of scheduling, planning, and design [66–68]. AI technologies are also employed in green buildings for monitoring building health, safety, and risk assessment, sustainability ranking, CDW management, resource optimisation, and lifecycle cost reduction [69].

Future trends in the construction sector include the development of construction robots to reduce workforce dependency and improve efficiency, the utilisation of cloud-based virtual and augmented reality for enhanced inspection and safety, AI of things (AIoT), DT, 4D printing, and BCT [67]. Currently, the main challenges for AI application within the construction sector encompass site management, financial expenses, security concerns, data availability, and the disparity between the accuracy of machine learning algorithms and practical application [66, 68].

Designing construction site layouts remains a challenging problem in construction projects. Spatial and temporal parameters of site layouts are crucial for efficient site management [70, 71]. These parameters include access routes, material storage, material handling methods, administrative buildings, and job equipment. While defining an optimal layout has proven difficult [70], a valuable research direction is to determine an optimal site layout with circularity in mind. Although machine learning has been applied to job site optimisation, the use of satellite images and explanatory visualisation techniques to identify site similarities remains unexplored.

Despite advancements in the CE, deep learning has not seen widespread use in this field, primarily due to the absence of large-scale multimodal datasets. Existing assessments and indexes heavily rely on open datasets available in municipalities, such as material flow data in industrial sectors [72, 73]. This reliance introduces limitations and accuracy issues, particularly for developing and less developed countries.

17.2.8 Big Data Analytics (BDA)

In the past decade, deep learning has emerged as a powerful AI methodology, effectively addressing a wide range of challenges across various domains. These applications include object detection in visual data, automatic speech recognition, neural translation, and tumour segmentation in computer tomography scans. While artificial neural networks (ANNs), the precursor of deep learning, trace their roots back to the 1960s, it was in the 2010s that deep learning systems experienced a remarkable surge in performance. This transformation was facilitated by the availability of graphical processing units for computation and the advent of Big Data Analytics (BDA). This is the process of examining and analysing concealed patterns, correlations, trends, and insights within these vast data collections, with the primary objective of extracting valuable information and knowledge. This information is then utilised to drive data-informed decision-making, enhance business processes, and tackle intricate challenges.

In the field of CE, the application of BDA is seen as a promising methodology for harnessing information gleaned from various systems of record, including sensors and IoT devices. This empowers decision-making capabilities, especially in logistics and supply chain management (SCM), which is pivotal for the successful implementation of CE and the advancement of its comprehensive principles [74]. It's worth noting that Big Data is often treated not as an isolated concept but rather as an analytical approach applied to analyse extensive data originating from diverse sources. Through the integration of comprehensive and lifelong information, Big Data facilitates the implementation of innovative strategies [56].

From the perspective of stakeholders, the adoption of BDA would significantly enhance decision-making across a spectrum of business sectors. However, the existing literature faces a challenge in understanding how BDA contributes to better decision-making, primarily due to a lack of detailed investigation [75]. This can be partially attributed to the varying interpretations of the CE concept among scholars.

For instance, some studies characterise CE as the management of closed loops in linear industrial production [76], while others believe in the spiral-loop system concept as in [77]. According to Tseng et al. [78], the central concept of SCM, the "closing-loops" strategy, has conventionally been employed in linear production systems, typically within a single supply chain and connected with vertically integrated decision-making systems. Nonetheless, this "closing loops" approach is also applicable in industrial and urban symbiosis within multi-supply-chain networks, involving cross-industry decision-making.

17.2.9 Cloud Computing and Applications

Cloud computing is a revolutionary paradigm for managing and utilising both hardware and software resources. It empowers businesses to share various aspects of their information technology infrastructure (IT), including both physical and non-physical components. Integrating an enterprise's IT infrastructure into projects can lead to substantial reductions in initial investment costs [79]. Despite its potential, the construction industry has been hesitant to embrace these new technologies due to high upfront costs, resulting in limited cloud computing applications [80].

The potential benefits of cloud computing technology in construction are numerous:

- Economic Efficiency: It offers economic benefits by decreasing the operational costs for construction companies [79].
- Level Playing Field: It creates a level playing field for small and medium-sized enterprises (SMEs) to compete with larger corporations without significant upfront investments [81].
- Secure Data Storage: It ensures the secure storage of construction data, meeting the required security standards for IT infrastructures [79].
- Remote Data Access: It facilitates remote storage and retrieval of vast construction data without space and time limitations [79].
- Centralised Data Repository: It creates a central repository system for construction data, facilitating stakeholder integration [82].

The impact of cloud computing applications on CE in construction has gained significant recognition [83–85] due to their role in reducing material waste at construction sites, minimising incorrect deliveries, and streamlining file organisation, contributing to cost reduction and improved project timelines [86–88].

Construction sites are inherently hazardous due to their dynamic and complex structures, which increases risks without real-time on-site safety information. However, leveraging cloud technology to provide instant access to safety information can reduce occupational accidents [89, 90]. Sustainability goals are also achievable by managing energy consumption and reducing CO_2 emissions through cloud technologies, which enable the efficient management of building energy information alongside safety data [91]. Timely material supply to construction sites significantly influences project cost and duration. In this regards, cloud technologies and IoT sensors play critical role in ensuring efficient and timely delivery by monitoring material supply movements [92] and enhancing cooperation and communication among numerous stakeholders [84].

17.2.10 Virtual and Augmented Reality (VR/AR)

Virtual Reality (VR) and Augmented Reality (AR) are two technologies that have the potential to support and enhance the CE. AR technology overlays digital content, including images, videos, and 3D models, onto real-life environments and physical objects, enhancing the user perception of reality by transforming their immediate surroundings into an interactive learning environment with virtual elements [93]. In contrast, VR immerses users in a simulated environment [94], offering a completely virtual experience with diverse applications, including education and training. In the context of the CE, both AR and VR can be employed to provide information and guidance on recycling, waste sorting, sustainable consumption, and to simulate and visualise sustainable practices and processes [93].

Several applications of VR in promoting the CE in the construction sector include the integration of VR and BIM for effective construction planning and enhanced safety. This BIM-based system enables advanced simulation and communication, offering an immersive experience to all project stakeholders. Real-time synchronisation between BIM and VR models allows for automatic updates, streamlining decision-making during construction.

Combining VR with BIM and LCA contributes to the assessment and reduction of carbon footprints in construction projects. During the conceptual design phase, VR and BIM play a pivotal role in generating LCA and cost assessments that assist designers and clients in making well-informed decisions. Experiments have shown that users prefer economical solutions without compromising aesthetics, and their concern for sustainability increases when exposed to LCA data. Moreover, simplified cost and carbon footprint results have been found to influence users' perceptions. This underscores the potential of VR-BIM-LCA integration in making informed decisions regarding material selection and sustainable solutions.

Augmented Reality (AR) technology has the potential to enable environmental designers, urban planners, and other infrastructure development roles within the built environment to help key decision-makers invest in a CE for their city or community. AR can be used to explore CE solutions, enabling key audiences and actors to be engaged in a more active way [95], by fostering their interest perception on CE principles. Additionally, AR can serve as an engagement tool to increase end-users' interest and engagement with CE principles, educating the public about CE and promoting sustainable practices [96].

Moreover, AR technology can be used for disaster training and response. AR mobile applications can effectively engage both citizens and disaster response authorities, thereby enhancing their preparedness and response capabilities. By leveraging

AR technology, disaster training and response efforts can provide immersive, real-life scenario simulations, leading to more effective emergency response [97].

17.2.11 Geographic Information System (GIS)

Geographic Information Systems (GIS) are advanced computer systems designed to collect, store, manipulate, analyse, manage, and map various types of geographically referenced information [98, 99]. Within GIS, data is seamlessly integrated with descriptive information on a map, which aids users in identifying patterns, relationships, and geographical contexts [99]. Notably, GIS combines data with cartographic elements, creating a synergy of spatial attributes and contextual descriptions that greatly enhance the understanding of spatial patterns, relationships, and geographic contexts [100]. The versatility of GIS extends across a broad spectrum of fields and industries, making it an invaluable tool for cartographic production, analytical inquiries, information dissemination, and the resolution of complex challenges.

The literature strongly supports the idea that GIS can play a pivotal role in promoting the adoption of a CE in the built environment. Firstly, GIS solutions actively facilitate circular logistics planning and environmental and economic impact assessments in the built environment [101]. By integrating data related to waste generation, material flows, and resource availability, GIS can effectively identify opportunities to optimise resource utilisation, reduce waste, and encourage circular practices. Secondly, GIS can be employed to map and manage resources in the built environment, including emissions, air pollution, and waste. It is instrumental in identifying and locating sources of reclaimed materials, such as salvaged building components or recycled materials, and streamlining their incorporation into construction projects [48, 98]. Thirdly, GIS can be seamlessly integrated into decision support systems for CE initiatives in the built environment. It offers decision-makers a comprehensive view by combining spatial data with other relevant information, such as economic factors, environmental impacts, and regulatory requirements [101]. This aids in evaluating the feasibility and potential benefits of CE strategies.

Furthermore, GIS can support the monitoring and evaluation of CE initiatives in the built environment. It can track project progress, measure resource efficiency, and assess the environmental and economic impacts of circular practices [48]. GIS also facilitates data sharing and collaboration among stakeholders, enabling better coordination and communication in CE projects. Finally, GIS serves as a valuable tool for engaging stakeholders in CE initiatives. By visualising data and scenarios, GIS effectively communicates the benefits and potential outcomes of circular practices to various stakeholders, promoting awareness, participation, and collaboration [101].

17.2.12 City Information Modelling (CIM)

City Information Modelling (CIM) is a novel concept that encompasses the use of intelligent urban models with high quality geospatial information and an update and comprehensive database [102]. CIM can also be defined as a digital representation of a city that integrates various data sources, including spatial data, infrastructure information, and environmental data [103, 104]. This integration enables the visualisation, analysis, and simulation of urban systems, empowering decision-making processes [102, 105].

The literature presents various interpretations and definitions of the CIM concept. In general, CIM aligns with the use of geospatial information and digital technologies [106]. As presented by Kehmlani [107], one of the early adopters of the acronym, CIM can be likened to BIM but specifically applied to urban environments. In this regard, intelligent city models should closely resemble intelligent building and infrastructure models, providing comprehensive information to simulate various aspects of cities, such as traffic flows, energy use, and natural disaster impacts [107]. Stojanovski et al. [108] propose that the CIM concept blends elements of GIS, Computer-Aided Design (CAD), and BIM, forming the basis for digital tools to plan and design smart cities. Xu et al. [109] state that CIM is inspired by BIM and should include all aspects of city information, establishing the integration of BIM and GIS, where building information is provided through BIM and external information is provided by GIS. Almeida and Andrade [110] perceive CIM as an intelligent computational model that incorporates processes, policies, and technologies, facilitating collaboration among various stakeholders to develop sustainable, participatory, and competitive cities. Dall'O' et al. [111] consider CIM the "latest advancement of BIM" and highlight its potential for analysing city components and creating richly informative 3D models. They also emphasise the benefits of using CIM for decision-making, management, monitoring, control, and maintenance in the energy sector. Thompson et al. [112] discuss the planning of future cities and consider CIM as the practical application of the digital processes for the management and planning of cities, involving the active participation of citizens and stakeholders. Sirakova [113] proposes that the CIM model can be seen as a continuous process of development and renewal, mirroring how cities evolve like living organisms. Wang and Tian [114] define CIM as an organic synthesis of 3D models and urban information, integrating BIM, GIS, IoT, and other technologies. According to the authors, CIM exhibits four main characteristics: multidimensionality, visualisation, openness, and perception. Based on their findings, city information models should be based on the integration of data across various spatial scales, emphasising the importance of BIM, GIS, and IoT as key technologies for CIM.

While a consensus on the CIM concept is lacking, the literature indicates an understanding of its equivalence to the BIM concept, but with a focus on urban environments, and a tendency to associate CIM with the integration of BIM and GIS. Although not universally embraced by urban planners, researchers, and the software industry, it is noteworthy that CIM has garnered increased attention, evidenced by the growing body of research published on the topic in recent years.

17.2.13 Digital Platforms and Market Places

An online or virtual platform is a digital service based on a software system that operates via the internet, facilitating interactions among and between independent users [13]. These platforms bring together diverse user groups, forming multi-sided networks that enable data collection and use through various modes of production, consumption, collaboration, and sharing [13, 32].

Online digital platforms provide valuable opportunities for visualising distribution channels, including online shops and market places, as well as the exchange digital products and services [115]. These platforms are believed to have positive environmental and circularity impacts [116], by promoting the closing, slowing, and narrowing of material loops [117]. The environmental benefits and CE value arise from the information provided by these platforms regarding product availability and location. This information enhances users' access to shared use through sharing platforms and facilitates the exchange of goods via digital marketplaces. Furthermore, these digital platforms support increased data collection, promoting better end-of-life management, and enhancing residual value by enabling improved maintenance, repair, refurbishment, remanufacturing, and recycling [33, 115, 117, 118].

Online platforms provide a means to create new markets for secondary materials within the context of the CE, connecting supply and demand for various stakeholders, including individuals and companies [13, 33]. They can also play a crucial role in supporting innovative circular business models for product-service systems [117, 118] particularly in the construction industry, enhancing competitiveness and efficiency across the value chain [13, 119].

Depending on their operational context, digital platforms offer two primary types of exchanges: business-to-business (B2B) interactions, such as the Excess Material Exchange in the Netherlands [120], which promotes the elevated-value reuse of materials and waste across industries, and business-to-consumer (B2C) exchanges, like the Enviromate platform in the UK [121], which connects consumers with providers of leftover construction materials to encourage closed-loop resource utilisation.

The availability of these platforms and markets significantly influences social aspects [13], impacting user behaviours towards accepting CE products such as secondary construction materials and reclaimed goods, by creating favourable market conditions. These platforms also empower communities to co-create circular products and services [117] and support other social factors by serving as venues for job advertisements and demands for construction service providers within the construction industry.

The use of digital marketplaces and online platforms is widely supported by national and European legislation, exemplified by the EU's Digital Single Market strategy [119]. While many CE experts emphasise the value of establishing digital platforms for circular material flows, the low number of users remains a significant challenge to the widespread adoption of these tools [118].

Despite the numerous advantages of digital platforms, only a few studies in the literature have addressed their potential, identifying two primary approaches. The first approach is known as tool-based platforms, which focus on the production processes of buildings, with BIM playing a key role. The second approach is collaboration platforms, which engage various stakeholders to improve the management aspects of building projects [117, 118].

17.2.14 Material Passports (MP)

Material Passports (MP), also known as digital passports or cradle-to-cradle passports, are comprehensive digital records that accompany physical products, serving as an auditable account of a product's entire lifecycle from design to EoL stages. These passports provide vital information about the product's composition, embedded material types, and grades [118]. They enumerate all the materials integrated into a product or construction project throughout its lifecycle. The primary objective of digital MPs is to facilitate circularity decisions in supply chain management by enabling the identification of opportunities for recovery, recycling, and re-use. The digitisation process plays a pivotal role in promoting circular buildings, with digital MPs serving as a crucial enabler in this transformative shift.

In the EU regulation, these passports are known as Digital Product Passports (DPPs) and are defined as "a structured collection of product-related data" encompassing "information related to sustainability, circularity, and value retention for reuse, remanufacturing, and recycling." As per the regulation, DPPs are required to furnish details regarding the origin and composition of materials, options for repair and disassembly, as well as avenues for recycling and disposal at the end of the product's life cycle [122]. However, for the effective implementation of DPPs in practical applications, there is a crucial need for a standardised format, structure, and terminology for these passports, which is currently lacking [123].

Digital MPs offer several advantages that contribute to improved sustainability, supply chain management, and compliance with regulations. Initially, they enhance data accessibility by providing comprehensive information about materials used in products or construction projects. This easily shareable data can be accessed by stakeholders throughout the supply chain, facilitating informed decision-making and promoting transparency. Digital MPs enable efficient material traceability, ensuring compliance with regulations and effective material management. By tracking materials throughout their lifecycle, these passports help ascertain their origins, a critical aspect in meeting regulatory requirements. This, in turn, promotes resource efficiency, reduces waste generation, and contributes to a more sustainable approach.

One of the significant advantages of digitalisation lies in its capacity to visualise the environmental impact along the entire value chain. Through the use of digital technologies such as BIM, stakeholders can make well-informed decisions regarding intelligent design, production, and usage that enhance material and eco-efficiency. This visualisation aids in identifying opportunities to minimise waste and optimise resource utilisation, ultimately leading to more sustainable construction practices [124]. BIM has been widely investigated to develop digital MP that enhances design efficiency by minimising waste and environmental impacts. The key benefit of this automated approach lies in its ability to facilitate comparisons among various design variants. However, successful automation of MP generation necessitates accurate modelling in BIM, encompassing the appropriate use of BIM objects, geometry, materials, and other relevant components [125].

Costa and Hoolahan [126] provide guidance and a policy framework on implementing MPs to facilitate a CE in construction. Their recommendations include conducting pre-redevelopment audits, leading to pre-demolition/refurbishment audits, followed by the gathering of metric data, the implementation of an MP strategy, and incorporation of reused materials before construction commences. A deconstruction plan is then drafted before the building is handed over for use. The proposed MP strategy can be used to constitute Product Passports, which can subsequently be combined to produce System Passports. The MPs are based upon 'types', similar to 'levels' terminology used in other frameworks. These types were aligned with the Uniclass classification system and can then be combined into Element Passports and/or Building Passports.

17.3 The Role and Benefits of Digitalisation in Promoting More Circular Buildings

17.3.1 Managerial Value

Information Transfer for Improved Value Chain Management. Industry 4.0 has brought forth multiple technologies to aid sustainable and circular supply chain management by providing tools to support decision-making for the realisation of circular development in the construction industry [127]. The role of digitalisation in enabling efficient and cost-effective information transfer to support proper management is essential for fostering the CE and maximising its potential [128]. Information transfer among stakeholders across value chains remains a major challenge in implementing CE practices [129]. Fortunately, digital tools, platforms, databases, and other technological solutions can address this challenge by facilitating interactions between products, processes, and stakeholders throughout a project's lifecycle [130], thereby promoting closed material loops. These tools and solutions have the added advantage of collecting vast amounts of data, which is vital for implementing CE strategies such as maintenance, repair, lifecycle extension, and adaptive reuse of buildings.

Efficient information flow regarding sourcing, usage, durability, disposal, and recycling potential is crucial for optimising circular usage of products and materials throughout their lifecycles. Seamless data transfer and sharing empower various stakeholders in the value chain, including suppliers, service providers, contractors, engineers, users, and waste operators, to adopt circular practices such as repair, maintenance, reuse, recycling, and proper disposal [129]. Digitalisation can offer opportunities for collaboration and integration among stakeholders in the construction industry, leading to business opportunities [129]. Information sharing platforms and BIM systems enable project teams to collaborate effectively and embed circularity objectives throughout the entire project lifecycle. By facilitating communication and knowledge exchange, digital technologies create an environment conducive to sustainable and circular transformation in the construction sector through circular feedback systems.

The synergies between CE and centralised management models in a digitalised environment, such as in BIM models, are highly appreciated for efficient information management and informed decision-making at various stages of a construction project's lifecycle, including planning, design, supply chain integration among other. The use of digital tools empowers stakeholders to make well-informed choices that align with circularity principles and promote sustainability at any stage of a project's lifecycle. While CE initiatives alone may not adequately address the complexity of systems and strategies to provide smart solutions for (EoL) and waste management, the integration of CE strategies within digitalised systems can enhance their effectiveness and efficiency [131].

Data Management. In today's resource-efficient CE, digitalisation and data availability are paramount for achieving optimal results. By harnessing digital tools, processes, and logistics in CE practices, they can be optimised, leading to increased efficiency and sustainability [132]. Online platforms, digital data, and product passports, among others, are revolutionising the way information is documented and shared, filling the gap of poor documentation and information loss that used to occur throughout the lifecycle of a building and its components due to changes that take place during different stages. These platforms and tools also serve certification purposes and are highly valued by academics and industry professionals as vital assets for maximising circularity potential in buildings and the built environment.

A fundamental aspect of data management in the CE is the creation of digital representations of buildings and their components, along with associated information. This approach offers several advantages for stakeholders involved in circular planning, design, and EoL solutions. Centralised digital models, such as BIM, have emerged as valuable tools for integrating diverse information related to buildings, elements, and geometry [133]. Stakeholders can access and leverage the information stored in these models to make informed decisions throughout the lifecycle of a building.

The development of digital technologies to monitor material flows and track data has been significantly amplified by BCTs. BCT plays a pivotal role in enabling efficient and effective reuse and recycling processes by securely storing, recording, and sharing important information about various materials and elements [133]. Through

BCs, the transparency and traceability of materials are enhanced, fostering trust among stakeholders and facilitating the implementation of circular practices.

Optimising individual processing steps and material flows along the value chain is critical for efficient resource management [132]. Digital data analytics plays a vital role in this regard by providing insights to predict materials requirements and enabling efficient supply–demand processes, resulting in significant time and cost savings. However, the extent of digitalisation determines the full potential of existing data. The higher the level of digitalisation, the more data can be processed and integrated for meaningful analysis. Increased data integration through digitalisation also facilitates the establishment of a historical path, offering valuable insights for future decision-making. Building such a data and digital wisdom requires a systematic data strategy that integrates multiple types of tools throughout the entire process, enabling robust and timely reactions to upcoming requirements.

17.3.2 Environmental Value

Circularity Implementation and Assessment Throughout the Building Lifecycle. The pivotal role of digitalisation in fostering the transition to a CE cannot be overstated. It harnesses the potential of digital technologies and interconnected objects, promising substantial reductions in resource consumption and the realisation of circular feedback systems [134].

Given the intricacy of buildings and the enormous resources they encapsulate, addressing the challenges of the building lifecycle necessitates a comprehensive, four-phase approach encompassing production, construction, operation, and EoL stages [26]. Although the operational phase of buildings is the longest and often the most environmentally impactful, it is crucial to recognise that the decisions made during the pre-use and design phases are pivotal. They significantly influence the operational performance of buildings, leading to substantial resource savings and reduced carbon emissions [26].

At the product level, digitalisation's role is particularly pronounced, offering easy access to product information critical for reducing resource consumption and optimising the product lifecycle. This accessibility empowers circularity options [135].

During the design phase, digital technologies play a critical role in implementing circularity strategies, expanding their impact on operational efficiency. Notably, digital parametric design tools are essential instruments for crafting regenerative building designs, while AI technologies, when integrated, enable extensive data interpretation and its application to design practices [26]. Moreover, digital tools support stakeholders to harness the value of circularity in buildings where circularity assessment necessities the handling of a large amount of information and data. Digital tools are perceived as great enablers for this process given their ability to address collection and management of data in a timely manner for efficient and effective assessments [136]. BIM provides a potential tool due to its potential to incorporate complex data and automatise the assessment [137]. Recently, BIM-based circularity indicators have been introduced [138], e.g., Zhai [136] proposed a BIM framework to automate the circularity assessment of buildings from the early design stage. In the use phase, digital technologies play a vital role in extending a building's lifetime, thereby slowing the loop. They support repair and maintenance activities, offering scheduled maintenance and planned replacements. Moreover, they provide insights on how to safely replace and recover broken or EoL elements.

The EoL phase is a critical juncture for reintroducing building materials and resources into further cycles, in alignment with the waste hierarchy principles of reduce, reuse, and recycle, ultimately closing the loop. Multiple platforms and add-ins have been developed to facilitate and measure material recovery possibilities [26]. Integrating BIM into project processes opens new avenues for circularity, allowing the exploration and simulation of design and EoL options that enhance resource efficiency and minimise emissions. BIM acts as a decision-support tool by simulating and comparing multiple scenarios efficiently. It also automates various processes and calculations essential for making decisions at any stage of a building's lifecycle.

BIM's ability to centralise design and associated information empowers the examination of disassembly and deconstruction potential, paving the way for resource recovery at the end of a building's life [139]. For instance, the Disassembly and Deconstruction Analytics System (D-DAS) plug-in offers design engineers a powerful tool to assess EoL performance in the context of the CE [139]. The Design for Disassembly (DfD) functionality within this plug-in serves as a pivotal decision-support instrument, illustrating the impact of design and material choices on waste generation in the EoL phase.

Lifecycle Analysis (LCA) and Environmental Impacts. In the context of environmental sustainability, digitalisation plays a crucial role in decoupling economic activities from the depletion of natural resources and mitigating their environmental consequences. This objective aligns closely with the principles of a CE [13]. The fusion of circularity practices with digital technologies not only enhances environmental benefits but also provides a means to visualise the environmental impacts associated with different stages of the product life cycle along the value chain. This visualisation, in turn, facilitates environmentally-conscious design, production, and usage, ultimately increasing eco-efficiency [140].

Additive manufacturing tools like 3D printing help minimise the carbon footprint of some construction materials such as concrete. Comparing to conventional building techniques, 3D printing can significantly reduce emissions and energy consumption [140].

The integration of digital management models such as BIM and MPs with methods like Life Cycle Analysis (LCA) and Material Flow Analysis (MFA) holds the potential to significantly improve the efficiency of assessing a project's environmental performance [140]. By incorporating LCA methodologies into the design phase, these technologies enable the measurement and evaluation of resource consumption and environmental footprints right from the outset. Traditional manual LCA processes have been criticised for their time-consuming nature, but when integrated into BIM, early assessment becomes possible, facilitating informed decision-making and highlighting opportunities for improvement. This, in turn, encourages the adoption of more sustainable practices. By continually tracking and monitoring resource usage throughout the construction process, digital technologies play a vital role in promoting circularity and minimising environmental impacts.

Numerous studies have explored the application of BIM-based LCA for evaluating and appraising design alternatives, starting from the early stages of a project's lifecycle, as exemplified by [141]. This approach extends the traditional use of LCA, which typically reported environmental impact and energy use at a specific point in a building's lifecycle for sustainability assessment and certification purposes. By incorporating LCA into the decision-making process, stakeholders can optimise material choices and design alternatives in line with circular construction principles. This approach addresses the previous constraint of time-consuming traditional LCA processes.

While many studies have focused on using BIM-supported LCA techniques for sustainability studies, the integration's potential has primarily revolved around certification purposes [141]. However, only a few have extended this research direction to support the circular design process and promote the use of circular materials.

Another study has integrated the LCA in the BIM-based MP which enabled a comparison between the environmental impacts and the reusability potential of buildings. The combined approach allows for optimisations of the building design in earlier design stages without neglecting the LCA or circularity impacts [142].

Multiple tools and BIM software plug-ins have been developed to enable BIM-based LCA by linking material libraries from BIM software with an LCA database. This integration permits the assessment of environmental impacts at different stages of a building's lifecycle. Many studies recognise the potential for extending this use to promote the implementation of CE principles. Such integration would enable stakeholders to achieve their circularity objectives without compromising other critical emissions and environmental aspects or, at the very least, minimise the trade-offs between these essential concepts.

Efficient Resource and Construction and Demolition Waste (CDW) Management. Fostering effective CDW management requires the use of advanced technologies that facilitate the efficient tracking of building elements. This, in turn, enables more streamlined and effective waste collection, separation, and redirection into circularity paths, including reuse, remanufacturing, repurposing, and recycling.

Sensor technologies, when combined with digital tools, offer the capability to plan waste routes and collections in real-time, based on demand [132]. An example of this combination is the Radio Frequency Identification (RFID) tags, which integrate sensors and identification technology through internet connectivity [13]. These RFID tags can be affixed to waste and recycling containers, facilitating the implementation of "Pay-as-you-throw" waste programmes in select cities, optimising municipal waste collection. These technologies provide real-time data storage, cloud processing, and seamless exchange of information between the cloud, waste collection vehicles, containers, recycling facilities, and secondary material retailers. This comprehensive tracking system monitors container content characteristics and conditions, managing routes and productivity to ensure safe and cost-efficient sorting, reuse, and recycling [13].

In the pursuit of efficient CDW management, the role of IoT and BCT cannot be understated, as they play a pivotal role in storing, recording, and sharing critical information about various materials and elements [133].

Moreover, digital marking of materials, combined with AI, enhances the effectiveness of recycling processes, while digital marketplaces and platforms create channels and market conditions that promote the use of reclaimed materials [132].

BIM also plays a crucial role in establishing circular waste management channels. This tool, through a central information approach, aggregates data from diverse sources, including documents, on-site investigations, and the potential for reusing various building elements. This, in turn, aids in the accurate identification of components with circular value for recovery and urban mining [143]. By streamlining processes and promoting CE practices, BIM simplifies interconnected issues in the waste management landscape.

In the face of the challenges that stakeholders encounter when striving for high-quality work, maintaining efficiency, and addressing crucial aspects such as certification and waste management promotion, digital technologies continue to evolve, persistently offering solutions to tackle these concerns.

17.3.3 Economic Value

Cost Analysis and Life Cycle Costing (LCC). Life Cycle Costing (LCC) is a methodology employed to calculate the comprehensive expenses incurred throughout a product or system's entire life cycle. This aids in informed decision-making during the product development process [144, 145, 146]. LCC analysis allows for the comparison of products or systems in terms of the estimated costs involved over the project's entire life cycle. It therefore helps promote the most cost-effective design and process alternatives to achieve closed loop building life cycles. LCC contributes to managing circular businesses, cost reduction, and the mitigation of environmental impacts [144].

Applying LCC within a CE framework involves regarding products as composite entities comprising components and parts with distinct and multiple use cycles. In this context, evaluating products within a CE perspective necessitates extending their lifespan, with a focus on design elements such as repair, reuse, upgradability, disassembly, and recycling. Consequently, value retention processes (VRPs) become central in extending product lifespans and should be integrated into the evaluation. This approach encompasses post-use processes, providing practical and actionable insights to all stakeholders involved and enabling alignment with LCA methodologies [145].

A review of the literature highlights the possibilities, advantages, and challenges of integrating BIM and LCC [144, 147, 148]. While tools for integrating LCC and

LCA within BIM are available, it is important to note that these tools predominantly focus on new construction projects and lack examples demonstrating the assessment of circularity strategies' implications in existing assets, such as material salvaging and recycling [144]. Still, BIM can serve as a valuable tool for assessing LCC within a CE model in new and existing construction.

BIM streamlines the integration and visualisation of project data, enhancing the precision of LCC assessments. By connecting cost data to specific building elements and components, it enables precise calculations throughout the life cycle. Furthermore, BIM's parametric modelling capabilities support iterative design processes, optimising both performance and cost aspects [148, 149]. It offers early-stage decision support by evaluating the life cycle costs of design options and material choices, thereby facilitating the adoption of CE strategies for optimised resource utilisation and waste reduction [144]. BIM, in this way, fosters collaboration among stakeholders, promoting knowledge sharing and effective communication. This collaborative environment ensures that LCC considerations are integrated throughout the project life cycle, thereby enhancing transparency and informed decision-making [147]. During the operational phase, BIM's integration with facility management systems facilitates ongoing LCC evaluation. By monitoring energy consumption, maintenance costs, and performance data, BIM supports well-informed decisions regarding retrofits and renovations costs implications, thereby enhancing a building's CE performance [144].

Several challenges arise when implementing LCC and BIM integration, including the absence of standardised LCC cost estimation methods, unstructured and non-standardised data formats, interoperability issues, consistent and interpretable data sets, limitations on stakeholders directly involved in the model, and the need to clearly define system boundaries [145, 147].

New Business Models. Circular business models (CBMs) represent an innovative approach to harnessing the latent economic value present in products by extending their utility through closed material loops within an economic system [116]. These models outline how organisations create, deliver, and capture value within these closed loops, which consist of both forward and reverse supply chains that reintegrate reclaimed products [135]. CBMs promote product longevity, product reuse, residual value extraction from by-products, and enhancing product design and manufacturing efficiency [150]. They pivot around core elements of value proposition, delivery, creation, and capture, with an ever-growing emphasis on sustainability and circularity [151].

CBMs extend beyond environmental concerns, focusing on maximising product lifecycles across the entire supply chain. They aim to transform unusable products into new sources of value within the same or other supply chains. Effective collaboration between policymakers and companies is pivotal in either facilitating or hindering the development of CBMs through regulatory norms [152]. Hence, collaboration with a network of stakeholders, including suppliers, is vital for the development of circular solutions. CBM innovation is a system-wide phenomenon that demands interaction among all stakeholders, encompassing both the core business network and external participants [153].

Nevertheless, businesses are often restrained by cost-centric models and existing partnerships that impede their engagement with circularity. A shift towards long-term value creation and consideration of non-economic benefits is imperative [151]. Current business modelling tools and methodologies often lack the requisite components for innovating CBMs comprehensively and disruptively. Embracing circularity requires maximising the value of products and materials, thereby reducing resource consumption and fostering positive societal and environmental outcomes. Incremental changes alone are inadequate; radical and transformative business models are indispensable to tackle prevailing challenges and usher in a CE.

A pivotal step is for companies to perceive their customers not as mere buyers but as users, thereby emphasising a shift from a product-centric approach to that of service provision. This transformation necessitates a redesign of value networks and associated business models to accommodate new players and evolving roles [153].

The core principles and components of CBMs can be drawn from the foundational principles of the CE. Numerous frameworks and definitions elucidate and characterise these components, including the ReSOLVE framework, circular value creation, normative prerequisites, and areas for integration [116]. Consequently, fundamental facets of CBMs encompass durability, renewability, reusability, repairability, upgradability, refurbishment, servitisation (e.g., product as a service like air conditioning), capacity sharing, and dematerialisation [152].

Digitalisation, driven by AI, IoT, big data, and online platforms, is revolutionising value chains across industries. These technologies can monitor and manage physical objects, generating extensive data on materials, products, and processes. By enabling optimised production systems and smarter products and services and creating a continuous information flow that mitigates market inefficiencies, digital tools can lead to reduced waste, longer product lifespans, and circular design. Thus, digitalisation fosters value creation and a more sustainable economy [154].

The commitment of managerial leadership is pivotal to the successful co-creation and co-capture of value [152]. CBMs thrive on a foundation of data and knowledge management. Different models require specific information at various stages of the value chain. In this regard, the use of digital tools can facilitate the adoption of CBM by:

- Sharing models (e.g., logistics, retail) rely on data like asset location and condition to connect users with what they need. Understanding user behaviour fuels personalised experiences.
- Product life extension models leverage data on product health and materials to optimise repair and reuse, keeping resources in circulation longer.
- Circular supply models depend on material composition and origin data to ensure transparency and efficient closed-loop systems. BCT plays a key role here.
- Resource recovery models (recycling, industrial symbiosis) require data on waste composition and reusability, along with knowledge about material life cycles, to transform waste into valuable secondary materials.

- Product service systems focus on providing access to services, not ownership. Data on product availability and condition, coupled with knowledge of user preferences, is crucial for smooth operation [154].

Effectively managing data and knowledge is essential for the success of diverse CBMs. It empowers them to operate efficiently and contribute to a more sustainable future. Each digital technology, through its combinatorial power and data processing capabilities, can address specific market failures that impede the scalability of circular activities. For example, combining online platforms, BCT, and AI can enable the creation of digital sourcing platforms that facilitate the exchange of products and materials at their optimal reuse potential [154].

Consequently, the implementation of CBMs necessitates a holistic perspective that spans all dimensions of value and encompasses numerous relationships along the value chain. Active engagement of stakeholders is imperative for value creation. Nonetheless, empirical evidence regarding the application of digital technologies for achieving CE goals remains limited. The transition to CBMs calls for ongoing monitoring, verification of achieved objectives, and prompt corrective measures. In this context, policymakers play a crucial role in steering the shift from a linear to a circular production model [152].

17.3.4 Social Value

Digital transformation stands as a widely recognised catalyst for economic and social progress. It serves as a potent instrument for unlocking the advantages of inclusive and sustainable growth, ultimately leading to enhanced societal well-being [13]. The advocacy for a digital CE in the construction and building industry brings forth numerous social advantages for both labourers and residents, contributing to the development of more inclusive and liveable communities. Digitalisation not only empowers consumers by involving them in product and service innovation but also enables companies to engage with their customers more effectively than ever before [153]. The integration of digital intelligence provides opportunities to disseminate knowledge, structure, ownership, and varying degrees of customisation, leading to more connected and enduring relationships with customers and end users [134].

Furthermore, by enabling digitalised planning, visualisation, and simulation of building and construction projects, professionals can enhance safety and comfort measures. Certain digital tools can also function as monitoring systems to ensure process quality and compliance with standards. The adoption of digital tools for circular construction necessitates a diverse range of skill sets, thereby creating new employment opportunities in the sector. However, this transformation calls for investment in training programmes to cultivate a skilled workforce capable of driving the transition towards a circular, sustainable built environment fortified with technological resilience.

Another critical dimension addressed by these tools is the challenge of access to affordable housing. By embracing circular design strategies that enable incremental construction, potential cost reductions can be realised. Additionally, the promotion of material health and the integration of principles to enhance air quality, passive techniques for thermal comfort, and energy efficiency needs can result in circular buildings that offer healthier living environments and comfortable spaces, positively impacting user well-being and overall quality of life.

17.4 Barriers and Critical Success Factors (CSF) for Digitalisation

17.4.1 Technical and Technological Challenges

Complexity of Buildings. The construction of buildings is an intricate and multifaceted process that involves the collaboration of various stakeholders throughout its different phases. Consequently, the complexity and fragmentation of the construction industry present a significant challenge for the successful integration of digital technologies [118]. To enhance the efficiency and effectiveness of construction projects through digitalisation, it is imperative that all stakeholders embrace digital transformation strategies for their internal and collaborative processes.

A critical issue highlighted by Berlak et al. [155] is the prevalence of imbalances within the industry. This imbalance arises when one company invests in digital technologies, while another remains resistant to such investments. The resistance of the latter inhibits the overall progress of digitalisation within the construction sector, irrespective of the efforts made by individual companies. This dynamic sheds light on why the level of digital adoption remains relatively low within the construction industry [155].

Lack of Integration and Interoperability Among Digital Tools. Numerous digital tools play a pivotal role in streamlining the construction process. However, a significant challenge arises from the lack of compatibility between these tools and the inadequate integration of hardware, software, and data channels. This integration shortfall hampers the full utilisation of digitalisation for specific construction purposes and inhibits its seamless application throughout the entire construction life cycle. Consequently, these tools often function independently, diminishing the overall effectiveness of digitisation [156]. This challenge of integration is further underscored by the findings of Yu et al. [101] and Zhang et al. [157], who highlighted the pressing need for seamless interoperability between digital tools to ensure uninterrupted operations. According to Yu et al. [101], the current level of technological integration falls short of facilitating the effective integration of a CE within the construction industry.

Lack of Standardisation. The digitalisation of the construction industry presents a significant challenge in the realm of standardisation for digital tools and devices.

This challenge stems from the fact that various digital transformation devices possess diverse requirements and constraints relating to energy consumption, data processing, security, and computational capabilities. Standardisation plays a pivotal role in harmonising these discrepancies in requirements and, in turn, streamlining the digitalisation process. However, the rapid pace of digital transformation often hinders the development of these much-needed standards [158].

As indicated by Olanipekun and Sutrisna [156], the absence of standardised practices restricts the effective implementation of digital tools within the construction sector. Without universally accepted guidelines for technology integration, companies face a reduced array of options when selecting digital tools for their ecosystem. This dearth of standardisation also poses a challenge when it comes to assessing the overall effectiveness of digitalisation efforts.

Zhang et al. [157] highlighted China's noteworthy contributions to the development of ISO standards for BIM. However, Olanipekun and Sutrisna [156] argued that the ISO guidelines for construction digital tools tend to overemphasise standardisation, neglecting the need for specific standards tailored to technologies widely employed across multiple industries. A prime example is 3D printing, which finds applications not only in construction but also in the manufacturing sector. Consequently, there is a need for a more nuanced approach to standardisation that accommodates the diverse needs of these multifaceted technologies.

Data Fragmentation and Insecurity. A large number of stakeholders throughout the construction value chain also creates the challenge of data fragmentation and its management. In a study of Bon-Gang et al. [159], the experts from Singapore construction companies identified data and information sharing as a critical challenge for effective smart technologies integration. They stated that this issue has a direct effect on the misuse and loss of data, misunderstanding within the team and inefficiencies within the project. Another study of Zhang et al. [157] revealed that data fragmentation is the most crucial challenge among technological barriers. The data fragmentation results in limitations in data sharing and negatively affect the digitisation of construction. This in turn leads to inefficient data sharing and data gap, miscommunication and conflicts, problematic information exchange between different stages, and data security.

With construction and built environment digitalisation processes, another crucial aspect that must be addressed is cyber-security. This broad and pressing topic presents several critical challenges. The challenge of data security is discussed in a study of Jemal et al. [130]. With the digitalisation of construction industry, a complex cyber network is created, that is prone to cyber-attacks. Nevertheless, the importance of data security has been neglected and led to significant threats of cyberattack. Therefore, the digitisation requires a proper cyber security infrastructure for construction companies. To mitigate these risks, various technologies can be leveraged. Encryption protocols, distributed database technology, cloud security, and BCT are instrumental in safeguarding key BIM components such as data ownership, data sharing, model federation, information workflows, data security, network security, and system security [160].

17.4.2 Resource Challenges

High Implementation Cost. Cost and investment capabilities are pivotal considerations for leaders in the construction industry when contemplating digital transformation [161]. Research underscores that the digitalisation of the construction sector incurs a substantial implementation cost, which is recognised as the most significant economic challenge faced by companies [157]. This high implementation cost is primarily attributed to the expensive equipment and extensive data storage requirements [158].

Lack of Expertise. The process of digitising the construction industry demands a proficient workforce equipped with cutting-edge digital skills. Unfortunately, a notable shortfall of digital technology experts in the construction sector has been documented in recent studies [162, 163]. The successful digital transformation of the construction field necessitates professionals specialising in machine learning, AI, data analytics, as well as hardware and software engineering [157]. This scarcity of skilled expertise has adverse repercussions on data processing and hinders the overall progress of digitalisation within the construction industry.

17.4.3 Cultural Challenges

It is essential to acknowledge that realising the full potential of digitalisation in promoting circular buildings necessitates more than just technological advancements. Institutional, behavioural, and socio-economic system changes are imperative to affect a transition towards a circular and digital economy. Collaborative efforts among various stakeholders, including policymakers, industry professionals, and consumers, are indispensable in creating a supportive environment that encourages circular building practices and maximises the benefits of digitalisation. In the construction industry, stakeholders often exhibit resistance to embracing technological advancements and tend to rely on existing tools and conventional practices. This resistance has a detrimental impact on the digitisation of the construction sector [101]. Bon-Gang et al. [159] identified the reluctance to adopt new technologies as a primary organisational challenge faced by construction companies. The resistance among stakeholders can be attributed to several factors, including a lack of expertise in modern digital technologies and their potential benefits, the presence of high risks and penalties associated with unsuccessful project completion, as well as deeply entrenched organisational cultures [101, 163]. Furthermore, this hesitation to adopt digital solutions is not confined to a specific level of the organisation. This reluctance has been also observed among both employees and top management [161]. Adding to the complexity of this issue, it has been also found that there is often insufficient support from company leadership, exacerbating employees' resistance to the adoption of digital technologies [162].

17.4.4 Critical Success Factors (CSF)

Given the barriers and challenges associated with the extensive integration of digitalisation within the construction and building sector, several critical success factors have emerged as pivotal in overcoming these hurdles, as follows:

Collaboration and Communication. Effective collaboration is a crucial element for successfully addressing the inherent complexities of the construction industry. Collaboration and communication are essential for fostering a shared vision and common interests among stakeholders and encouraging the collaborative implementation of digital technologies. This cooperative effort also serves to mitigate the challenges associated with data sharing, system integration, and standardisation [156, 159].

Professional Trainings. In today's rapidly evolving landscape, professional training in digital technologies is of paramount importance for the construction industry. This training not only equips the workforce with essential skills but also significantly amplifies the effectiveness of digitisation efforts within the sector. By elevating the understanding of digital transformation and its associated advantages, we empower individuals to become proficient experts and simultaneously diminish the barriers to embracing technological change. This transformative approach is pivotal in driving progress within the construction industry [159].

Government Incentives. In addition to organisations, it is imperative for governments to play an active role in promoting shared values and fostering digital literacy across the entire value chain. Furthermore, government incentives are pivotal in aiding companies to surmount the elevated integration costs associated with digitisation. With government support, businesses can harness their investment capabilities for professional training and preliminary testing. A noteworthy example of the effectiveness of government incentives can be found in Singapore's construction industry, which boasts a sophisticated BIM integration compared to many other countries [159].

17.5 Discussion and Conclusions

The technologies advanced by Industry 4.0 hold immense potential for bolstering CE models within the built environment. This study sheds light on the pivotal roles played by 14 digital technologies in supporting the dual transition towards sustainability and digitalisation. The analysis shows the numerous benefits of implementing these technologies to support an efficient and effective application of multiple circularity strategies by enabling real-time monitoring and control of production processes, enhance supply chain management, facilitate material reuse and recycling, and extend the lifespan of products [29]. Ultimately, these measures reduce the environmental impact of economic activities, among other environmental, economic, and social benefits.

It is worth noting that the digital toolbox extends beyond the technologies discussed in this study. Among the additional digital tools and technologies with potential applications in the construction and building sector are:

- Robotics and Automation: These technologies enhance the efficiency, precision, and productivity of manufacturing processes. They also enable the implementation of flexible and agile manufacturing systems, allowing for product customisation and adaptation, thus reducing the need for new production [29]. Additionally, automated processes reduce errors and minimise waste generation.
- Cybersecurity: Cybersecurity measures are vital for protecting systems against unauthorised access and cyber threats. This is achieved through encryption, authentication protocols, regular system updates, and employee training in cybersecurity best practices.

Among the various technologies explored in this study, BIM stands out as the most prevalent technology in the construction sector. Nevertheless, BIM exhibits significant interactions with most of the other technologies, resulting in increased efficiency, effectiveness, and objectivity.

The analysis of diverse digital tools and technologies applicable to the construction sector reveals that their successful implementation necessitates collaboration among different stakeholders, including manufacturers, suppliers, and consumers [164]. It also demands a holistic approach that takes into account the entire life cycle of projects and associated products. This is because these digital technologies exhibit varying levels of interdependence throughout the life cycle of buildings, interacting with or depending on each other during the execution of specific tasks [118] which restricts their standalone use.

It is vital to acknowledge that, despite the numerous advantages and benefits these technologies offer to the environment, economy, and society, their improper application and mismanagement can introduce several threats at multiple levels. For instance, the increased connectivity of Industry 4.0 technologies may give rise to potential environmental risks that must be addressed to ensure sustainable CE practices. Some of these risks encompass increased energy consumption if the use of connected devices is not adequately managed, potentially leading to elevated greenhouse gas emissions and contributing to climate change [29]. Another risk involves the generation of electronic waste (e-waste), posing environmental hazards due to the presence of hazardous materials [29]. Furthermore, the heightened connectivity and data sharing in Industry 4.0 systems make them vulnerable to cybersecurity threats, which, if breached, can have environmental consequences, such as unauthorised access to control systems resulting in accidents or disruptions [29].

To mitigate these environmental risks and foster sustainable CE practices, several measures can be implemented as outlined by Laskurain-Iturbe et al. [29]:

- Enhancing energy efficiency practices and technologies to minimise the energy consumption of Industry 4.0 systems. This may involve optimising algorithms, utilising energy-efficient hardware, and adopting renewable energy sources.
- Establishing effective e-waste management systems that promote recycling, refurbishment, and responsible disposal of electronic devices. This may include implementing collection programmes, designing products for easy disassembly and recycling, and promoting the use of recycled materials in manufacturing.
- Implementing robust cybersecurity measures to safeguard Industry 4.0 systems against unauthorised access and cyber threats. This can encompass encryption, authentication protocols, regular system updates, and employee training on cybersecurity best practices.
- Conducting life cycle assessments of Industry 4.0 technologies and systems to identify and mitigate potential environmental impacts. This can help optimise resource utilisation, reduce waste generation, and identify opportunities for improvement throughout the product life cycle.
- Developing and enforcing regulations and standards that promote sustainable practices in the adoption and implementation of Industry 4.0 technologies. These regulations may include requirements for energy efficiency, e-waste management, and cybersecurity measures.

By addressing these environmental risks and implementing these measures, the integration of Industry 4.0 technologies into CE practices can be achieved sustainably and with a responsible approach.

Another essential challenge hindering the successful implementation of digital technologies in CE models is the absence of a well-defined regulatory framework that both upholds CE principles and promotes sustainable practices of digital technologies and tools. This obstacle is exacerbated by the substantial requirement for investments in novel technologies and infrastructure. Additionally, fostering a significant shift in mindset and culture is imperative, a task that proves challenging without robust leadership and active stakeholder engagement [164].

Despite these challenges, the thoughtful combination of Industry 4.0 and the CE in construction offers several benefits, including:

- Improved Resource Efficiency: Enhancing resource efficiency [6, 29, 165].
- Enhanced Sustainable Business Performance: Reducing demand for natural resources and extending product life cycles [165].
- Positive Environmental Impact: Minimising waste generation and promoting reuse and recycling of materials, resulting in a reduced environmental footprint [165].
- Collaboration and Transparency: Encouraging increased collaboration and transparency [165].
- Competitive Advantage: Offering a distinctive competitive advantage for companies [165].
- Improved Operational Performance: Increasing efficiency, productivity, and quality in operations [165].

All of these factors contribute to improved economic performance for companies, driven by synergistic effects between the CE and digitalisation, leading to increased resource efficiency, cost savings, and enhanced competitiveness [165]. Moreover, this approach also has the potential to reduce the demand for natural resources, decrease environmental impact, create local employment opportunities, and contribute to economic development in the region [165].

Nonetheless, further research and effort are required to:

- Identify the primary drivers and obstacles in the adoption of digital tools and technologies for promoting circularity practices in the construction sector.
- Explore innovative business models that facilitate the transition to a digital circular economy.
- Investigate the role of digital technologies and platforms, not only those addressed in this study but also potential ones.
- Assess the environmental and economic impact of digitalisation on circularity practices to provide compelling evidence of their benefits and guide decision-making.
- Evaluate the effectiveness of existing policies and regulations in advancing the shift towards a digital CE and pinpoint areas requiring improvement.
- Develop strategies to encourage collaboration and engagement among diverse stakeholders, including businesses, governments, and consumers, to drive the adoption of digitalised circular practices [165].

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Chapter 18
Material and Building Passports as Supportive Tools for Enhancing Circularity in Buildings

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Abstract The twin transition driven by European agendas emphasises the dual benefits of integrating digital technologies with green sustainability concepts. In the built environment and construction sector, this integration is exemplified by leveraging digitalisation to enhance circularity in construction processes. This chapter explores this synergy by focusing on the development and application of Material and Building Passports (MPs and BPs). It discusses how these passports are digitally utilised to optimise circularity aspects of buildings and construction materials. The chapter

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delineates the evolution of MPs and BPs, clarifying their various definitions, variants, and potential applications to support the sector's twin transition. Additionally, it examines numerous initiatives and pilot projects aimed at defining the passports, including their requirements and conditions, and the standardisation efforts to ensure their widespread adoption through a unified content structure. The roles of MPs and BPs across different lifecycle stages are elaborated, with a particular emphasis on the enhanced functionalities enabled by Building Information Modelling (BIM). Moreover, the chapter identifies several barriers impeding the full adoption of these passports, such as legislative and standardisation challenges, information security concerns, lack of collaboration, and issues with information accessibility and sharing. It concludes by suggesting future research directions to further refine the passports for optimised use by construction industry stakeholders.

18.1 Introduction

18.1.1 Motivation

Current trends reveal an alarming pattern of resource consumption surpassing sustainable limits. The European Commission, in its new European Circular Economy Action Plan (ECEAP) (2020) foresee a potential doubling of mineral, biomass, metal, and fossil fuel consumption in the next four decades, coupled with a 70% surge in annual waste generation by 2050. The recent energy crisis sparked by Russia's war in Ukraine underscores the imperative for European countries to establish robust independence from external resources, emphasising the need to harness internal resources to create a more sustainable system [60]. In response to this challenge, the Circular economy (CE) emerges as a pivotal solution for resource preservation [85]. This approach focuses on minimising both resource consumption and waste generation, thereby mitigating environmental impact of industries.

At the core of the European Union's strategies for the forthcoming years is the ambitious goal of achieving total decarbonisation by 2050 included in The European Green Deal [40]. According to the EU report Closing the Loop—An EU Action Plan for the Circular Economy [39], to realise this objective, one of the key strategies for CE involves maximising recycling and renovation rates. By doing so, the aim is to diminish reliance on primary resources [9]. The ECEAP (2020) takes a comprehensive approach, intending to transform consumption patterns and prevent waste generation. It emphasises the creation of a well-functioning internal market for high quality secondary raw materials, reinforcing reusing and recycling efforts. In this sense, Europe is committed to leading the global transition to a CE, offering influence, expertise and financial resources to achieve the 2030 Sustainable Development Goals in accordance with Agenda 2030.

18.1.2 Circular Economy in the Construction Sector

The construction sector, a fundamental pillar of the global economy, is one of the largest energy consumers and contributors to environmental degradation and resource consumption. It accounts for 37% of global energy-related CO_2 emissions [35], 40–50% of raw material consumption worldwide and over 35% of all waste generated in the EU, as reported by Eurostats 2016 in the EU report for a cleaner and more competitive Europe (2020). Given this significant impact, there is a pressing need to address energy and resource consumption by rethinking building related-practices and operations. This includes accelerating building renovations and extending the value of construction materials and components, aligning with CE principles.

Current EU renovation rates do not exceed 0.2% for energy renovations on average, while EU targets outlined in the report for A Renovation Wave for Europe (2020) aim to double these figures by 2030, and foster deep renovations (Sibileau et al. 2021). One of the recognised CE strategies to that aim is urban mining, which according to [84], involves the exploration and observation of materials "in the infrastructure, buildings, and movables" (p. 667), as well as mining of waste, already included in the classic concept of recycling. In words of Munaro and Tavares [102], "the concept of urban mining (…) are closely related to the CE as an effort to reduce resource consumption while keeping goods and products as long as possible in the economic cycle" (p. 776).

Further advancing CE in construction involves the adoption of flexible building designs to accommodate future modifications. This is facilitated by developing tools and methods that support circular building design, such as design for disassembly and design for adaptability. These approaches enable efficient material tracking along value chains, optimising resource use and supporting circular pathways like recycling, reuse, refurbishment, and remanufacturing. Essential to these efforts are Material and Building Passports (MPs and BPs), which serve as critical tools guiding the management of materials and buildings throughout their life cycles.

18.1.3 Digital Technologies for the Construction Sector

Digitalisation in construction is one of the major goals in the EU digitalisation action plan. Digital technologies have been widely investigated as important enablers to foster efficient construction-related processes and operations. Tools such as big data, artificial intelligence (AI), blockchain and the Internet of things (IoT), among others, are witnessing ongoing efforts to be employed in serving construction processes with a focus on the implementation of CE principles [26]. A special focus is given to Building Information Modelling (BIM) for its capacity to enhance multiple aspects of building sustainability, circularity and management during the entire lifecycle. BIM plays key role in the design phase by appraising the best alternatives, in the use phase by planning effective maintenance, and in the end-of-life phase by managing deconstruction and material recovery and reuse. Moreover, BIM is often used in collaboration with other digital tools to synergise their capabilities for enhanced decision-making. A prominent example is the synergy between BIM and MPs, which brings benefits in tracking materials and providing information on how they can be used most effectively in terms of sustainability and circularity. The role of digital technologies transcends the focus on optimising the technical aspects of construction to also promote process aspects, including ensuring the connectivity of value chain stakeholders by providing access to information through centralised systems. The multiple capabilities of digital technologies provide the construction sector with new opportunities to shift from traditional business models to circular business models. One such model is the Product-service system (PSS), which has been acknowledged as an important business model innovation for achieving a digitalisation-enabled CE [26].

18.1.4 Twin Transition Through Digitalised Circularity

Circularity can significantly enhance the quality of products in terms of functionality, safety, efficiency, affordability, and durability, particularly through designing for reuse, repair and recycling. Concurrently, the ECEAP (2020) states that digitalisation is intended to "bring about a better quality of life, innovative jobs and upgraded knowledge and skills" (p. 2). The twin transition to a green and digital built environment can be exemplified through synergising CE principles with digital technologies, thereby amplifying the individual impacts of each concept.

Digital tools hold significant potential to support CE in Architecture, Engineering and Construction (AEC) in multiple ways, such as resource assessment and the prediction and optimisation of upcoming waste and recycling masses [88]. This is achieved by leveraging digitalisation capabilities to foster efficient use of circularity concepts by enabling real-time monitoring, enhanced management, proactive planning and scenario simulation and comparison for effective decision-making.

The chapter sheds light on one example of digitalisation and CE synergies through the use of MPs and BPs—CE-promoted concepts—within a digital environment. This collaboration enhances circularity in building processes and materials, providing multiple benefits and showcasing the potential of integrated approaches in driving sustainable practices in the construction sector.

18.1.5 Study Scope and Structure

MPs and BPs provide high potential in the transition to a CE and digitalisation. This includes raising awareness of building performance among all involved stakeholders and end users, digitally storing large amounts of information, serving as consultation tools for stakeholders before any lifecycle intervention or renovation action, aiding in energy management, recording building operation activities and material data, and providing a common language for all stakeholders through standardisation of data and indicators.

The role and importance of MPs and BPs have been widely recognised in recent literature on digital tools and technologies enabling circularity in buildings. Examples include review studies on digital tools such as those by [20, 23, 122], and [72], which underscore the role of passports in driving digital transformation. Conversely, other studies highlight the passports' role in supporting circularity concepts and the implementation of lifecycle thinking, such as those by Benachio et al. [52], Luscuere [94], and Liu & Ramakrishna [91].

Given this context, the need for passports is easily justified by their role in supporting the twin transition to a circular and digital built environment. This chapter sheds light on the roles and benefits of passports. Section 2 presents the historical background on the development of passports and their variants, including different definitions and terminological variations introduced by literature studies, along with standardisation and regulatory initiatives. Section 3 provides an overview of passport applications at various scales in the built environment, including composition requirements and methods for data collection. Section 4 offers insights into the four main roles of passports in supporting circularity in buildings and material value chains. Section 5 explores examples of synergies between passports and BIM applications. Section 6 details examples of passport applications and commercialisation efforts. Section 7 highlights the main barriers and challenges to the uptake of passports and the leveraging of their full potential. Finally, Sect. 8 discusses and concludes with avenues for further development in this research field.

18.2 Passports Development and Variations

18.2.1 Historical Background and Passports Evolution

The term Building Passport have existed in Europe for decades. Its origin dates back nearly 30 years, to the mid-90 s, when the "Building Passport" appeared in Germany [118] and the "Det digitaleenergimærke" arose in Denmark [41]. Despite these old roots, there is no universally agreed-upon definition of the tool, and different approaches—from energy performance to technological data—have coexisted across various European regions [118]. What seems to be unanimous is that BPs are tools that provide relevant information on buildings to various stakeholders in the building sector, from users to technicians, financiers, or insurers. However, the content and format differ among the various initiatives.

In 2002, Energy Performance Certificates (EPCs) were introduced through the first Energy Performance of Buildings Directive (EPBD) -Directive 22/91/EC-, with the aim of making the assessment of the energy performance of European buildings more transparent [50]. However, its update, Directive 2010/31/EU ("Energy Performance of Buildings Directive" or "EPBD"), became the main legal instrument in the European Union to provide binding standards. In 2019, the Commission issued two recommendations on building renovation and on building modernisation based on the 2018 EPBD revision to facilitate the Directive's by member states. Furthermore, the EPBD expanded the scope of technical building systems subject to mandatory regular inspections or alternative measures based on automation and control, or electronic monitoring in certain non-residential buildings. The "Fit for 55" Package mandates that all new buildings should be transformed into zero-emission buildings by 2030, and existing buildings should be transformed into zero-emission buildings by 2050. The European parliament formally adopted the laws on April 18th 2023.

This event was very relevant for the development of BPs, since some authors consider that EPCs were the predecessors of a BP typology: The Building Renovation Passport (BRP) [118]. What differentiates them is that, in addition to providing a diagnosis of the building with a focus on energy performance, BRPs go one step further, detailing the measures needed to transform the assessed building into a zero-emission building by 2050 [46].

Unlike the BP, which was relegated to national or regional initiatives, the BRP has been included in European legislation due to its potential to trigger building renovation, which is a European priority. In 2021, through the first version of the proposal for the EPBD recast, the BRP was given an officially agreed-upon definition—slightly modified in the 2023 amended version of the Directive—and an agreed common scheme will be developed to be applicable to all EU Member States in the near future.

The recent development around the BRP contrasts with the fact that the first scientific article addressing the BRP dates back to 1982 [36]. However, no significant developments were identified until 2016, when the Buildings Performance Institute Europe (BPIE) proposed a non-official definition of the tool [50].

In parallel, in recent years, another type of similar passports, known as the Material Passport, has been developed. MPs have the objective of gathering and storing data on the materials that make up buildings, providing valuable information to analyse buildings' circularity and facilitate decision-making on recovery, recycling and reuse [68]. The concept of MPs traces back to earlier discussions on similar concepts; notably, [108] referred to a similar idea as the "Product Passport". However, [11] assert that the concept first appeared in Germany in 1997. The term "Material Passport" was formally introduced by McDonough and Braungart (2003) who envisioned it as a tracking code with molecular markers. Currently, this concept is being introduced into European legislation as the Digital Product Passport (DPP), whose definition and content are detailed in the proposal for a new Ecodesign for Sustainable Products Regulation (ESPR), published in 2022 [45. While the DPP does not focus specifically on building materials specifically, it includes them.

As stated by [18], MPs can stand alone or be an integral part of a multifunctional system, such BPs. In this regard, the European Commission is developing a new tool—the European Digital Building Logbook (DBL)— that will serve as a repository for all data, documents and certificates related to buildings, such as EPCs, BRPs and MPs-DPPs.

Despite the fact that the DBL has often been considered one of the two components that make up the BRP, it was introduced as an autonomous tool at the European scale in the Renovation Wave strategy in 2020 [55]. The first definition of the DBL was provided in the initial proposal for the EPBD recast in 2021.

18.2.2 Definitions and Terminologies for Passport Variants

Many formal and informal definitions and terminologies have been proposed for the passports, resulting in different variants. However, while the term "Material Passport" is the most commonly used, "Product Passport" is technically more accurate. This is because the most valuable passports encompass a broader range of information beyond basic material data (such as type, geometric dimensions, mass, or volume), including lifecycle and circularity-related product information, such as reuse and recycling potentials [123]. This aligns with the common goal of the passports, which is to provide information on the composition of components and materials, the origin (whether from primary or secondary source), reuse and recycling value, and other circularity features (e.g., disassembly guidelines, hazardous content). The passports enable dynamic accessibility to this information by relevant stakeholders throughout an element's lifecycle, providing a history timeline and future pathways. Some studies offer variations in definitions to highlight specific purposes, such as "Recycling Passports" focusing on the recycling phase and related aspects [66], or "Building Renovation Passports" concentrating on renovation requirements and relevant information.

At the building scale, multiple passport variants have emerged to highlight building cases at specific lifecycle stages or specific condition to help manage building operation and other process. Among those are:

- Digital Building Logbook: A comprehensive dataset containing all relevant building data, including data related to energy performance such as energy performance certificates, renovation passports and smart readiness indicators, as well as data related to the lifecycle GWP, which facilitates informed decision making and information sharing within the construction sector, and among building owners and occupants, financial institutions and public bodies (Directive (EU) 2024/1275).
- Building passport): This passport collects the most important performance characteristics and technological data of a building as well as various building-related documents (plans, calculations, lists and declarations of materials and products used, operating and maintenance guidelines, etc. [118].
- Building renovation passport: The term first used by Eichstadt [36], referring to existing buildings. Like the BP, it consists of the DBL to store the data, and a roadmap to guide end users through a step-by-step retrofit process.

- Roadmap for Building Renovation: A guiding document tailored to particular cases, fitting user needs and intervention possibilities at specific points in the lifecycle [50].

At the material scale, various definitions and types of passports address multiple aspects to enhance product traceability and integrate the CE philosophy into supply chain management [123]. MPs can be manual records of materials, including their impacts and supply chains, or they can be digitally represented on an online platform linked to a Structured Query Language (SQL) database. SQL is a relational database that organises structured tables with highly detailed information, enabling the creation, storage, updating and retrieval of data. Some of the definitions of passport variants in materials are:

- Material passport: A qualitative and quantitative documentation of the material composition of a building, highlighting embedded materials, their recycling potential, and environmental impact [7].
- Product Passport: A MP with a digital interface that provides a certified identity of a single product by accessing product-linked life cycle registrations. It offers insights into the sustainability and circularity characteristics, circularity value estimation, and circularity opportunities for both the product and its components [123].
- Digital Product Passport: Defined by the EC as a digital data set accessible through a data carrier to electronically register, process and share product-related information among supply chain businesses, authorities and consumers. The DPP would provide information on the origin, composition, and repair and disassembly possibilities of a product, including how the various components can be recycled or disposed of at end of life. This information can enable the upscaling of CE strategies such as predictive maintenance, repair, remanufacturing and recycling. It also informs consumers and other stakeholders of the sustainability characteristics of products and materials [60].
- Nutrient Passport: Introduced by [62], this passport highlights the importance of reclaimed materials as nutrients for other industrial processes.
- Recycling Passport: A detailed yet straightforward information source for professional dismantling and disposal. It provides essential data on material composition, appliance weight, accessibility, and hazardous substances. Spanning four to five pages, it focuses on product identification, details the removal of device cover plates, and includes supportive illustrations [66].
- Resource Passport: a standardised format that records data about a product or material, such as composition, origin, volume, and quality. It serves as a centralised information system, giving each product or material a unique identity, similar to an ID card, and enabling easy comparison and use across value chains [30].

Despite the lack of standardisation and agreed-upon definition, these passports play a crucial role in advancing the CE by providing detailed information on material composition, recycling potential, and environmental impact. They facilitate better decision-making across the supply chain, promote sustainability, and enable efficient resource management. As the industry continues to evolve, developing a standardised framework for these passports will be essential to ensure consistency, interoperability, and widespread adoption, ultimately enhancing the transparency and circularity of material flows in the built environment.

18.2.3 Regulations and Standards

The role of standards in harmonising technical requirements and facilitating the adoption of MPs and BPs has been significant. These standards are crucial for their recognition and uptake across the industry and value chain stakeholders. The recast of the EPBD had a strong effect on harmonising the key building energy metrics, culminating in the development of practical BPs.

The new Standard EN 17,680 (European Standard: Final Draft: Sustainability of construction works—Evaluation of the potential for sustainable refurbishment of buildings FprEN 17,680) stands as a benchmark for circularity in the building sector. It introduces a system for the sustainability assessment of buildings through a lifecycle approach. The adoption of EN 17,680 serves as a new guide for evaluating existing buildings and outlining steps for circular refurbishment processes. Its classification system is designed to aid in identifying subsequent actions in renovation projects, thus providing critical data for BPs. However, this standard sometimes overlooks local climate conditions and traditional architectural styles. For instance, the lack of an air conditioning system in a building is classified as a Class 3 indicator, denoting a "Catastrophic and Action Needed" status. Such generalisations indicate that while the standard is promising, it requires refinement to ensure it is both realistic and applicable in diverse contexts.

In parallel, MPs are addressed under ISO 37 101 (Sustainable development in communities—Management system for sustainable development—Requirements with guidance for use), which aims to evaluate performance. Yet, this standard falls short of providing a clear metric for the indexing of materials, which remains a critical gap for effective implementation.

Regarding regulatory terminology within the EU, the term "Product Passport" has become standard. The Ecodesign for Sustainable Products Regulation (ESPR) introduces the Digital Product Passport (DPP) as a pivotal tool for enhancing the traceability of products and their components. Despite its potential, the DPP primarily targets products rather than building materials, failing to fully address the intricacies of material indexing within the construction sector. This distinction underscores the need for ongoing refinement in regulations to ensure they effectively encompass the specific needs and complexities of building materials and sustainability assessments.

18.3 Application Scope and Requirements

18.3.1 Application Scales

The passports can be used to promote circularity at different scales, from materials through individual buildings to urban clusters and cities. Their application on a larger urban scale can support the estimation of current stock of certain materials important to circularity, such as steel, and facilitate their urban mining. The smart city initiative follows this approach in a reversed way, progressing from regional level to the building scale.

MPs are important tools to support circularity practices in all stages of a building's lifecycle. During the design phase, passports guarantee that all materials and components in a building are designed for easy reuse, recovery and repair in the future. This helps conceptualise buildings as material banks, optimising the design while minimising the use of primary resources. By ensuring that all materials and components are designed for disassembly, a waste-free CE can be achieved. The novelty of MPs at this stage lies in providing precise determination of embedded materials, which helps optimise the design. In the operation phase, passports serve as key tools for efficient maintenance and repair. They provide detailed information on material composition and condition, allowing for proactive management and extending the lifespan of building components. At the end-of-life phase, passports offer circular pathways for environmentally-sound alternatives through reuse, upcycle and recover. They promote the most advantageous circularity options, ensuring that materials are effectively repurposed and waste is reduced.

Ideally, passports should be prepared and used before the construction phase. In this case, they serve to create specific scenarios for informed decision-making strategies for data management and governance. However, developing passports for existing buildings using other digital tools like scanning and technologies and plan analysis can greatly benefit stakeholders by aiding maintenance decisions and understanding the current quality of specific materials. This is also important for renovation projects by evaluating and comparing scenarios.

18.3.2 Outlines and Structure

Almost every passport relies on a digital representation of the physical composition and technical characteristics of an object. Although there is a wide variety of MP variants with multiple characteristics and types of information, the most frequent contents include quality conditions, service history, maintenance guidelines, safety recommendations, recycling potential and guidelines, object value, environmental performance indicators, Environmental Product Declarations (EPDs), and energy certificates [123]. Other circularity features and indicators may also be incorporated, although this is not commonly adopted by existing studies.

Given the large number of BPs worldwide, each with its own structure, presenting a precise outline and structure is challenging. However, there is growing interest in creating a common EU-wide BRP. In this regard, the BPIE [50] proposed a common structure applicable throughout the EU, which has been widely accepted in the literature. The BRP has usually been considered to be made up of two parts: a data repository or DBL and a renovation roadmap, which details all the steps needed to achieve the final goal, based on the data stored in the DBL.

Currently, efforts are underway to define a European DBL model, aiming to specify the indicators or data fields that the document must include. Although there is still no consensus on these indicators, the categories that should be included are becoming clearer.

18.3.3 Data Sources and Data Acquisition Methods

There are numerous databases that provide valuable information to feed BPs creation. Among these are national cadastres and land registries, as well as EPC registries. However, in some countries, different sources exist at the national and/or regional level, making it difficult to create a comprehensive picture of the situation across Europe. Furthermore, although there are databases at the European scale, such as those included in the Building Stock Observatory (BSO), they host very scarce data.

To collect information that is not stored or accessible through existing databases, new data sources have been identified in the literature. These include the use of new technologies for data acquisition, such as 3D scanning and smart monitoring, and the use of upcoming EU tools to support circularity and energy efficiency, such as the Level(s) framework or the Smart Readiness Indicator (SRI). These tools are expected to generate valuable data on the building stock [56].

Defining the exact material volume and composition in an existing building to build its MPs can be a challenging procedure due to the lack of existing data. This challenge is amplified by the wide range of data required for each material, the involvement of various stakeholders in the data collection process, and the need to keep this information constantly updated throughout the building's life cycle [102]. Various methods can be used to obtain the required data, such as using of Ground Penetrating Radar (GPR) to define materials composition [67]. GPR sends and receives electromagnetic waves, illustrating the waves' energy. Through this procedure, the material densities collected can be compared with material inventories, however, this method contains a degree of uncertainty.

When the MP aims to facilitate the demolition of a building and waste management, techniques like coupling Geographic Information System (GIS) with street photographs to define cladding materials and roof type can be found in the literature [83]. In another study, a building's material identification was conducted via a Demolition Acquisition (DA) and an Urban Mining Assessment (UMA) [70]. DA is a survey conducted during the pre-demolition waste audit, during which data is collected through visual assessment, while additional chemical analyses can also be conducted. These methods can be combined with other invasive techniques to acquire a more precise view of the elements' stratification and the materials' composition if the building is about to be demolished.

A very useful framework has been developed for existing social housing stocks, where data sources have been defined for each data category, along with all the involved stakeholders [25]. In particular, for the general building information, public records can be used, while general information regarding products can be retrieved from third-party websites. General product properties can be defined by scanning techniques used by site inspectors, while product properties regarding hazardous materials, safety and environmental issues can be defined using drone and satellite images, along with data retrieved by waste repositories. All the collected data analysed by safety inspectors, and the operational condition of the products can also be retrieved from housing images. Finally, images and scanning technologies can be used by engineers and reuse companies to determine the end-of-life aspects.

18.3.4 Inventory Supply Chain and Data Management Tools for Passports

The characteristics of inventory supply chains in the construction industry necessitate a variety of information and collaboration system requirements, including affordability and system adaptability. Construction inventory supply chains are distinguished by the participation of numerous businesses from a wide range of crafts [74]. Therefore, coordination and transparency are necessary for information sharing and system integration [112]. Due to the dynamic nature of construction supply chains and the frequent changes in organisational structure and project teams, it is challenging for project participants to work together long enough to develop sufficient trust and openly share knowledge. To achieve high recycling rates in the building sector, it is crucial to gather comprehensive information regarding the material composition of buildings. Since buildings are typically unique projects tailored to specific factors such as location, climate, orientation, and available technologies, understanding their material composition is essential [69]. Therefore, there is a necessity for new inventory supply chain methods and tools to establish a secondary raw materials registry that catalogs the materials integrated into the building stock. Early design stages are critical for determining the future recycling potential of buildings because decisions on material composition are made during this phase. To enhance the recycling potential of buildings, planners require innovative design-oriented tools and methodologies. The primary challenge hindering the assessment of recycling potential is the absence of methods to visualise the material composition and evaluate the recyclability of buildings.

Numerous initiatives are being undertaken in the manufacturing sector to develop strategies, technologies, and tools to facilitate communication and collaboration among supply chain actors. Some companies use Electronic Data Change (EDI) or Enterprise Resource Planning (ERP) systems to support various company operations. Accessing and combining these dispersed data sources and systems should be possible through a supply chain integration system. Nevertheless, different projects may require various system functions based on factors such as project organisations, planning and management scopes, hardware and software used by stakeholders, and the materials and components involved in the project [99]. The functionality of a pre-packaged commercial ERP system is often complex and expensive to adjust for business applications in building projects. Application Programming Interfaces (APIs) are widely used to extend the functionality of software programmes like CAD applications. The usability of systems will be substantially improved if collaborative systems for enterprise-wide integration can easily extend their capabilities [127].

The Internet and information technology are now being used to enhance cross-organisational partnerships in the construction sector. Examples include web-based design and learning collaborations, document and information management, and project monitoring and management [32]. Current methods of web-based communication and collaboration in the construction sector are categorised in Fig. 18.1. More and more construction projects are using Construction Project Extranets (CPE) and Web-based Project Management Systems (WPMS) to assist communication. Web-based project management systems (WPMS) and construction project extranets (CPE) in particular are being utilised more frequently to assist communication in construction projects [14, 107, 125]. However, constraints such as security concerns, a lack of management commitment, high costs, and deployment rigidity often prevent the use of these tools in the construction business [92]. The literature discusses Service-oriented Architecture (SOA) as a viable solution to this issue.

In this strategy, information sources and software features are provided as separate, stand-alone service units, which are then dispersed across a network and integrated to construct business applications to tackle challenging issues. SOA allows supply chains to be dynamically reconfigured, making them more flexible to changing business models, expanding internationalisation, and improving coordination [81]. Using the SOA methodology, information sources and systems are transformed into modular service components that they can be found, used, and discovered by other

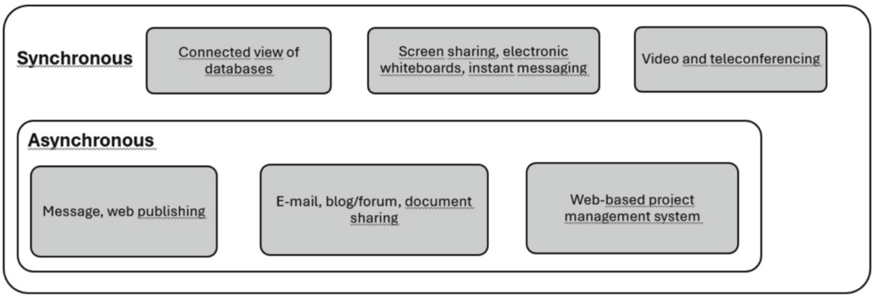

Fig. 18.1 Generic form of web-based collaborative tools for communication and information sharing (Adapted from [27])

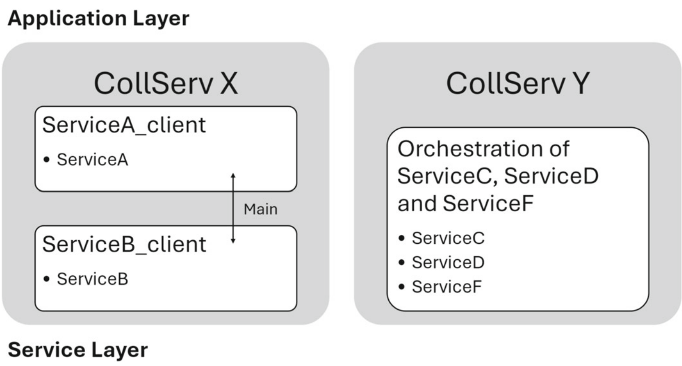

Fig. 18.2 Service-oriented architecture framework (Adapted from [79])

applications via a standard protocol [111]. The service's component parts can be used by other applications or network-based services. The essential elements of service-oriented architecture are the services on which applications are based. For example, a collaboration service, or CollServ X, is an application that calls the ServiceA_client and the ServiceB_client, as shown in Fig. 18.2.

Each customer will call the appropriate service in turn. A service can also be an orchestration of other services, as is the case with CollServ Y, which orchestrates Services C, D, and F. Various languages can be used for specifying CollServ Y when Web service technology is used to implement SOA, such as BPEL (Business Process Execution Language) or BPEL4WS (Business Process Execution Language for Web Services), and BPML (Business Process Management Language).

Web portal technology allows for the aggregation of dispersed web services. A web portal is a web-based platform that serves as a doorway to a more extensive system or network of web applications [29]. It is a valuable tool for combining dispersed, distributed information and services into a single point of access, regardless of their location or storage method. Web portlets, which are small programmes that contain one or more web applications, are the fundamental operational components of a portal system. Portlets need to be housed in a portal system in order to be visible and accessible because they only produce a portion of a complete HTML code. Multiple information sources and applications can be retrieved, accessed, and merged into one another through the portal system. In other words, web portals are frequently used to create intranets for managing material and documents within businesses. They function as a collection point for data storage, publication, and retrieval. Web portals enable system administrators to manage vast amounts of data in a consolidated manner while allowing users to securely access sensitive personal information, thanks to their security and customisability. Building portal systems for cross-organisational collaboration is another current trend.

18.4 Passports Values in Promoting Circularity in Buildings

Numerous benefits of MPs and BPs have been highlighted by literature studies and practical examples, demonstrating their potential to support the digital-enabled circular transition in the construction sector. These benefits encompass both technical and process-related aspects. Technically, passports facilitate a better understanding of circularity practices for materials and buildings, enabling efficient calculations and scenario comparisons across different lifecycle stages. Process-wise, they enhance efficiency through data sharing and improved accessibility for stakeholders. In the following paragraphs four main uses of MPs and BPs in supporting both technical and process aspects are discussed.

18.4.1 Certification and Integration into Sustainability Schemes

Several tools and methodologies have been developed in recent years to facilitate early-stage building design with an emphasis on sustainability through life-cycle assessment (LCA). These tools aim to evaluate the environmental, economic, and social impacts of building designs. Some of the tools use a building element tool, that is a material catalogue in combination with construction properties.

The BIM-LCA Method by Basbagill et al. from 2013 integrates Building Information Modelling (BIM), LCA, and energy simulation. This method is designed to help architects rapidly determine the building components that contribute the most to embodied impact. It uses a combination of user inputs and a proprietary AEC database to perform carbon footprint calculations, energy simulations, and an embodied carbon sensitivity analysis.

Hollberg et al. in 2020 developed a Parametric LCA Tool that provides LCA estimates from minimal inputs and becomes more accurate as more detailed data is provided. The tool's data spans across four levels of detail, namely building, element, component, and material. If certain data is missing, the tool approximates that information from the next highest level of detail. It accesses material data through a Grasshopper plugin, sourcing from the Bombyx and Swiss Bauteilkatalog databases.

Furthermore, the BIM-LCA Workflow proposed by Kaushal et al. in 2022 investigates the current BIM-LCA workflows and suggests potential workflows for different design phases. The methodology they proposed includes a two-phase design process: The project specification phase and the competition design phase. They also offer guidelines on BIM-based LCA for various stakeholders, ranging from architects to national organisations.

Among the various tools mentioned, BauteilKatalog stands out as a web-based tool designed for early design stages. It offers LCA calculations based on the KBOB database. Eco-Sai and Minergie Eco are additional tools that facilitate LCA and energy simulations at different design stages, drawing information from databases such as KBOB and Okobaudat. The web-based application, One Click LCA, is versatile and caters to all design stages, providing LCA calculations using the KBOB database. For thermal calculations in the late design stage, Enercad and Enerweb are prominent tools leveraging the KBOB database.

A notable method introduced by Soust-Verdaguer et al. in 2022 is the BIM-based Life Cycle Sustainability Assessment (LCSA). This method suggests a way to link Industry Foundation Classes (IFC) file components in BIM models to a specific cost estimation data structure known as BCCA. They emphasised the potential of modelling foundational and structural elements in the early design stages. Following this, Llatas et al. in 2020 presented an implementation of this method that links IFC properties in BIM to a variety of data sources, which then evaluate the design in terms of environmental, economic, and employment data.

The trend is clearly moving towards integrating BIM with LCA in the early design stages, ensuring that buildings are designed with sustainability and environmental consciousness in mind.

Information from sustainability certification schemes such as LEED, BREEAM, DGNB or other framework such as Level(s), its individual criteria, building's Energy Performance Certificate (EPC) and modelling, conducting material flow analysis (MFA), Life Cycle Assessment (LCA) and Life Cycle Cost (LCC), could be easily incorporated into MPs and BPs [64].

For example, DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen, in English the German Sustainable Building Council) is a German certification system developed for evaluating the sustainability of buildings. At the annual digital congress dedicated to the development of the DGNB, a key tool for collecting documentation—the new Building Material Passport—was launched. The official website has published a full version and a short version, depending on how much building information is available. The MP is presented as a fillable template based on a building component catalogue, BIM model export or building cataloguing in appropriate tools. It comprises six main categories and 25 aspects, both mandatory and optional. Looking forward, this passport serves as the foundation for a sustainable closed-loop economy in construction, where all lifecycle stages, from design to reuse and recycling, are closely linked and interconnected. Transparency regarding material data, cost and origin is essential [33].

In 2019, the BREEAM Approved Innovative Applications project developed the Building Materials Passport through a parametric translation process to create a practical and widespread application of the concept [17]. This initiative utilised existing BIM data, and through the creation of a parametric translation script, successfully converted this data into a format suitable for the Building Materials Passport. This pioneering work not only demonstrated the feasibility of the concept but also showed its scalability and potential for wider application. Furthermore, the inclusion of this innovative project in the BREEAM list of approved innovative applications demonstrates its recognition in the field of sustainable construction and will soon appear in the evaluation manuals.

Göswein et al. [59] proposed a new framework for Circular Material Passport (CMP) harmonised with the EU Level(s) framework using basic sustainability indicators for buildings. This framework can be used as a theoretical guideline to further development of CMPs. The design considers relevant indicators within the Level(s) framework, viewed through the "Resource Efficient and Circular Material Life Cycles" macro objective. It aims to provide detailed information regarding the use, location and amount of the materials, their method of connection, as well as their potential for future reuse, recovery or recycling.

18.4.2 End-Of-Life and CDW Management

When analysing end-of-life and Construction and Demolition Waste (CDW) management in a CE, the first point of reference should be the waste hierarchy, part of the Waste Framework Directive, which defines the most effective ways of managing waste [47, 86]. The hierarchy emphasises waste prevention as the most effective method of waste management [1]. For CDW, this could involve leveraging modern technologies such as additive manufacturing for building applications [98]. Regulatory documents advocate considering such alternatives connected with methods of production for construction elements or whole structures. Following the hierarchy, the next appropriate form of waste management is reuse. For CDW management, modularity and ease of assembly and disassembly of building elements are crucial for maximising recovery [11, 114]. Effective product reuse requires the use of MPs containing information about parameters for reusing particular elements. Notably, this waste management approach is typically more economical than conventional recycling, making it appealing to companies [85]. In all these cases, MPs should be linked with lifecycle inventory data to evaluate the environmental impacts of the building materials and guide best practices for deconstruction [97].

The subsequent steps in the waste hierarchy are recycling and energy recovery. While these methods should be used when prevention and reuse are not possible, they remain the most practical methods for CDW management and should be developed further. Recycling CDW is challenging due to the variety of materials used in construction and their local specifications [51]. Designing a comprehensive method for separating and recycling these materials is a daunting task. In this regard, MPs can facilitate the processing of CDW by providing detailed information on material composition. Moreover, documents such as Waste Material Passports (WMPs) can aid in cross-jurisdictional trading and minimise information asymmetry between parties [93, 126] These documents should include information such as material types, properties, circularity options, handling history, and more, with the potential for further expansion [93].

Overall, in the context of end-of-life and CDW management, MP methods are key in providing recycling potential and assessing the environmental impact of materials embedded in buildings. They ensure the selection of the most suitable route for waste management for a building at its end-of-life stage [70].

18.4.3 Renovation and Rehabilitation Projects

The building sector plays a crucial role in achieving the EU's decarbonisation objectives, as the current European building stock is highly inefficient. Renovating buildings is the most effective way to improve their energy efficiency. However, the current renovation rate is very low (around 0.4–1.2%), far below the 3% recommended by the European Commission (EPBD (EU) 2018/844).

Several barriers hinder the increase in renovation rates, including technical challenges, administrative burdens, a lack of construction professionals, and difficulty in accessing funding. Additionally, according to [49, 118], a recurring issue is the lack of knowledge about which measures to implement in a renovation process and how to execute them effectively.

BPs or BRPs play a crucial role in addressing these challenges. They collect all the relevant data on a building and provide a tailored renovation roadmap, guiding the building owner through the entire renovation process. This helps overcome the barriers to renovation by offering clear, actionable information and support.

18.5 Integrating Material and Building Passports into BIM Models

The construction sector is a prolific consumer of resources, energy, and carbon, surpassing other industrial sectors. This intensive consumption results in substantial construction and demolition waste (CDW), which represents up to 30% of the EU's waste stream [4]. CDW is generated at various stages of a building's life cycle, including during construction due to design faults, on-site errors, workflow confusion, unexpected equipment failures, rehabilitation, and at the end of the lifecycle (EoL) when the building's service life concludes [4, 10, 61]. The evaluation of the effects of each building component on overall waste reduction rate in buildings has been poorly implemented due to existing standard quantitative control methodologies [121]. Consequently, there has not been a thorough inspection of landfill sites using the typical CE model procedures to mitigate landfill risk and prevent illegal building waste heaps during the Movement Control Order (MCO) period [77].

To address these challenges, innovative approaches are necessary, including integrated design and the adoption of automated technologies to effectively manage CDW. Intelligent waste recycling management systems, which benefit from advancements in waste reduction information and clean technologies, significantly improve the design and material efficiency of waste processing or treatment facilities and supply chain construction plans.

Resource conservation, waste reduction and salvaging building materials are cornerstones of the CE. In this regards, similar to MPs and BPs, BIM has been widely investigated as technological advancements to achieve these CE objectives. BIM plays an integral role in promoting waste hierarchy strategies across different

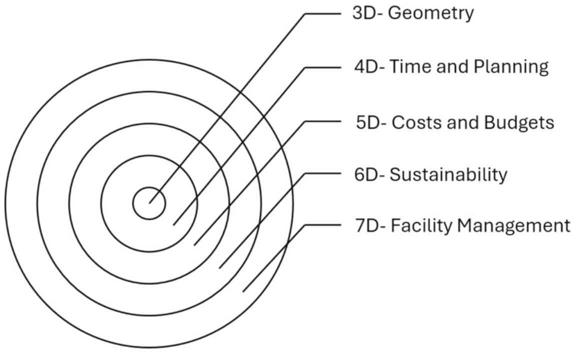

Fig. 18.3 The scheme of Building Information Modelling (BIM) dimensions (Adapted from [4])

building lifecycle stages, with a particular emphasis on end-of-life management strategies such as deconstruction (see Fig. 18.3 for the different dimensions of BIM supporting CE objectives).

BIM is an intelligent, object-oriented model that ensures any changes in object properties (quantity or quality) are automatically updated across all model views, sections, and schedules. It facilitates the automatic calculation of the total volume of materials, their qualities, and object dimensions.

Significant literature underscores BIM's potential in this area. Akanbi et al. (2018) developed a BIM-based whole-life performance estimator aimed at maximising the lifespan and utility of building materials, treating buildings and their components as potential resource mines even after their primary lifecycle ends (Lismont & Allacker 2019). Akinade et al. [5] introduced a BIM-based Deconstructability Assessment Score (BIM-DAS), showcasing the potential of BIM. Furthermore, Sanchez et al. (2021) proposed a BIM-based framework to support the disassembly and reuse of building components. Additionally, Cheng and Ma (2013) discussed a BIM-based system specifically designed for estimating and planning demolition and renovation waste, highlighting BIM's capability in resource estimation and waste reduction.

Arora et al. (2020) explored the use of BIM to effectively identify and optimise urban mining opportunities, emphasising the potential to recover and reuse building components. [65] investigated the calculation and evaluation of circularity indicators using BIM, highlighting its relevance in understanding the built environment's sustainability metrics.

Given the potential opportunities of using BIM to enhance CE strategies, the integration of MPs and BPs into BIM models offers a promising pathway for advancing circularity principles in the construction sector. BIM's robust capabilities, combined with the tracking systems and data collection provided by MPs and BPs, enable stakeholders to make more informed decisions that align with CE principles. This ensures efficient resource usage and significant waste reduction. This section explores the value of integrating MPs and BPs within BIM and discusses the practical applications of this integration for enhancing circularity and sustainability in construction.

18.5.1 BIM-Based Material Passports

MPs promote circularity, sustainability, and waste reduction in the construction sector. Their contribution and effectiveness can be significantly enhanced with new technologies such as BIM. The integration of MPs in BIM models is a field gathering a surging research interest. Currently, international literature shows efforts to connect MPs with BIM for both new and existing buildings, using various technologies.

For existing buildings, an as-built BIM model was created within the framework of the SCI_BIM project. Researchers evaluated a building's energy performance, optimised it, and examined its recycling potential [67]. They used laser scanning to record the building's geometry and Ground Penetrating Radar (GPR) scanning to detect and evaluate the building's material composition. The BIM model was generated based on the point cloud data gathered during the scanning processes. Two discipline models were then generated to assess energy consumption and the building material use. After optimising the building's energy performance, they created an MP for its materials composition and recycling potential. Through gamification, building users could interact with the BIM model containing all this information. Challenges with GPR scanning in existing buildings include interference from furniture and users, and a pre-demolition audit may be necessary for more precise perception of the building materials [70, 87].

For new constructions, Honic et al. [69] developed a BIM-based MP to assess the environmental impact and recycling potential of construction materials. They used BIM software for building modelling and the Material Inventory and Analysis Tool BuildingOne (BO) for bi-directional data communication and synchronisation between the BIM model and the MP, opting not to use the IFC format due to its limitations in this regard. They used the Austrian IBO database and developed a data-stakeholder management framework to address challenges in data and stakeholder management. [11] incorporated the MPs into BIM models using Revit, creating twelve shared parameters to automate sustainability assessment. They modelled sustainability indicators with the Dynamo visual programming tool and validated their approach in a building case study, recording reduced calculation time and error elimination with the digitalised MPs. Reference [21] created an MP for a sandwich panel using the BAMB framework, integrating it into a BIM model developed in Revit, which can generate IFC files. They worked on LOD500 (Level of Development) to associate MP data with the BIM model, manually correlating MP parameters with Revit fields due to inconsistencies. The required data were exported in a.txt file and the process was repeated for the rest of the products.

The integration of MPs into BIM models is a developing field, with many researchers working on relevant models to promote circularity. Such models can also be useful for the assessment of agricultural waste for suitability as construction material substitutes [124], potentially eliminating hazardous substances. [115] proposed the integration of BIM-based MPs in architectural, civil engineering and environmental engineering school curricula to raise awareness and familiarisation with circularity and sustainability measures among students.

18.5.2 BIM-Based Building Passports

Unlike the numerous studies existing on the integration of the MPs into BIM, only a few examine the combination of BPs with BIMs. BPs encompass a wider range of information about a building than BIMs. Consequently, most existing literature focusses on linking BIMs to DBLs as a data source. According to Gomez-Gil et al. [55], BIMs, as part of Digital Twins development, can provide various data about a construction, including general information, architectural survey/geometry, construction details, material inventory, predictive maintenance plans, building systems features, accessibility conditions, what-if analysis, performance optimisation, real-time energy use measurement, behavioural insights, water resources assessment, health and comfort assessment, and lifecycle optimisation.

Among the different forms developed for the DBL within European projects, the one created by the BIM4EEB project was designed to be stored in the BIM Management System (BIMMS). This allows all involved stakeholders access to the data, which can be updated or enriched at any time [31]. The DBL proposed by the EUB SuperHub Horizon project consists of eight main categories, with the eighth named "Building Documentation BIM". Various documents related to the building and a BIM model are inserted into the DBL using IFC files to manage the latter (MalinovecPucek et al. 2023). A similar category for the DBL structure was proposed in the ALDREN BuildLog, whose sixth module is named "Documentation and BIM" [119]. Other developed DBLs, like X-Tendo Logbook and Study EU DBL can also be integrated into BIM models, with BIM forming an indicator in both [55].

Another example is the LdE-e tool, which aims to enhance multifamily building renovations by combining the BRP and Scheduled Renovations Roadmap into one tool [38]. The integration of BIM and blockchain technologies into LdE-e promises optimal results. The technology, already adopted by Spanish regulations based on the eCOB standard of the IFC files, is used to achieve the desired integration of BIM into the LdE-e. The hierarchal "tree structure" of the IFC files facilitates the exchange of building data. The BIM files can be stored in the tool's Warehouse (P0), accessible to all involved stakeholders. However, BIM's integration is feasible only for new constructions and their future renovations, as existing buildings typically lack precise and detailed data.

Coupling BIM models and BPs remains an active research field. Interoperability is crucial for a successful connection between these two technologies. The IFC data format is the most commonly identified solution in existing studies, though other options are available or under development. For instance, the Ecodomus software developed by Siemens supports BIM-based digital twins using data from BIMs or point clouds, allowing for data export to excel files [55].

The construction sector seems eager to employ BIM in design for deconstruction (DfD) tools to enhance lifecycle management and data transparency. The collaborative nature of BIM is particularly appealing to those involved in BIM-based building projects. However, it the capability of BIM tools to hold extensive information that is

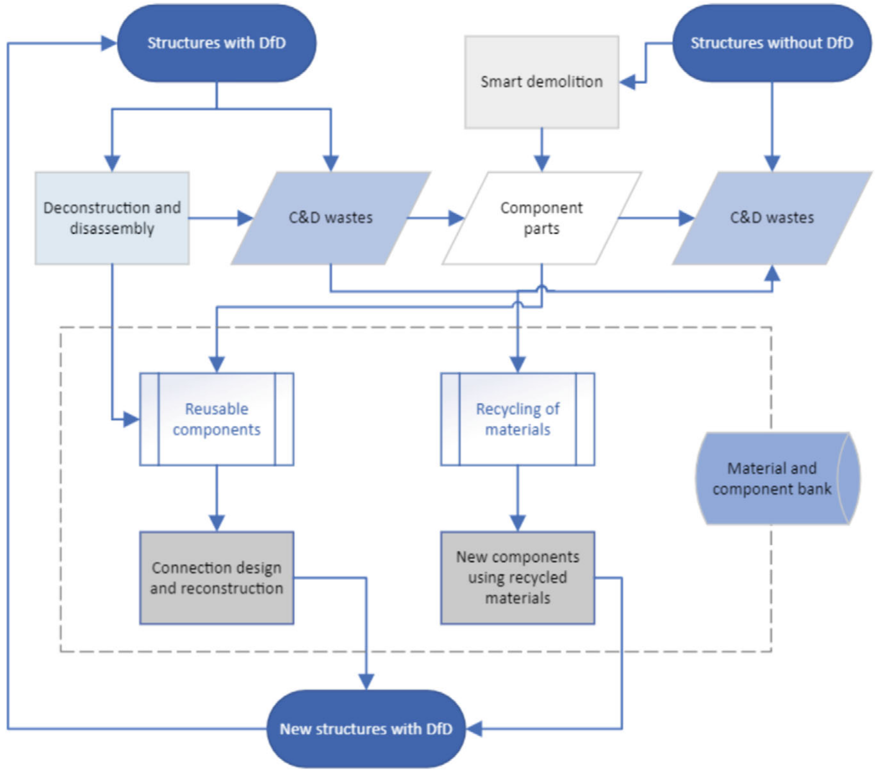

Fig. 18.4 A modified framework of the interconnection between deconstruction, DfD and secondary material streams with the Materials/Components Bank (M/C Bank) (Adapted from [19])

more attractive to professionals working in DfD [13, 78, 106]. Figure 18.4 provides an example of the information necessary for DfD models.

This is partially due to the massive amount of documentation required for DfD and the uncertainty regarding the timing of future deconstruction actions, when such documents must be provided. Considering EoL scenarios, it is feasible to add a layer of information to each BIM item to prepare for future EoL applications, such as deconstruction guidelines, guarantees, environmental assessment scores, and legal requirements [5, 103]. As part of a sustainable and circular Building Stock 4.0, BIM not only aids in deconstruction planning and execution but also fosters a culture of digital deconstruction [22].

18.6 MPs and BPs European Initiatives and Pilots

Several initiatives and pilot platforms were developed to introduce and refine proposals for the generation, composition, and utilisation patterns of passports. These initiatives provided insights into the requirements, usage conditions, and challenges associated with passports.

For BPs, various H2020 projects were developed before the tool was introduced by continental legislation:

- iBRoad—Individual Building (Renovation) Roadmaps (IBRoad 2023). This project aims to address the barriers to building renovation by implementing Individual Building Renovation Roadmaps. These roadmaps guide building owners through the renovation process providing tailored step-by-step plans (iBRoad-Plan), designed using data from a building logbook (iBRoad-Log), which acts as a data repository. The primary focus of iBRoad's is on single-family houses. Pilot tests of this initiative were conducted in Bulgaria, Poland, and Portugal.
- ALDREN Project—Alliance for Deep RENovation in Buildings (ALDREN 2023). ALDREN aims to overcome market barriers hindering growth of renovation projects by proposing a voluntary, modular framework that implements the European Voluntary Certification Scheme (EVCS) to assess the energy performance of buildings on a unified European basis. The framework consists of four standalone modules: Energy Rating and Target, Energy Verification, Comfort and Well-being, and Cost Value Risk. It also includes two reporting tools: the European Voluntary Certificate (EVC) and the Building Renovation Passport (BRP), which features the ALDREN BuildLog (a data repository), and the ALDREN RenoMap. This framework is tailored for non-residential buildings, mainly hotels and offices, and was tested in France, Spain, Slovakia, the United Kingdom, and Italy.

As for MPs, multiple initiatives were made providing online platforms and applications of the passports. Examples include:

- The BAMB Project: The "BAMB2020 - Building As Material Banks" project, initiated under the EU's Horizon 2020 framework, represents a pioneering effort in the adoption of circular construction practices. The project is noted for developing an electronic MP, serving as a comprehensive repository for material information crucial for recovery and reuse. This passport includes detailed data on materials' physical, chemical, and biological characteristics, health data, transportation details, and more, aimed at facilitating effective evaluation and certification [64].
- Although historically the concept of MP was first introduced in 1997 in Germany, encapsulating information about operational costs, quality of use, building services, and technical properties [11], The BAMB2020's approach is considered the first exhaustive implementation of such a passport in the construction sector. Significant outcomes of the BAMB project include the establishment of MP reports that enhance the industry's capacity to leverage materials for reuse

and waste reduction. Currently, the BAMB platform is in prototype mode and available exclusively to industry partners for testing purposes.

- Madaster Platform: Madaster exemplifies the commercial application of Building Material Passports (BMPs). This digital platform, based in the Netherlands, acts as an extensive online library for materials and products accounting (Madaster 2023). The Madaster platform supports both BIM files and traditional Excel spreadsheets. An MP is created from a set of source files uploaded to the platform. The platform allows the creation of several databases at different levels, and categorisation of materials based on the six shearing layers of buildings as identified in Brand's model: Site, Structure, Skin, Services, Space plan and Stuff [16]. Through this platform, stakeholders can ascertain the financial and residual value of materials, manage material cycles, and calculate circularity indicators for the construction, use and end-of-life phases [65]. Circularise Platform: Circularise is a commercial blockchain-based Digital Product Passport (DPP) platform originating from the Netherlands. It provides worldwide companies with traceability software to monitor product and material details such as origin, certification, and CO2 emissions. The platform enhances supply chain transparency by using tangible data carriers and ensures the confidentiality of information among supply chain members. This feature potentially optimises communication between value chain stakeholders, making interactions easier and faster. The project has successfully collaborated with the municipality of Amsterdam in the construction industry. Its software facilitated detailed traceability throughout the supply chain of a concrete manufacturer and a company that converts workwear into polymer infrastructure elements. The project securely transferred vital data to the City of Amsterdam without compromising data confidentiality [28].

Positive pilot cases show, that sharing MPs in a digital platform could form an Internet of Materials that would support designers and engineers in developing more sustainable and circular products [109].

18.7 Barriers and Challenges Against the Uptake of the Passports

18.7.1 Lack of Legislations and Standards

The absence of standardised guidelines for passports hinders their widespread adoption and practicality. Currently, there is no official agreement on a unified definition of passports and their defining features [123]. Various types of passports exist, each with different information formats, categorisations, taxonomies, terminologies, and guidelines. These differences lead to varying scopes and system boundaries for the information provided [69].

Standardisation in passports is crucial to facilitate data linkage and exchange among different passport stakeholders across supply and value chains [123]. However, achieving this standardisation poses significant challenges due to diverse stakeholder requirements, varying degrees of detail, and the need for proper categorisation of information. Additionally, recording continuous data updates throughout the system lifecycle can be complex, especially when materials or components are reused across cycles, creating issues with transferring relevant information.

Moreover, evolving regulations can impact data consistency, particularly in long-life products like buildings [101, 102, 123] (Munaro et al. 2019; Munaro& Tavares 2021; [123]). To mitigate data variability and enhance compatibility, standardised building catalogues and classification systems are utilised. These measures ensure accuracy in data interoperability, exchange, and linkage.

An effective approach involves supporting these standardised systems with a central registry that issues a Unified Object Identifier (UOI) for each main object. This enables stakeholders to access all relevant information about an object or any of its elements without the need for central data registration [123]. Such a system streamlines access and promotes efficient data handling for all involved parties.

Given the fact that there is no standard definition of BRPs, Sesana and Salvalai [118] gathered together the potentialities and barriers regarding the BRPs in their review of different ongoing and proposed initiatives. The review is aimed at finding a definition of this particular tool based on what has been already developed by different countries.

Regulations and perceptions on quality also play a key role [120]. In Munaro et al. [101], the main challenges for the introduction of BMP are discussed, emphasising the need for joint action based on political initiatives and regulations that allow and facilitate circularity practices in construction. Besides, ISO endeavours and standardisation, and creation of Product Circularity Data Sheet (PCDS) can be found in [100]. The importance of policy development for the promotion of a standardised and regulated use of this tool needs to be highlighted [59]. A major concern is that such WMPs are not issued by authorities that can guarantee authentication [126].

Furthermore, the Indexing of material into a numbering schema is a considerable barrier and needs to be addressed in further standardisation efforts.

18.7.2 Insufficient Stakeholders Collaboration and Unbalanced Responsibilities

The identification of involved actors along with their respective roles in the passports creation and operation is crucial to support proper governance throughout a product's lifecycle, including extraction and origin, manufacturing, transportation, utilisation and maintenance and lastly disposal, recycling or reuse [123]. To achieve this objective, a multi-stakeholder network must collaborate and hold various responsibilities to provide required data to meet information flow in multiple chains including ownership, governance, financial and production chains that are associated with the main value chain [123]. These information requirements must be provided by and circulated among the stakeholders involved in each of the four aforementioned chains to ensure proper management to support decision-making regarding acquisition, maintenance and user requirements. The imposed barrier in this context is the lack of collaboration among the stakeholders in terms of balancing the responsibilities. This happens when a specific group of stakeholders deals with the information acquisition and registration while the others only benefit from the provided registry for their own interests.

The data and stakeholder management framework presents the required collaboration of various stakeholders in order to achieve a successful implementation of the MP in the AEC industry [69]. Furthermore, the vertical integration of trades and long-term relationships with suppliers improve transparency and reduce fragmentation in information flow [80].

18.7.3 Lack of Data Availability and Accessibility

A significant body of research highlights the challenges in data availability and accessibility within the context of digitalisation and the CE. [26] conducted a literature review on digitalisation technologies and their integration into CE, identifying several barriers. These include policy-related factors, unpredictability, psychological factors and vulnerability in information security, which collectively impede the digitalisation-led CE transition.

Furthermore, studies on the specific availability and accessibility of MP-relevant information have been conducted. For instance, [80] analysed data practices at a prominent Swedish industrialised housing construction firm, uncovering a critical lack of accessible and shared information about materials. Similarly, Panza, Faveto, et al. [109] pointed out a significant gap in shared material information, which is crucial for enhancing transparency and efficiency. The research also underscores the necessity of systematic data collection and public data provision to ensure the practical applicability of CE strategies. Schützenhofer et al. [116] emphasised this in the context of lacking data, which hinders effective implementation. Additionally, Munaro et al. [101] identified barriers in developing Building Material Passports (BMP) concerning life cycle assessment (LCA) data and end-of-life material information, highlighting the complexities involved in data management throughout a building's lifecycle.

Gómez-Gil et al. [57, 58] further explored the challenges associated with data acquisition for MPs and BPs, which are essential tools for accumulating and managing data across a building's lifespan. They noted that much of the required data remains paper-based or locked within private databases, complicating data collection efforts. Moreover, the lack of interoperability among numerous public open data sources presents additional obstacles to data sharing and integration.

Overall, addressing these challenges requires developing strategic approaches to manage and correlate the vast amounts of data generated during a building's lifecycle, ensuring the effectiveness of MPs and BPs as gateways to sustainable construction practices.

18.7.4 Financial Barriers

The widespread adoption of MPs faces significant economic challenges, primarily stemming from the high capital and operational costs [102, 123]. Although the benefits of passports can be substantial in the long term, many stakeholders may not perceive the initial data registration costs as justified, especially those seeking short-term profitability [123]. Some stakeholders view passports as a potential threat, as they reveal data that can create a competitive disadvantage for their businesses [120]. To address this conflict, it is essential to ensure that the benefits of MPs are shared among all value chain stakeholders. Developing appropriate business models can help achieve this goal [102, 120, 123].

However, integrating critical information about circularity into passports may face challenges due to limited interest in materials reuse and the narrow adoption of secondary materials. These materials often have lower safety standards, uncertain service life, and may not be as profitable for market players, which can influence circularity practices such as recycling and material recovery through disassembly [123]. In relation to cost efficiency, there is a financial barrier to overcome as storage, transport, and handling of recycled material can be, in some cases, costlier than the use of fresh material (e.g., recycled concrete).

To minimise the financial risks associated with passport adoption, the government's role becomes crucial. By providing regulatory frameworks for market uptake and ensuring the prevention of unpleasant behaviour from certain commercial entities that control information exchange, governments can foster a conducive environment for the successful use of passports [123].

18.7.5 Lack of Knowledge and Expertise

Kirchherr [82] thoroughly analysed the absence of a precise definition of the CE concept and how this ambiguity can serve as a barrier to its full implementation. This issue is also applicable to MPs and BPs, where many stakeholders, including developers, architects, and builders, remain unfamiliar with the benefits and operational aspects of these tools. Currently, the primary tool widely used in this sector that implicitly promotes building improvement is the Energy Performance Certificate (EPC). However, the EPC is limited in its ability to provide tailored information to encourage renovation [49]. As Kirchherr [82] pointed out, "it is oftentimes not highlighted that CE necessitates a systemic shift" (p. 221) and not merely the adoption of the recycle-reduce-reuse concept (the 3R framework). One of the most frequently cited barriers is the lack of knowledge regarding where to begin, what actions to take, and the sequence in which measures should be implemented. The underdevelopment of techniques, standard definitions, and guidelines for their application continues to impede the full adoption of CE within an industry that is traditionally conservative and resistant to adopting new practices and technologies without clear short-term benefits [82].

Challenges and barriers related to the lack of knowledge and expertise on MPs and BPs are well documented in the literature. Munaro [102] concluded that there is a dearth of information on best practices and examples that could facilitate the implementation of these tools in the construction sector. Theoretical guidance is needed for actors involved in supply chains to enable them to harness the benefits of MPs. It should be clearly articulated how MPs will contribute to making the system more sustainable, as well as how they will foster new business opportunities, innovation strategies, and communication technology systems.

Regarding the digital transition, [24] identified twelve challenges that impede the broader adoption of digital technologies including the passports in the social housing sector. Among these challenges, those related to unfamiliarity with technological aspects revealed that interviewees were uncertain about data requirements and lacked guidance on data management mechanisms. Furthermore, as noted by Kirchherr [82], there is often a reluctance within the social housing sector to adopt advanced technologies in day-to-day operations. This reluctance is compounded by a corporate culture that is not committed to making significant investment decisions necessary for systemic change. Market challenges arise when organisations fail to see short-term benefits in developing full MPs for new buildings that will be utilised in the long term, and they often find it more feasible to develop MPs for existing buildings prior to demolition. However, the question remains: how can the new and existing building sectors be brought together to adopt circular strategies?

The rapid evolution of technologies and construction methods necessitates that passport systems be continuously updated, which presents a challenge. Additionally, in the context of achieving a circular system, the updating of information on the materials and components of a building throughout its lifecycle must be encouraged, which is an ongoing and time-consuming task. Overall, the adoption of these tools and their full implementation within the system must be part of a strategy of continuous technological evolution. As Selman and Gade [117] observed, CE remains a complex issue with many unresolved aspects, and it is imperative that stakeholders act as true intermediaries, raising awareness of progress towards sustainability objectives.

18.8 Discussion and Conclusions

MPs and BPs represent pivotal tools in the design of circular buildings. The MP serves as a comprehensive record, aimed at facilitating the implementation and monitoring of buildings' circularity by gathering and preserving data about the materials constituting buildings, aiding in decisions regarding recovery, recycling, and reuse. However, the adoption of MPs is hindered by significant challenges such as the need for transparency and the protection of data confidentiality. Ensuring that the data in MPs is accessible to relevant stakeholders is essential for driving practical and actionable outcomes.

On the other hand, BPs have been acknowledged as instrumental in providing essential information to various players in the building sector, including users, technicians, financiers, and insurers. Yet, these tools vary significantly in format and content across different projects.

The evolution of the BP has laid a foundation for assessing building energy performance in a standardised format. However, the standardisation of MPs, while progressing, lacks the same level of detail and international consensus seen in other standards, such as those demonstrated by initiatives like BAMB2020. There remains no comprehensive international standard for indexing building materials for circularity. Furthermore, the proper management of this data requires robust information exchange among all stakeholders involved in the lifecycle of a building, from construction to maintenance to decommissioning, to facilitate informed decision-making.

Financial barriers also play a critical role, as the costs associated with the transport, storage, and upgrading of used building materials must be evaluated to offset potential quality reductions from reuse and recycling. Government involvement is crucial in mitigating the financial risks associated with the adoption of passports, through the establishment of regulatory frameworks that encourage market adoption and prevent monopolistic practices by firms controlling information exchanges.

Furthermore, the literature suggests leveraging BIM as comprehensive repositories of building data, which could enhance the utility of MPs by providing accurate and detailed information (Khosakitchalert, Yabuki, and Fukuda 2019). However, challenges persist, especially in existing buildings where BIM-based quantity take-off needs significant accuracy improvements for complex elements to ensure the reliability of the data within MPs.

Additional barriers include the lack of market knowledge and unclear stakeholder responsibilities. Some stakeholders perceive passports as a threat to their competitive edge due to the transparency they bring. To overcome these challenges, the benefits of passports must be equitably distributed among all stakeholders in the value chain.

From current practices, it is evident that standardising the format and ensuring interoperability of data in MPs and BPs is necessary. Adopting a light set of open data standards—either directly by the industry or through the development of European and global standards—could catalyse this harmonisation. Given the global challenges of resource scarcity and climate change, which have shifted societal values and heightened demands for sectoral transparency, it is imperative to align production and consumption patterns with sustainable development goals. Stakeholders are increasingly committed to environmental and societal responsibilities, making the availability of measurable, reportable, and verifiable data crucial. Such data not only supports investment and financial decisions but also aids in setting baselines and targets for climate-related strategies in both developed and developing markets.

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Chapter 19
Implementation and Consideration of Circularity Within International Sustainability Assessment Methods

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Abstract The construction sector is a major contributor to environmental degradation, prompting the need for integrating sustainability into its practices. This need has driven the development of sustainability assessment methods across various scales of the built environment. Simultaneously, the recent emphasis on Circular

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Economy (CE) principles has introduced challenges in translating these principles into measurable outcomes within the construction sector. This study aims to investigate the extent to which circularity principles are embedded within existing sustainability assessment methods for new buildings. The study begins by addressing the interrelationships and distinctions between circularity and sustainability concepts, establishing a foundation for the subsequent analysis. Five internationally recognised sustainability assessment methods for new buildings—BREEAM, DGNB, LEED, Level(s), SBTool—were examined to assess their incorporation of circularity aspects. Each component of these methods was scrutinised for alignment with the 10 circularity strategies outlined in the well-established 10-R framework of waste hierarchy. Expert groups, consisting of CircularB COST Action members, independently evaluated the methods and provided opinions on the direct and indirect associations between the assessed components and the 10-R principles. Disagreements were resolved through group discussions. The analysis revealed varying degrees of integration and explicit reference to circularity principles across the assessed methods. The study also highlighted the subjectivity inherent in identifying correlations and the challenges connected to linking certain circularity-related concepts in the built environment—such as resilience and adaptability—with the 10-R strategies. The findings underscore the need for a more in-depth analysis before making direct comparisons of the integration of circularity principles among different sustainability assessment methods, given their methodological differences. The study also identifies directions for future research.

Keywords Circular economy · Sustainability · Buildings' Sustainability assessment · 10-R Framework

19.1 Introduction

The main aim of this chapter is to investigate the extent to which circular economy-related aspects and strategies are integrated in the evaluation process supported and performed by well-known sustainability assessment methods of buildings.

The need for this investigation arises from the intersection of COST Action CircularB's objectives and the evolving role and nature of sustainability assessment methods in the built environment. Among the core targets of CircularB Action is the proposal of appropriate circularity indicators for evaluating the built environment. These indicators may be existing ones, modified versions, or entirely new proposals, and their effective development and application should be supported by robust data and frameworks, including regulatory standards. In parallel, Level(s) framework represents one of this Action's main interests, with the effective integration of circularity indicators into its structure being one of the foreseen research areas. Although Level(s) has distinct characteristics, it shares important similarities with other sustainability assessment methods used in the built environment.

Over the past decades, sustainability assessment methods for the built environment have evolved significantly and gained widespread adoption and recognition globally. These methods are crucial for embedding sustainability principles into the built environment. They essentially comprise sets of criteria and or indicators well-structured, relevant to the built environment and accompanied by grids of standards, data and regulations.

The combination of these factors, along with the recognition that sustainability, while closely related, is not synonymous with circularity, underscores the importance of the work presented in this chapter. The concepts and scopes of circularity and sustainability are discussed in Sect. 19.2, primarily through a comparative lens that highlights their interrelationships and distinctions.

This study involved the selection of five widely recognised sustainability assessment methods for buildings and their examination within the context of a circular economy framework. The methods considered are: BREEAM, DGNB, LEED, Level(s), and SBTool.

In both academic and practical settings, various R-frameworks have been employed to define strategies encompassed by the circular economy concept. At the European Union level, the 4-R framework (Reduce, Reuse, Recycle, Recover), which forms the core of the EU Waste Framework Directive [18], was expanded with the introduction of the EU's Circular Economy Action Plan (CEAP) in 2015 and the updated CEAP in 2020 (European Commission, 2020). These developments are integral to the EU Industrial Strategy, a key component of the European Green Deal. A more comprehensive framework, as presented by [28], includes 10 common circular economy (CE) strategies as illustrated in Fig. 19.1: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. This framework was adopted in this study to scrutinise all the aspects covered by the selected assessment protocols in terms of circularity, given its clear and nearly exhaustive representation of existing CE strategies. It is worth noting that other similar frameworks exist in the literature, such as those proposed by [34] and [38].

The investigation focused on analysing whether, to what extent, and how circularity principles and strategies are implemented in the examined sustainability assessment methods. This analysis was conducted at the most granular, self-contained, distinct, and scored level within each method's assessment structure, as explained in the respective sections. The methodology involved conducting expert focus group exercises with five sub-groups (corresponding to the five examined methods), composed of researchers contributing to this study. Participation in each sub-group was voluntary, with the number of members varying; some researchers participated in multiple sub-groups, while others were involved in only one. Detailed information regarding the number of contributors in each sub-group is provided in the respective sections of this chapter.

Each sub-group analysed a specific protocol/assessment method by studying the technical manuals, guides, or descriptive materials accompanying each method, which contain comprehensive descriptions of the content, benchmarks, and intended goals of the assessment levels under consideration. For SBTool, the analysis was based on the study of the method's computational tools (Excel-type files). The

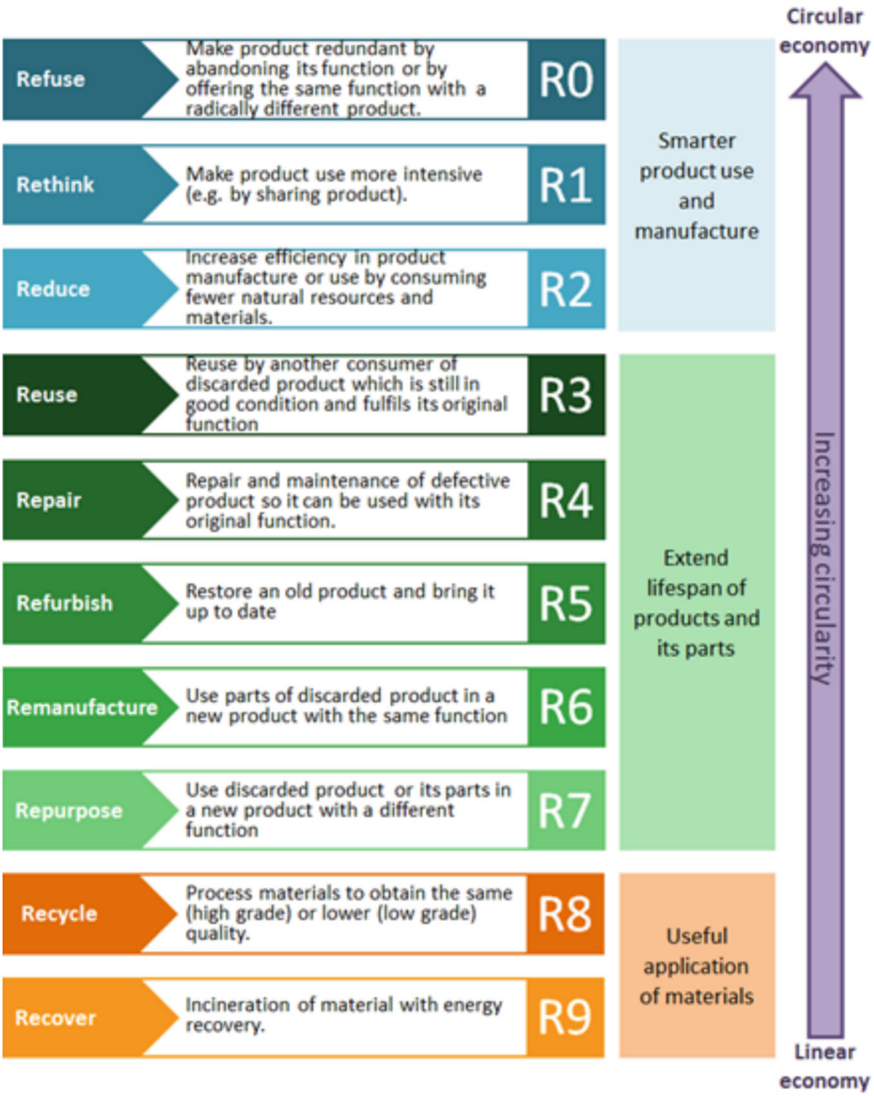

Fig. 19.1 The employed 10-R framework (adapted from [28])

members of each subgroup independently provided their opinions on whether and which of the strategies outlined in the 10-R framework are reflected in the examined components of the analysed method. It is important to note that, for this correlation to be meaningful and effective in the context of individual buildings, the investigation centred on assessing building products and buildings as products through the lens of the 10-R framework. Differences in estimations and assessments within each sub-group were resolved through discussions. Through this process, two types of associations were established: direct and indirect. Direct associations are based on direct, explicit references to one or more of the employed framework's strategies/ principles within the content, aim, indicators, and overall structure of the examined component. Indirect associations reflect relationships where no explicit references were found, but correlations could be inferred on a consequential basis. More detailed classifications, and information on each method's unique features influencing the treatment of this issue, are provided in the sections presenting the results for the examined methods.

The results are presented in tables listing the components of each method directly and indirectly associated with the 10-R strategies. The discussion of the findings follows. This approach outlines the consideration of various circular strategies in the context of the examined methods, highlighting the differences and similarities among the adopted approaches. An important outcome of this analysis pertains to the challenge of distinguishing between sustainability and circularity and the resulting variations in the related interpretations.

The structure of the chapter is as follows: Sect. 19.2 discusses the interrelationships and distinctions between circularity and sustainability. Section 19.3 provides an overview of sustainability assessment methods for the built environment and analyses the integration of circularity in five international methods: BREEAM, DGNB, LEED, Level(s), and SBTool. Finally, Sect. 4 concludes the chapter.

19.2 Sustainability Versus Circularity

The relationship between the concepts of circular economy (CE) and sustainability has sparked an ongoing debate [33]. However, the lack of clear boundaries defining each concept has fueled this conflict, despite their widespread use among scholars and practitioners. Unfortunately, this lack of clarity hinders the effective application of these concepts in both theory and practice [22]. Sustainability can be defined as the balanced integration of economic performance, social value, and environmental resilience, benefiting both present and future generations [22]. On the other hand, the circular economy is defined as an industrial system intentionally designed for restoration and regeneration. It aims to replace the concept of disposal "end-of-life" with regenerative growth, prioritise renewable energy, eliminate toxic chemicals that hinder reuse, and strive for waste elimination through superior material, product, system, and business model design [17]. While various scholars have proposed multiple definitions of circular economy, the definition put forth by the Ellen MacArthur Foundation is the most accepted [23, 28].

While both sustainability and circular economy share concerns about technological advancements, industrial practices, and consumption patterns, they also highlight the importance of integrating environmental and social dimensions with economic progress [22]. Despite these similarities, the two approaches differ significantly in their origins, objectives, scopes, motivations, institutionalisations, timespans, and beneficiaries [22]. Sustainability embodies a more open-ended essence in the context of sustainable development compared to a circular economy [22, 46]. It encompasses a wide range of goals that can be reframed over time to align with the interests of involved parties. Conversely, the circular economy is more specific in defining its goals and aspirations for closed-loop systems that eliminate waste and minimise emissions. These goals are to be achieved within defined theoretical and practical thresholds [17].

Scholars diverge into two directions regarding the relationship between CE and sustainability. The first direction argues that CE surpasses the linear thinking models of sustainability and offers prospective solutions to its shortcomings [28, 40]. Geissdoerfer et al. [22] provide a more comprehensive perspective, acknowledging both positions. They identify three major types of relationships between sustainability and circular economy: (1) circular economy as a condition for sustainability, (2) a mutually beneficial relation, or (3) a trade-off. These relationship patterns foster diversity and encourage the deployment of a wide range of complementary strategies. According to Brundtland Report (1987), sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This definition highlights that sustainable development is an ever-evolving goal for our planet and society. A circular economy, in this regard, establishes new sustainability benchmarks to meet modern-day goals for sustainable development. However, employing the circular economy without considering sustainability would lead to undesirable results. For example, multiple cycles of reusing or recycling a product may eventually either produce more emissions or consume more energy than producing a new one. Therefore, it is crucial to strike the right balance between resource circularity and their environmental, economic, and social impacts, taking into account case-specific requirements.

The relationship between circular economy and sustainability also extends to the built environment, particularly the building sector [27]. However, while sustainability has often been associated with "doing less bad" instead of good, the CE has been all about "doing good". Sustainability comes from the gradual optimisation of things, whilst the circular economy is about new business models that sell services rather than products [27]. Many literature studies on circular economy prioritise environmental improvements, neglecting a systemic integration of all three pillars of sustainability. The strong relationship between circular economy and environmental sustainability lies in the efficient solutions that circular economy concepts provide to alleviate the pressure of human activities on natural ecosystems [33]. However, most cases tend to link the environmental focus with economic aspects, paying marginal attention to social and institutional levels. The social value brought by the circular economy is often overlooked, with discussions mainly centred around job creation. This limited coverage of social aspects reflects a blurred perception of the circular economy's ability to contribute to subjective well-being [22]. The marginal attention given to social issues in circular economy studies may be attributed to their focus on an industrial context [12]. Consequently, the circular economy should broaden its scope to include societal concerns, which require a radical shift in consumer and stakeholders' attitudes. However, recent studies show a growing awareness of the need for a more inclusive approach that embraces the triple bottom line of sustainability [33].

Table 19.1 Differences between sustainability and circular economy on various levels

Aspects	Sustainability	Circular economy
Objective	More open-ended essence regarding sustainable development	More specific in defining its goals and aspirations for closed-loop systems that eliminate waste and minimise emissions
Impact	"doing less bad"	"doing good"
Focus	Focuses on the triple bottom line: People, the Planet and the Economy	Focuses on Resource Cycles
Practice ground	The practice of sustainability is grounded in and focused on the Biosphere	The practice of circularity is grounded in and focused on the Techno and Bio spheres
Responsibility	Responsibility is shared but not clearly defined	More defined responsibility primarily focusing on private businesses, regulators and policymakers
Beneficiaries	Main beneficiaries: the environment, the economy, and society	Main beneficiaries: the economic actors that implement the system
Interests	Interests are aligned between stakeholders and can be reframed over time	Interests prioritise financial advantages for companies
Prioritised aspects	Comes around the gradual optimisation of things	Prioritises improvements on the environmental aspect while the social aspect is marginally addressed

Table 19.1 summarises the differences between sustainability and circular economy in terms of objective, impact, focus, practice ground, responsibility, beneficiaries, interest and prioritised aspects.

19.3 Analysis of Circularity Implementation in Five Well-Known International Methods (BREEAM, DGNB, LEED, Level(S), SBTool)

19.3.1 General Information

Over the past few decades, sustainability assessment methods for buildings have evolved into a critical asset for implementing sustainability principles in the building sector. These methods have gained significant acceptance and recognition internationally across various stakeholders. The 1990s marked the inception of environmental performance assessment methods for buildings, with the first versions of BREEAM and LEED being published in 1990 and 1998, respectively [1, 41]. Additionally, GBTool, later known as SBTool, was initially launched in 1998 following an international development effort that began in 1996 [11]. In subsequent years, numerous sustainability assessment methods have been developed by organisations, institutions, and researchers across various countries and continents [4, 45, 16].

These methods exhibit varying degrees of similarity and differentiation in terms of their philosophy, scope of application (whether international or national, building uses addressed, etc.), range of criteria, and methodological structure. Notably, some differences can also be observed among the successive versions of these methods themselves, as they continuously evolve, expand in scope, and adapt to new challenges and conditions, which is key to their effectiveness and relevance.

When considering trends in the sustainability assessment of the built environment, it is important to note the growing interest in scales larger than individual buildings. Methods addressing neighbourhood or even city scales have emerged as early as the 2000s, with their development receiving continuous and intensive enhancement. While many issues at the building scale are being adequately addressed (with room for improvement), the broader scope offers greater opportunities and challenges, leading to a focus on larger entities within the built environment. Moreover, the principles of the Circular Economy can be effectively applied not only at the building scale but also at the neighbourhood and urban scales, considering key factors of circularity in the built environment. Prominent sustainability assessment methods for buildings, such as BREEAM, LEED, DGNB, and CASBEE, have expanded to develop tools for the urban scale (e.g., BREEAM Communities, LEED for Neighborhood Development, DGNB for Urban Districts, and CASBEE for Urban Development, respectively).

Another example of a multi-scale approach is CESBA (Common European Sustainable Built Environment Assessments), which extends the reliability of SBTool to both the building and neighbourhood scales. CESBA represents a bottom-up initiative aimed at promoting the harmonisation of sustainability assessments across Europe, from buildings to neighbourhoods and regions. It particularly emphasises a neighbourhood-level approach to developing synergies in energy efficiency[1]. However, the analysis in this work focuses on the building scale.

A significant number of comparative reviews of building sustainability assessment methods can be found in the literature, addressing their basic characteristics or their approaches to specific performance aspects (for example, see [2–6, 10, 15, 21, 24, 35–37, 39, 41, 45]. Detailed information about comparative review studies of such tools can also be found in various works, e.g., in [30]. Some of the most widely known and applied sustainability assessment methods appear more frequently in these review studies, highlighting their importance and influence. It is evident that the simultaneous, critical, and comparative consideration of multiple methods has been a focal point in scientific efforts aimed at improving these tools since their early development.

In this review, the analysis focuses on four sustainability assessment methods for buildings: BREEAM, DGNB, LEED, and SBTool. The versions studied are the most

[1] The CESBA SNTool led to the MED Passport enabling the comparison of the performances of buildings and neighbourhoods, in line with the EC COM 2014 445. A CESBA MED network of cities was setup in order to maximise the transferability of results [9].

recent, applicable to new buildings and suitable for international use. Where different schemes exist for tertiary and residential buildings, the tertiary sector version is examined. These methods were selected based on their widespread use in Europe and their international scope. Additionally, Level(s) is included in this review. Although Level(s) differs in some aspects of its philosophy compared to the other "typical" methods examined, it is a constantly evolving common European framework that may serve as a common axis for implementing sustainability assessment principles and procedures in the building sector and construction practices in the future. Moreover, given that Level(s) is a focal point of CircularB Action's interests, its inclusion alongside the other methods is essential.

19.3.2 BREEAM

Introductory remarks. BREEAM (Building Research Establishment Environmental Assessment Method) is a widely recognised environmental assessment method and rating system used to evaluate and measure the sustainability performance of various building types. Developed by the Building Research Establishment (BRE) in the United Kingdom in 1990, BREEAM has continuously evolved, adapting to advancements in sustainability practices and expanding its scope [7]. The system employs established performance indicators that adhere to defined standards and benchmarks, assessing the technical performance, design, construction, and ongoing use of buildings. These indicators encompass a broad range of factors, from energy consumption to ecological impact, covering multiple dimensions of environmental performance.

BREEAM's holistic approach and continuous development have enabled it to be successfully adapted to almost any building type and to various scales within the built environment. The method includes applications for different scenarios, such as evaluating new sustainable building projects through BREEAM New Construction or its international counterpart, assessing existing non-domestic, commercial, industrial, retail, and institutional buildings using the BREEAM In-Use scheme, applying a sustainable assessment method for refurbishment projects with BREEAM Refurbishment, and even planning for the creation of neighbourhoods and urban areas for new communities through BREEAM Communities [7].

This analysis focuses on the BREEAM International New Construction 2021 scheme (BRE [8]). BREEAM currently categorises its assessment into nine *environmental sections*: (i) Management, (ii) Health and Wellbeing, (iii) Energy, (iv) Transport, (v) Water, (vi) Materials, (vii) Waste, (viii) Land Use and Ecology, (ix) Pollution and an additional one – (x) Innovation. Each environmental *section* contains a varying number of specific issues. For example, the Management *section* includes five *issues*; Health and Wellbeing comprises nine *issues*; Energy covers 11 *issues*; Transport includes seven *issues*; both Water and Materials comprise four *issues* each; Land Use and Ecology and Waste cover four and seven *issues* respectively; Pollution

BREEAM Rating	Outstanding	Excellent	Very Good	Good	Pass	Unclassified
	★★★★★	☆★★★★	☆☆★★★	☆☆☆★★	☆☆☆☆★	☆☆☆☆☆
Score [%]	≥ 85	≥ 70	≥ 55	≥ 45	≥ 30	<30

Fig. 19.2 BREEAM rating benchmarks for new construction [7]

includes five *issues*; and the Innovation category, while not containing specific *issues*, contributes to the overall assessment.[2]

The assessment process in BREEAM is based on evaluating each *issue* against specific *criteria*. Each of the ten major BREEAM categories is assigned a certain number of credits based on its compliance with the relevant sustainability *criteria*, with each *issue* accompanied by a number of available credits. The total number of points awarded for each *environmental section* is divided by the total number of points available for it, and this ratio is multiplied by the *section's* relative weighting. The sum of these weighted scores, along with the potential contribution from the Innovation *section*, determines the overall BREEAM score, expressed as a percentage. This percentage score corresponds to a range of ratings, from "Pass" for basic levels of sustainability to "Outstanding" for exceptional and comprehensive sustainability performance (Fig. 19.2).

To achieve a "Pass" rating, a building must meet minimum standards in critical areas such as energy and water, with the requirements varying by building typology. As the rating level increases, the mandatory criteria and percentage scores required for each ranking become progressively broader.

Circularity implementation. In this study, the investigation of circularity implementation is conducted at the most granular rated level of BREEAM's structure, which is the level of individual *issues*. Each *issue* is examined based on specific assessment *criteria*, and, as outlined in the introductory remarks, credits are awarded or withheld depending on compliance with these *criteria*.

To identify the *issues* associated with circular economy-related strategies and principles, as defined in the employed framework, a comprehensive review of the entire BREEAM assessment structure was conducted. The identified *issues* are presented in Tables 19.2 and 19.3, which show *criteria* directly associated with circular economy principles and those that are indirectly related, respectively. The content of each *issue*, including assessment *criteria* and compliance conditions, was thoroughly analysed to determine the nature and type of association (direct or indirect).

Additionally, the tables provide information on the specific circular principles and strategies that are reflected within each *issue*, along with estimations regarding

[2] The numbers of the *issues* mentioned as being part of BREEAM's *environmental sections* exclude the ones that are not addressed as stand-alone *issues* in the context of the examined version of the method. Furthermore, it is noted that if an *issue* is differentiated for two types of building uses (e.g., Ene2a and Ene2b), it is counted as being two individual items (in the previous example, Ene 2a and Ene 2b are counted as two *issues* – and are treated as such in Tables 19.2 and 19.3).

Table 19.2 *Issues* which are directly[3] associated with circularity (circular principles as reflected in the employed framework)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Management (Man)	Man 02	Life cycle cost and service life planning	REDUCE primary materials and resources consumption (weaker direct association, since this principle is addressed through the LCC planning and the service life considerations)	Material & design & management
Health and wellbeing (Hea)	Hea 02	Indoor air quality	REDUCE: doing more with the same system (flexibility and adaptability of ventilation system is considered) is promoted RETHINK existing building ventilation strategy is designed to be flexible and adaptable to potential building occupant needs and climatic scenarios	Site & design
	Hea 04	Thermal comfort	REDUCE: doing more with the same system (adaptability to a projected climate change scenario is considered) is promoted REFURBISH: in case that the response to the projected climate change scenario is not satisfactory, then adaptation potential using passive strategies must be demonstrated for the related credit to be awarded RETHINK existing design solutions in order to be easily adapted in the future	Design
Energy (Ene)	Ene 01	Reduction of energy use and carbon emissions	REDUCE consumption of energy for operation (resources)	Design (site, material and management issues are involved)
	Ene 03	External lighting	REFUSE external lighting RETHINK existing design and management approach of external lighting in order to prevent operation during daylight hours	Design & management

(continued)

[3] Direct association: direct reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion.

Table 19.2 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Ene 04	Low carbon design	REDUCE non-renewable energy consumption (passive design and low or zero carbon technologies)	Design
	Ene 05	Energy efficient cold storage	REDUCE consumption of energy (resources)	Materials & design & management
	Ene 06	Energy efficient transportation systems	REDUCE consumption of energy (resources)	Design & management (in terms of how the transportation systems are fitted and work)
	Ene 07	Energy efficient laboratory systems	REDUCE consumption of energy (resources)	Design & management
	Ene 08	Energy efficient equipment	REDUCE consumption of energy (resources)	Materials (in the sense of appliances/systems) & design
Trasport (Tra)	Tra 01	Public transport accessibility	REFUSE private transport use (objective as a whole) REDUCE: refusing, in consequence reduce transport-related pollution and emissions	Site & design
	Tra 03a	Alternative modes of transport	RETHINK: car sharing is considered in the context of one option REDUCE: more indirectly associated in comparison to the other elements of the 10-Rs; the use of high carbon transport modes and individual journeys is considered in the objective as a whole REFUSE using previous approach of using inefficient modes of transport	Site & design

(continued)

Table 19.2 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Tra 03b	Alternative modes of transport	RETHINK: car sharing is considered in the context of one option REDUCE: more indirectly associated in comparison to the other elements of the 10-Rs; the use of high carbon transport modes and individual journeys is considered in the objective as a whole REFUSE using previous approach of using inefficient modes of transport	Site & design
Water (Wat)	Wat 01	Water consumption	REDUCE: water consumption (use of efficient systems is also considered), consuming fewer water resources RECYCLE & REUSE: greywater/ rainwater (the existence of such systems is taken into consideration)-REUSE water as a "product" RETHINK: multifunctional systems for efficient water consumption	Design & management (some site-related aspects are also taken into consideration)
	Wat 03	Water leak detection and prevention	REPAIR: as a result of detecting problems REDUCE: water consumption by preventing leaks	Design & management
	Wat 04	Water efficient equipment	REDUCE: water consumption (use of efficient systems is also considered)	Design

(continued)

Table 19.2 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Materials (Mat)	Mat 01	Life cycle impacts	This issue is concerned with the use of LCA on the project, and the robustness of the method or tools used. At present the performance is not benchmarked As such: RETHINK & REDUCE, since the reliable consideration of the life cycle impact is promoted. Furthermore, performance of LCA studies may lead to the examination of more alternatives and the adoption of environmentally friendly solutions REDUCE: by calculating life cycle impact, using data from the EPDs and conducting this analysis, environmental emissions-related impacts could be reduced	Material & design
	Mat 05	Designing for durability and resilience	REDUCE raw materials consumption (resilient and durable structures requiring fewer repairs): resilience and (raw materials consumption) - durability; frequent repairs	Material & design
	Mat 06	Material efficiency	RETHINK: increase of materials' and their use's efficiency is promoted REDUCE: increase of materials efficiency, reduce impacts and waste and, use of primary materials REUSE: of existing materials is considered RECYCLE: the procurement of materials with higher levels of recycled content is included among the potential practices for increased efficiency in use of recycled content	Material & design (some management-related issues are taken into consideration)

(continued)

Table 19.2 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Waste (Wst)	Wst 01	Construction waste management	REDUCE: construction waste reduction and consuming fewer materials REUSE & RECYCLE: construction waste and key refurbishment and demolition materials RECOVER of waste materials is considered	Material, construction & management
	Wst 02	Recycled aggregates	RECYCLE: aggregates REPURPOSE of secondary aggregates REDUCE: raw materials consumption and primary sources (as a consequence of the above)	Material
	Wst 03a	Operational waste	RECYCLE: the enabling and facilitation of operational waste recycling is considered RETHINK: old approaches to the space for the provision of recycling-related facilities and spaces	Design & management (some material-related issues are also taken into consideration)
	Wst 03b	Operational waste (residential only)	RECYCLE: the enabling and facilitation of operational waste recycling is considered RETHINK old approaches to the space for the provision of recycling-related facilities and spaces	Design & management (some material-related and urban site-related issues are also taken into consideration)
	Wst 04	Speculative finishes	REDUCE the unnecessary waste of materials and refurbish in future	Material

(continued)

Table 19.2 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Wst 05	Adaptation to climate change	REDUCE resources consumption (reduced need for repair and reconfiguration as structural and fabric resilience is under consideration, with adaptation to climate change being also included as an exemplary credit) RETHINK: the previous design approach by conducting a climate change adaptation strategy, as one of the principles of circular construction, appraisal for structural and fabric resilience by the end of Concept Design	Design
	Wst 06	Functional adaptability	REDUCE resources consumption for future adaptations and change of use (adaptability is under consideration) REFURBISH as the facilitation of an "update" of the building uses in the context of its adaptability RETHINK: the previous design approach by introducing functional adaptation measures, as one of the principles of circular construction, through the finalisation of the technical design	Material, design & management (in the sense of preparing a functional adaptation strategy study)
Land use and ecology (LE)	LE 01	Site selection	REUSE land—as a consequence: REDUCE the consumption ("occupation") of previously unoccupied land REUSE/REPURPOSE in terms of brownfields REFURBISH (in the sense of restoring) contaminated land	Site

the level at which these associations occur (e.g., site, material, design, construction, management). It is important to note that general circularity principles, such as adaptability and resilience, have also been considered in this analysis, even though they are not explicitly mentioned in the 10-R framework used. Where applicable, these general principles were correlated with one or more of the 10 strategies in the framework, and the related information is included in the tables.

Table 19.3 *Issues* which are indirectly[4] associated with circularity (circular principles as reflected in the employed framework)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Management (Man)	Man 03	Responsible construction practices	REDUCE: Environmental impacts as result of monitoring site impacts like waste or water	Site, material, design, construction & management
	Man 05	Aftercare	REDUCE: water and energy consumption (setting targets for those items in the context of the exemplary level criteria) RETHINK: by increasing multifunctionality, existing approach and start providing aftercare to ensure the building operates and adapts for future needs	Design & management
Health and wellbeing (Hea)	Hea 09	Water quality	REDUCE water contamination by increasing efficiency in product or system manufacture—e.g., greywater treatment at the building scale	Design & management
Energy (Ene)	Ene 02a	Energy monitoring	REDUCE: energy consumption by monitoring energy input and output (energy cycling process)	Management
	Ene 02b	Energy monitoring	REDUCE: energy consumption by monitoring energy input and output (energy cycling process)	Management
	Ene 10	Flexible demand side response	REDUCE: energy consumption reduction due to flexible demand side response capability for electricity, which is promoted. (adaptability/flexibility aspect issue)	Design & management
Trasport (Tra)	Tra 02	Proximity to amenities	REDUCE transport use and as result its impacts (objective as a whole), the need to access amenities elsewhere RETHINK the space in the neighbourhood	Site & design

(continued)

[4] Indirect association: no reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion. However, a clear connection of the following type can be seen: if this criterion is met, then, as a consequence, a circularity principle will be served.

Table 19.3 (continued)

Environmental section	Issue		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Tra 05	Travel plan	REDUCE reliance on and, therefore, use of forms of travel and transportation that have the highest environmental impact (objective as a whole) RETHINK existing travel plan issues	Site & design
	Tra 06	Home office	REDUCE/REFUSE transportation use to and from work as result its negative impacts (objective as a whole)	Site & design
Water (Wat)	Wat 02	Water monitoring	REDUCE water consumption by monitoring water input and output	Management
Pollution (Pol)	Pol 03	Surface water run-off	RETHINK: multifunctionality of green roofs REDUCE resources consumption in the sense of promoting flood resilience	Site & design

As with all the methods examined in this study, the results presented reflect the estimations and opinions of the sub-groups that worked on them. The determination of whether an association was direct or indirect was the outcome of discussions among sub-group members. These discussions led to a consensus on each *issue*; in cases where disagreements persisted, the majority opinion was recorded. The associations listed in the relevant columns of the tables indicate the principles that at least one sub-group member identified as being reflected in the respective BREEAM *criteria.*

The BREEAM study was conducted by a sub-group consisting of three researchers working on this chapter. As with the other methods examined, the researchers' opinions exhibited varying degrees of agreement and divergence. This variability is expected, given the inherent subjectivity in interpreting and estimating whether certain *issues* are more closely related to sustainability or circularity.

Based on the results shown in Tables 19.2 and 19.3, a key conclusion is that all the major *environmental sections* of the BREEAM method are represented to some extent, although with varying degrees of emphasis. It is important to note that the Innovation is neither included in Table 19.4 nor in the preceding analysis. This exclusion is due to the fact that credits in the Innovation section are awarded either for exemplary performance in certain *issues* (as defined in the BREEAM manual [8]) or when a "particular building technology or feature, design, construction method, or process" [8], p. 35, is recognised as innovative. In the first case, these associations are considered within the context of the respective *issues*, while the second case cannot be easily categorised or included in this type of analysis.

Regarding the nine *environmental sections* examined, it is evident that some are more strongly represented in Tables 19.2 and 19.3 than others. Specifically, direct associations were identified for all *issues* (seven out of seven) in the Waste *environmental section.* Another strongly represented *environmental section* is Water, where three out of four *issues* have direct associations, with the remaining *issue* being indirectly related to the employed circular economy framework. The Energy *section* presents a similar image, with seven directly and three indirectly associated *issues* among the ten ones that are included in it. The Transport *section* also shows a significant connection to circularity, with three direct and three indirect associations out of a total of seven *issues*. The Materials *section* is similarly well-represented, with three of its four *issues* included in Table 19.2.

In contrast, Health and Well-being *section* and the Management *section* are less represented in Table 19.2, with only two out of nine and one out of five *issues*, respectively, showing direct associations. The same pattern is observed in Table 19.3, where only one of the nine Health and Well-being *issues* and two of the five Management *issues* are indirectly related to circularity. The Land Use and Ecology *section* is represented by one *issue* in Table 19.2, while the Pollution *section* shows even weaker representation, with only one indirect association identified.

Overall, direct associations outnumber indirect ones. However, it is important to remember that BREEAM uses weighted scores, meaning that some *issues* contribute more to the final score than others. For instance, the fact that three out of nine Health and Well-being *issues* are associated with circularity does not imply that one-third of the available credits in this *section* are linked to circular principles or strategies. Moreover, within any given *issue*, only a portion of the available credits may be related to circularity. Additionally, each *environmental section* has its own relative weighting, which affects its contribution to the final score.

The results in Tables 19.2 and 19.3 also indicate that certain strategies and principles are more strongly represented than others in the identified associations. For example, the "Reduce" principle appears frequently across different *sections*. "Rethink" is also commonly found in both tables, while "Recycle" and "Reuse" are strongly represented among the direct associations.

All levels examined (site, material, design, construction, management) appear in Tables 19.2 and 19.3, with some levels being more frequently encountered than others. It is expected that the design level is the most frequently referenced, given that the examined BREEAM method primarily addresses new constructions.

19.3.3 DGNB

Introductory remarks. Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) System is a buildings' environmental performance assessment system developed by the German Sustainable Building Council (DGNB in German). The rating system was

Table 19.4 *Criteria* which are directly[5] associated with circularity (circular principles as reflected in the employed framework)

Topic	Criteria group	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Environmental quality (ENV)	ENV1-Effects on the global and local environment	ENV1.1	Building life cycle assessment	REUSE: reusing components or structural elements is taken into consideration (indicator 3) REDUCE: resources consumption (energy, materials) is considered (indicator 3) RECYCLE & RECOVER: taken into consideration within LCA (indicator 3) REPAIR: more indirect association in comparison to the other 3, detected in the fact that service-life considerations are included in LCA	Material & design & construction
		ENV1.3	Sustainable resource extraction	REDUCE the primary raw materials extraction (indicator 2) RECYCLE: for secondary raw materials use (indicator 2)	Material
	ENV2-Resource consumption and waste generation	ENV2.2	Potable water demand and wastewater volume	REDUCE waste water production and potable water consumption (indicator 1) RECYCLE greywater & rainwater (indicator 1)	Site & design
		ENV2.3	Land use	REPURPOSE/REUSE land and REDUCE "consumption" of free land (indicator 1) REPAIR land in case of contamination (CE bonus)	Site & design

(continued)

[5] Direct association: direct reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion. Also, CE association declared in the manual or CE bonus available.

Table 19.4 (continued)

Topic	Criteria group	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Economic quality (ECO)	ECO1-Life cycle costs	ECO1.1	Life cycle cost	REUSE of building components is taken into consideration (CE bonus) RECYCLE & RECOVER taken into consideration (CE bonus) REPAIR & REDUCE: more indirect association in comparison to the other 3 detected in the fact that service-life considerations are taken into consideration in LCC analysis	Material & design & management
	ECO2-Economic development	ECO2.1	Flexibility and adaptability	REDUCE: doing more with the same building (all indicators) RETHINK: high intensity of use (CE bonus), REUSE & REPURPOSE via the flexibility and adaptability promotion (all indicators)	Design
		ECO2.2	Commercial viability	RETHINK: contribution to circular economy by at least one party (CE bonus) *note:* the association of this criterion with circular economy is not considered to be as clear as in the other cases; its inclusion in this table is established by the fact that within its framework, a CE bonus is offered	Design & management

(continued)

Table 19.4 (continued)

Topic	Criteria group	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Technical quality (TEC)	TEC1-Technical quality	TEC1.4	Use and integration of building technology	REDUCE: promoting the reduction of non-renewable energy consumption by the integration of passive systems (indicators 1,2,4 and CE bonusses) REPAIR: All components of the technical facilities are easily accessible for repair. The technical facilities have a sufficient number of sufficiently large mounting openings, doors and corridors to minimise unnecessary interaction with materials during repair or maintenance REFURBISH: promoting the accessibility of the building technologies (indicator 3)	Design & management
		TEC1.6	Ease of recovery and recycling	REDUCE the primary resources required (CE Bonus 1.2-and general aim of the criterion) REUSE of building components taken into consideration (CE bonus 1.3), RECYCLE: easy to recycle materials (indicator 1), REFUSE: avoiding use of building components (CE bonus 1.3), RECOVER: the CE bonus promotes reuse and recovery of materials. The criteria assess the ability of building structures to be easily recoverable - ease of disassembly and ease of separation of building components in terms of max. possible material content (indicator 2)	Materials & design

(continued)

Table 19.4 (continued)

Topic	Criteria group	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		TEC3.1	Mobility infrastructure	REFUSE: refuse to use inefficient mobility infrastructure and old approaches - instead use bicycles, electric vehicles (indicator 1,3); refuse to use personal vehicles - instead use the concept of sharing. (CE bonus 2.1) RETHINK: mobility sharing is promoted (CE bonus 2.1) REDUCE: more indirect association in comparison to the previous ones, as resources consumption may be achieved, e.g. with the provision of bicycle parking facilities (indicators 1–4, taking into account the references in Innovation area)	Site & design & management
Process quality (PRO)	PRO1-Technical quality	PRO1.4	Sustainability aspects in tender phase	REUSE & REPURPOSE & RECYCLE: not excluding and or enhancing at the tender phase the use and or reuse of recycled and or secondary materials for specific applications is promoted (CE bonus 1.2)	Material & management
	PRO2-Construction quality assurance	PRO2.1	Construction site / construction process	REDUCE the amount of generated waste (indicator 4, CE bonus 4.4.)	Site & management
Site quality (SITE)	SITE1-Site quality	SITE1.4	Access to amenities	RETHINK the space and its possible uses (CE bonus) *note:* the association of this criterion with circular economy is not considered to be as clear as in the other cases; its inclusion in this table is established by the fact that within its framework, a CE bonus is offered	Site & design

initially launched in 2008 [4, 15], with its first version addressing the sustainability assessment of new administrative and office buildings in Germany. The certification scheme was used for the first time in the market in 2009 [15]. In the following years, the constantly evolving method expanded to involve additional building uses and lifecycle stages. Currently, schemes / differentiated versions of the method are available for buildings of a plethora of uses, with regard to different stages of their lifecycle, and to areas of application of more specific interest (e.g. "Interiors") are available. A DGNB system for the evaluation of built environment entities at larger scales (districts) has also been developed, encompassing schemes for business districts, event areas, commercial areas, industrial sites, urban districts and other cases (resorts and vertical cities) [15]. DGNB method can be applied also outside Germany (adaptation to local conditions, employment of international standards). The application of the method across Europe, but also in other continents keeps increasing.

In this review, DGNB System for new buildings version 2020 (international) [14] is examined. The method addresses various building uses (office, education, residential, hotel, consumer market, shopping centre, department store, logistics, production, assembly buildings) and has an international scope of application. The aspects of the building that are evaluated (and, consequently, the assessment *criteria*) are classified into six major *topics*: (i) Environmental Quality (including six *criteria*), (ii) Economic Quality (incl. three *criteria*), (iii) Sociocultural and functional Quality (incl. eight *criteria*), (iv) Technical Quality (incl. eight *criteria*), (v) Process Quality (incl. nine *criteria*) and (vi) Site Quality (incl. four *criteria*). Within each one of those *topics*, the *criteria* are organised into *criteria groups*. Each *criterion* includes a set of indicators, which form the basis for its assessment. Each indicator is associated with a maximum number of available points, which are awarded fully, partially or not at all to the assessed building, depending on whether and to which degree this building complies with the requirements and or conditions implemented in the examined indicator's structure and content. The maximum number of available points accompanying each indicator may differ for the various building uses. The score of each *criterion* is derived based on the points awarded to the building in the context of the indicators integrated in this criterion. Regarding the maximum number of points available to be awarded within each *criterion*, 100 is a key value; for some *criteria* 100 points can be achieved, for others more than 100 can be achieved but only 100 can be awarded, while in the context of several *criteria* additional (in regard to 100) bonus points can be "obtained" by the building. Based on the points achieved in the context of each *criterion* and its weighting factor,[6] the scores of the higher levels of the method's structure are calculated. Taking into consideration the derived performance indices and the relative weightings of the six major *topics* (Environmental Quality: 22,5%; Economic Quality: 22,5%; Sociocultural and Functional Quality: 22,5%; Technical Quality: 15%; Process Quality: 12,5% and Site Quality: 5%), an overall performance score is calculated (total performance index). This overall performance

[6] Each criterion is accompanied by a weighting factor, which is associated with its share in the total score. The value of this weighting factor remains the same across all building uses for some criteria, while for others some differentiations appear for specific uses.

Levels of certification	Total Performance Index	Min. Performance Index
Platinum	≥ 80%	65%
Gold	≥ 65%	50%
Silver	≥ 50%	35%
*Bronze**	≥ 35%	-

*only valid for the passed certificate or for the certificate "Buildings in operation"

Fig. 19.3 Levels of certification (ranking classes) of buildings assessed with the application of DGNB System (adapted from [13, 14])

score in combination with the individual performance indices calculated for the six major *topics*, all expressed as percentages, result in the classification of the buildings into a ranking level (platinum, gold or silver) as depicted in Fig. 19.3.

It is noted that there are a few performance requirements within certain *criteria* that must be met by the building in order for the assessment as a whole to be carried out.

Circularity implementation. The investigation of the circularity implementation is taking place at the level of criteria, i.e. the lowest rated level of the method's structure—where the evaluation takes place via the examined indicators for each criterion).

The *criteria* integrated in DGNB's assessment structure, which are additionally associated with the circular economy-related strategies/principles that are outlined in the employed framework, are listed in Tables 19.4 and 19.5. Specifically, Table 19.4 includes the directly associated *criteria*, while in Table 19.5. the indirectly related ones are shown. The additional information appearing in those tables is of the same types as the ones analytically explained for the respective tables (Tables 19.2 and 19.3) appearing in BREEAM's analysis. Following a uniform methodological approach for all the examined methods, the nature of the association is established based on the whole content of each *criterion* (indicators, benchmarks, aim, etc.) and the consideration of general circularity principles (adaptability, resilience, etc.) has also been attempted. In total, the information appearing in the following tables (Tables 19.4 and 19.5) reflects the analysis conducted by the sub-group of researchers involved in it, via the process described for BREEAM.

The sub-group working on DGNB consisted of four members. The fact that the opinions expressed by those researchers were characterised by differences and similarities of a smaller or larger degree, since subjectivity was inherent in the interpretations and the attempted estimations, with several issues lying in the limit between being considered as "sustainability-related" rather than "circularity-related" or vice versa. Specifically, for DGNB, the detection of the *criteria* association was facilitated by the fact that certain of them are accompanied by circular economy bonuses in the structure of the method itself. In those cases, a direct association with circular economy and, consequently, with one or more of the principles outlined in the employed framework is de facto established. However, it has to be pointed out that

Table 19.5 *Criteria* which are indirectly[7] associated with circularity (circular principles as reflected in the employed framework)

Topic	Criteria group	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
Process quality (PRO)	PRO1-Technical quality	PRO1.5	Documentation for sustainable management	REPAIR/REFURBISH: prolonging the lifespan of the building or of specific elements (indicator 1.1)	Management
	PRO2-Construction quality assurance	PRO2.2	Quality assurance of the construction	REDUCE/RECYCLE: with regard to the requirement lists on the construction site fulfilling ENV1.3 criteria (indicator 3.1)	Site& design & construction & management
		PRO2.5	FM-compliant planning	REDUCE energy consumption for buildings' future operation	Management
Site quality (SITE)	SITE1-Site quality	SITE 1.1	Local environment	*Resilience is under consideration; as such,* REDUCE (resources consumption for retrofitting), REUSE (facilities / buildings that have already been impacted by extreme events), REFURBISH (instead of demolishing constructions beyond repair) and RETHINK (the old design approaches and considering adaptability strategies, as one of the main circular principles, regarding the natural effects), *can be referred to*	Site & design & management

the associations detected in this study are not limited to the *criteria*, in the context of which circular economy bonuses are offered.

One of the basic observations resulting from Tables 19.4 and 19.5 is that the vast majority of the *criteria* in DGNB are estimated to be directly related to the examined principles. This is partly due to the fact that circular economy strategies and

[7] Indirect association: no reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion. However, a clear connection of the following type can be seen: if this criterion is met, then, as a consequence, a circularity principle will be served.

requirements are explicitly dealt with and considered in this assessment method. Furthermore, it is noted that several of the *criteria* (four out of six) belonging to the Environmental Quality topic and all of the *criteria* constituting Economic Quality are found to be directly associated with circularity. This is not the case for Sociocultural and Functional Quality (no associations were identified), while three out of the eight *criteria* included in Technical Quality are determined to be characterised by direct relationship with the employed circular economy framework. Process Quality is also represented in Tables 19.4 and 19.5 (two of the nine *criteria* of this *topic* are estimated to present direct associations, with additional three ones being characterised by indirect relationships), with Site Quality also participating with two out of its four *criteria.* At this point, it has to be mentioned that the presented numbers do not account for an exact outline of the contribution of the estimated to be associated *criteria* to the building's total score; indeed, each criterion in DGNB is accompanied by a relevance factor (i.e. a type of weighting) varying for the different building uses and, furthermore, a relative weight is set by the method for each *topic* (see "Introductory remarks" for DGNB).

Additionally, the results shown in the tables above indicate that certain principles seem to be more frequently encountered than others in the identified associations. For example, "Reduce" appears in almost all associations, with "Reuse" and "Recycle" having a considerable impact as well. Of course, other principles/strategies are also reflected in the provided estimations.

Finally, more than one level (site, material, design, construction, management) seem to be aimed at by the vast majority of the criteria presenting a kind of association with circular economy.

19.3.4 LEED

Introductory remarks. In 1998, Leadership in Energy and Environmental Design (LEED) was introduced by the US Green Building Council, as a pilot programme and became an official rating system in 2000. LEED certification serves as a framework for promoting healthy, highly efficient, and cost-saving green buildings, which deliver various environmental, social, and governance benefits. Recognised globally as a symbol of sustainability achievement, LEED certification is supported by a dedicated network of organisations and individuals driving market transformation [44].

LEED-certified buildings can play a key role in addressing climate change, achieving environmental, social and governance (ESG) goals, promoting resilience, and fostering equitable communities. Unlike a narrow focus on specific building elements like energy, water, or health, LEED takes a holistic approach, considering all essential aspects that contribute to creating better buildings [42].

The objective of LEED is to construct superior buildings that:

- Mitigate the impact on global climate change
- Enhance the well-being of individuals

- Safeguard and restore water resources
- Preserve and enrich biodiversity and ecosystem services
- Promote sustainable and regenerative material cycles
- Improve the quality of life for communities

Within the LEED framework, 35% of credits are dedicated to climate change, 20% directly impact human health, 15% focus on water resources, 10% address biodiversity, 10% contribute to the green economy, and 5% impact community and natural resources. In LEED v4.1 Building Design and Construction (the version examined in this report [43]) the majority of credits revolve around operational and embodied carbon considerations. Additionally, LEED categories can contribute to the achievement of the Sustainable Development Goals of the United Nations [42].

The examined performance aspects by the rating systems are divided into categories, which vary depending on the rating system. Each *category* has *prerequisites*, that are mandatory, and *credits*. *Credits* and *prerequisites* constitute the lowest autonomous scored level of the method's structure. To obtain LEED certification, a project accumulates points by meeting *prerequisites* and *credits* related to carbon, energy, water, waste, transportation, materials, health, and indoor environmental quality. These projects undergo a thorough verification and review process conducted by the Green Building Certification Institute (GBCI), which assigns points based on their performance. The number of points attained determines the level of LEED certification awarded: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points), and Platinum (80 + points) [42]. Figure 19.4 illustrates the levels of LEED certification.

Circularity implementation. As mentioned previously, to evaluate the relationship of circularity and the LEED certification, the Building Design and Construction (BD + C) rating system was chosen as the baseline for evaluation. All *categories*, *credits*, and *prerequisites* from BD + C were considered in the analysis.

The circular economy-related strategies and principles, along with their associated *credits* and *prerequisites*, are detailed in Tables 19.6 and 19.7. Table 19.6 outlines the directly related *credits* and *prerequisites*, while Table 19.7 covers the indirectly related ones. The comprehensive content of each *credit* and *prerequisite*, including intent, assessment criteria, and compliance conditions, serves as the basis for identifying the nature and type of association (direct or indirect). Tables 19.6 and 19.7 also provide information on the specific principles/strategies associated with each *credit/prerequisite*, along with estimations of the corresponding *category* (Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency,

LEED level of certification	*Platinum*	*Gold*	*Silver*	*Certified*
Score [number of points earned]	≥ 80	60-79	50-59	40-49

Fig. 19.4 Levels of LEED certification (adapted from [42])

Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation) linked to this association. General circularity principles such as adaptability and resilience have been considered, although not explicitly addressed by the employed 10-R framework. The taken approach involves correlating these general principles with one or more of the 10 strategies employed in the framework, and this information is presented in the tables for reference.

The results presented in the following tables indicate the estimations and opinions of the sub-group working on LEED. The process followed for the formulation of the listed results is the same as the one adopted for BREEAM and DGNB, including the way the associations presented in Tables 19.6 and 19.7 were identified.

The LEED sub-group comprised five members who expressed a range of opinions, varying in degree of similarity and difference. Notably, for LEED, the identification of circular economy association was facilitated by the presence of circular economy criteria and indicators accompanying certain *credits/prerequisites.* This established a direct link between circular economy and one or more principles outlined in the employed framework.

An important observation from Tables 19.6 and 19.7 is that approximately one-third of LEED *credits/prerequisites* are estimated to be directly related to the examined principles. However, some *categories* primarily address sustainability concerns rather than circular economy strategies and requirements. For instance, the Indoor Environmental Quality *category* focuses mainly on user comfort, rather than the circularity of resources. This is the reason why only one of its 12 *credits/prerequisites* is estimated to present an association (in fact an indirect association) with the employed framework. Sustainable Sites *category* follows, accounting for five *credits/prerequisites* estimated to present some kind of association (among which two are directly related and three indirectly) out of the 13 examined ones. In this *category* most of the concerns addressed are related to sustainability and site inherit characteristics.

On the other hand, the two *categories* presenting the highest number of *credits/prerequisites* directly related to the circularity framework, accounting for six *credits/prerequisites* each, are (i) Materials and (ii) Water Efficiency. In the case of Materials *category*, a total of 11 *credits/prerequisites* are available in the rating system, six of which are found to be directly related to circularity. This is due to the fact that those *credits/prerequisites* are based on CE principles, like Design for Flexibility, Construction and Demolition Waste Management, Building Life-Cycle Impact Reduction, and so on. "Rethink", "Reduce", and "Recycle" are the most associated principles/strategies with those *credits/ prerequisites*. It is important to remark that those identified as non-related in Materials *category* are *credits* specifically for healthcare facilities, not for the other typology of buildings. In regard to the Water Efficiency *category*, six of the total seven available *credits/ prerequisites* are estimated to be directly associated. "Reduce" is the principle that appears in all of the *credits/prerequisites*, once the main aim of the *category* is water reduction.

Location and Transportation as well as Energy and Atmosphere *categories* are estimated to be mostly related to the "Reduce" principle. Indirect associations were identified for five out of the existing eight *credits/prerequisites* in Location and

Table 19.6 *Credits/prerequisites* which are directly[8] associated with circularity (circular principles as reflected in the employed framework)

Category	Credit or prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
Integrative Process (IP)	Integrative project planning and design	RETHINK: in terms maximising opportunities for integrated design. Utilising innovative approaches and techniques REDUCE: IPPD can contribute to circularity by encouraging stakeholders to consider resource efficiency from the early planning stages of a project through optimising the use of materials, energy, and other resources and cost-effective adoption of green design and construction strategies REUSE: by emphasising the importance of reusing materials and products whenever possible REFURBISH & REMANUFACTURE: incorporate to circularity by designing products or systems that are easy to maintain, upgrade, or repair RECYCLE: promote recycling as a way to keep materials and resources in circulation	Site & design
	Integrative process	RETHINK: Utilising innovative approaches and techniques REDUCE: the integrative process encourages all stakeholders including architects, engineers, and builders to work together to consult and design buildings in the early design stages to implement resource-efficiency which can lead to reducing the overall use of materials, energy, and water, consequently minimising resource consumption REUSE: Under this step, it is important to make the necessary integration according to Reuse principles	Site & design

(continued)

[8] Direct association: direct reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion.

Table 19.6 (continued)

Category	Credit or prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
Sustainable Sites (SS)	Rainwater management	REUSE & RECYCLE: water as a "product", apply rainwater management strategies such as using rainwater harvesting technologies can lead to water reuse and increase water efficiency REDUCE: runoff volume, flooding downstream RECOVER & REPAIR: Collecting rainwater, keeping it for a certain period of time for the necessary sanitation process, and then using it is important for recovery & repair	Site & design
	Joint use of facilities	RETHINK: rethink of traditional practices, emphasising the efficient use of resources, space, and infrastructure and promoting sharing as a concept REDUCE: the need for multiple entities to build and maintain separate infrastructure, such as buildings, utilities, and transportation systems, and as a result - resource consumption, energy use, and land use	Site & design & management
Water Efficiency (WE)	Outdoor water use reduction	RETHINK: multifunctional systems for efficient water consumption, develop landscape design strategies for harvesting and using rain water for non-potable purposes REDUCE water consumption and outdoor potable water REUSE: use captured rainwater or recycled water for irrigation purposes RECYCLE: recycle water	Site & design & management
	Indoor water use reduction	RETHINK: developing design strategies for optimising and reduce water consumption REDUCE: water consumption REUSE: use captured rainwater/ or recycled water for non-potable uses RECYCLE: recycle water	Design & management
	Building-Level water metering	RETHINK & REDUCE: metering provides an index that can help to predict and identify management strategies to reduce water consumption in the future	Design & management

(continued)

Table 19.6 (continued)

Category	Credit or prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Outdoor water use Reduction	RETHINK: multifunctional systems for efficient water consumption, develop landscape design strategies for harvesting and using rain water for non-potable purposes REDUCE water consumption and outdoor potable water REUSE: use captured rainwater or recycled water for irrigation purposes RECYCLE: recycle water	Site & design & management
	Indoor water use reduction	REDUCE: water consumption REFUSE: using inefficient equipment (kitchen, washing mashines) which causes bigger water consumption	Design & management
	Optimize process Water Use	RETHINK: design strategies to reduce water consumption REDUCE water consumption REUSE: installing water treatment facilities to circulate indoor wastewater, use alternative water for cooling RECYCLE: recycle water	Design & management
	Water metering	RETHINK & REDUCE: metering provides an index that can help to predict and identify management strategies to reduce water consumption in the future	Design & management
Energy and Atmosphere (EA)	Minimum energy performance	RETHINK & REDUCE: adopting design strategies to optimise and reduce energy consumption	Design & management
	Optimize energy performance	RETHINK & REDUCE: adopting design strategies to optimise and reduce energy consumption and resources, as a result environmental and economic harms associated with excessive energy use and greenhouse gas emissions	Design & management
	Renewable energy	RETHINK: adopting strategies for transition to renewable & clean energy sources REDUCE fossil fuel consumption, GHG emission & carbon footprint	Site & design & management

(continued)

Table 19.6 (continued)

Category	Credit or prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
Materials and Resources (MR)	Storage and collection of recyclables	RECYCLE: promote recycling practices by providing dedicated areas for collection and storage of recyclable materials REDUCE: waste storage and collection can lead to a reduction in the demand for new materials REMANUFACTURE: by adopting these strategies, valuable materials can be Remanufactured	Design & management
	Building Life-Cycle impact reduction	RETHINK: by using innovative and eco-friendly design principles and encouraging adaptive reuse REDUCE: reduce the environmental impact of construction and operation by using fewer materials and resources REUSE: adopting strategies for reusing materials and components from existing buildings RECYCLE: encourage recycling of construction materials, such as concrete, steel, and wood	Material & design & construction
	Sourcing of raw materials	REFUSE: by encouraging and supporting products and materials from responsible sources, which provides materials with lower environmental impact. And by refusing irresponsible sources RETHINK: design strategies, products and materials. And selecting materials that are easier to disassemble, repair, or recycle REDUCE: responsible sourcing contributes to circularity by promoting the closed-loop use of materials and reducing the demand for new raw materials REUSE: reused materials are encouraged RECYCLE: by encouraging the use of materials/ products with recycled content	Material & design & construction
	Material ingredients	REFUSE: by preventing hazardous materials use RETHINK: design strategies, products and materials. By knowing information about the product, it is assumed that this product can last longer, not be harmful to users and reduce the need to replace it	Material & design & construction

(continued)

Table 19.6 (continued)

Category	Credit or prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Design for flexibility	RETHINK/ REPURPOSE: by encouraging adaptive reuse, flexibility and adaptability, and possibly reducing the repair needs REDUCE: by implementing strategies to increase building flexibility	Material & design & construction
	Construction and demolition waste management	RETHINK/ REPURPOSE: by applying design strategies to use CDW REDUCE: by adopting waste management strategies to reduce the generation of waste REUSE/ RECYCLE: reusing and recycling of demolition waste like metal, wood, glass, etc	Material & design & construction

Transportation *category*, while seven out of 10 *credits/prerequisites* (in which three are directly related and four indirectly) of Energy and Atmosphere *category* are included in Tables 19.6 and 19.7.

It is important to note, that as the LEED system is based on points awarded under the *categories*, and the number of possible points varies from *credit* to *credit*, the number of associations -by itself- within the circularity framework does not necessarily reflect the percentage of the available points that can be potentially achieved in the context of those *credits*.

Furthermore, the results presented in the tables highlight that certain principles, such as "Reduce" and "Rethink," appear in nearly all associations, while "Reuse" and "Recycle" also have a significant impact. Evidently, other principles and strategies have been listed in the preceding tables as well, outlining almost the whole spectrum of the considered framework.

19.3.5 Level(s)

Introductory remarks. The Level(s) framework is a comprehensive EU framework developed to establish a common language towards sustainability assessment in both new-built and renovation projects, with a particular focus on office and residential buildings. It is designed to align with the circular economy action plan and incorporates a lifecycle approach from cradle to cradle to ensure long-term resource efficiency. The framework also utilises a value and risk rating system to emphasise the importance of sustainability. While the core sustainability indicators of Level(s) primarily concentrate on the environmental performance of buildings throughout

Table 19.7 *Credits/prerequisites* which are indirectly[9] associated with circularity (circular principles as reflected in the employed framework)

Category	Credit or Prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
Location and Transportation (LT)	LEED for neighborhood development location	REFUSE: reduce vehicle distance travelled, avoid development on inappropriate sites RETHINK: design strategies REDUCE: encourage the reduction of automobile usage, adopting cost-effective strategies	Site & design
	Sensitive land protection	RETHINK: by promoting compact, mixed-use developments can reduce urban sprawl, preserve open space, and promoting efficient land use patterns REUSE: redevelopment of previously contaminated or underutilised areas can promote urban revitalisation and reusing existing infrastructure	Site
	High-priority site and equitable development	REUSE/RECOVER: by encouraging developments in Previously Developed Land and promoting the remediation of brownfields REDUCE: undeveloped land use	Site

(continued)

[9] Indirect association: no reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the criterion. However, a clear connection of the following type can be seen: if this criterion is met, then, as a consequence, a circularity principle will be served.

Table 19.7 (continued)

Category	Credit or Prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Surrounding density and diverse uses	REFUSE: promoting the reduction of vehicle distance travelled by encouraging development in areas with infrastructure RETHINK: design strategies REDUCE the use of the automobile by adopting cost-effective strategies REUSE: by promoting existing infrastructure. Higher urban density can reduce the overall consumption of land and resources per capita. Efficient land use minimises the need for transportation, lowers energy demand, and reduces the environmental footprint of urban areas REUSE/ REPURPOSE: diverse urban neighbourhoods often have older buildings that can be repurposed or adaptively reused for new functions which can preserve existing structures and reduce the need for new construction RECYCLE: urban areas with diverse uses can support robust recycling programs, allowing for the efficient collection and recycling of materials like paper, glass, and plastics	Site
	Access to quality transit	REDUCE/ REFUSE: reduce car dependency. Quality transit systems are typically more energy-efficient than private vehicles, which can lead to resource recovery and reduced energy consumption REPAIR/ REFUSBISH: regular maintenance and rehabilitation of transit vehicles and infrastructure extend their useful lifespan, allow for the reuse of existing assets rather than replacing them entirely, and reduce waste	Site

(continued)

Table 19.7 (continued)

Category	Credit or Prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
Sustainable Sites (SS)	Protect or restore habitat	REUSE: Environmental Site Assessment promotes the preservation of natural site features like wetlands, forests, and topography, which can be considered as a form of reuse by maintaining the ecological functions of the site	Site
	Site master plan	REUSE: by encouraging the preservation and adaptive reuse of existing natural and built features on the site, such as trees, historic structures, or infrastructures. It can also reduce waste and conserve resources	Site & design
	Tenant design and construction guidelines	REDUCE/ REPAIR: Development of such plans, which include recommendations for maintenance, description of design solutions - prolong the life of materials and building	Design & management
Energy and Atmosphere (EA)	Fundamental commissioning and verification	RETHINK: commissioning plan can implement strategies to extend product's life, and reduce material-water-energy consumption REDUCE: the Operations and Maintenance Plan could reduce unnecessary repair/ refurbish for equipment and plan maintenance activities carefully	Design & construction & management
	Building-level energy metering	RETHINK/ REDUCE: by identifying opportunities for energy savings. Metering provides an index that can help to predict and develop management strategies to optimise energy consumption in the future	Design & management
	Enhanced commissioning	RETHINK: commissioning plan, strategies to extend product's life	Design & construction & management

(continued)

Table 19.7 (continued)

Category	Credit or Prerequisite	Association with circularity (employed framework)	Level (site, material, design, construction, management)
	Advanced energy metering	RETHINK/ REDUCE: by identifying opportunities for energy savings. Metering provides an index that can help to predict and develop management strategies to optimise energy consumption in the future	Design & management
Indoor environmental Quality (EQ)	Daylight	RETHINK/ REDUCE: by applying design strategies to use more natural light reduce energy consumption for lighting	Design

their lifecycle, the framework also encompasses aspects related to comfort, health, and lifecycle costs.

By adopting six macro-objectives, Level(s) translates them into 16 measuring indicators that contribute to key target areas set by the EU, such as energy efficiency, resource consumption, waste generation, water usage, indoor comfort and cost and risk assessments. This holistic approach allows the framework to provide building performance reports on individual aspects accompanying a project professional course since the conceptual design, through implementation and construction up to completion and operation. The end-of-life stage is also considered, particularly in macro-objective 2: Resource efficient and circular material life cycles, which includes indicators like design for adaptability (DfA) and design for disassembly (DfD). Additionally, the methodology incorporates a simplified Life Cycle Analysis (LCA) that encompasses inputs from macro-objectives 1, 2, and 3 as well as Life Cycle Cost Analysis (LCCA) in macro-objective 6. Table 19.8 presents an overview of the six macro-objectives of Level(s) framework along with their scope and objectives.

Level(s) framework supports the project development at three levels of performance assessment:

- Level 1: Conceptual design, which employs a qualitative assessment methodology primarily using simple checklists to report the intended implementation concepts.
- Level 2: Detailed design and construction performance, which utilises a quantitative assessment methodology to evaluate the designed performance and monitor construction according to standardised units and methods.
- Level 3: As-built and in-use performance assessment, which also employs a quantitative assessment for monitoring and surveying activities during the building's use stage after completion.

These levels enable a progression in terms of reporting accuracy and expertise, empowering stakeholders to continuously refine and improve the sustainability

Table 19.8 Level(s) Macro objectives scope

Macro objective	Scope
MO1. Greenhouse Gas Emissions Along a Building's Life Cycle	Aims to reduce a building's carbon footprint. Considering all life cycle stages of buildings, greenhouse gas emissions contributing to global warming potential are evaluated. These emissions are referred to as whole life cycle carbon and apply to building materials and their management processes (embodied carbon emissions) as well as operational carbon emissions. Improvement of the building's carbon footprint can refer to optimisation of material flows, enhancing productivity, reducing delays, eliminating waste, and minimising energy usage for heating and cooling
MO2. Resource Efficient and Circular Material Life Cycles	Aims to improve building's performance by considering circularity principles, limiting the use of raw materials, identifying opportunities for reuse or recycling, and ensuring that buildings can be readily adapted to occupants' needs change over time. The aim of macro-objective 3 (efficient use of water resources) is to make use of water resources more efficiently, particularly in areas of identified long-term or projected water stress [13]. Macro-objective 4 (healthy and comfortable spaces) aims to create buildings more comfortable, attractive, and productive to live and work in. In these ways, human health protection can be improved [13]. Macro-objective 5 (adaptation and resilience to climate change) aims to make new building resilient against projected climate changes and thus protect the health and comfort of occupiers. Moreover, long-term risks to property values and investments can be minimised [13]. Macro-objective 6 aims to optimise the life cycle cost and value of buildings. Considering this approach, the potential for long-term performance is improved. Moreover, costs related to inclusion of acquisition, operation, maintenance, refurbishment, disposal, and end-of-life treatment are reduced [13]
MO3. Efficient Use of Water Resources	Aims to make use of water resources more efficiently, particularly in areas of identified long-term or projected water stress [13]
MO4. Healthy and Comfortable Spaces	Aims to create buildings more comfortable, attractive, and productive to live and work in. In these ways, human health protection can be improved [13]
MO5. Adaptation and Resilience to Climate Change	Aims to make new building resilient against projected climate changes and thus protect the health and comfort of occupiers. Moreover, long-term risks to property values and investments can be minimised [13]
MO6. Optimised life Cycle Cost and Value	Aims to optimise the life cycle cost and value of buildings. Considering this approach, the potential for long-term performance is improved. Moreover, costs related to inclusion of acquisition, operation, maintenance, refurbishment, disposal, and end-of-life treatment are reduced [13]

performance of their buildings. The Level(s) common framework offers multiple advantages for three main groups of stakeholders: (1) Project design teams, including architects, engineers, quantity surveyors, and specialist consultants; (2) Clients and investors, such as property owners, developers, managers, and investors; and (3) Public policy makers and procurers at national, regional, and local levels.

To calculate each indicator at the three levels of assessment, Level(s) provides specific instructions and guidelines. These can be found in the respective user manuals for each indicator. To ensure comparability between buildings with the same function, the framework recommends the use of national tools and standards, along with renowned private ones, utilising common measurement units for indicator calculation. The manual for each indicator provides these recommendations. The framework does not introduce a new methodology for sustainability calculation; instead, it emphasises the importance of reporting and using appropriate tools and methods for fixed key parameters throughout the lifecycle using the three levels of assessment. The measurement unit varies across indicators, and the final scores are neither normalised nor accumulated to provide an overall sustainability or circularity score for benchmarking building performance.

To utilise the framework, a Level(s) project plan must be established by following these steps:

- Step 1: Define the macro-objectives to be addressed in the project and identify the indicators to be used for performance assessment and reporting under each macro objective.
- Step 2: Determine the performance level of assessment for the preselected indicators.
- Step 3: Plan the workflow requirements and resources needed for assessment at different lifecycle stages, including defining roles and responsibilities of stakeholders, discussing expertise, and training requirements, establishing management models for information and data acquisition and flow, and setting specific deadlines.

The framework provides multiple tables and reporting formats to support the development of these steps. Additionally, it offers a specific format for a complete building description, which includes information on location and climate, typology and age, building usage, and building model and characteristics. This information is necessary for the calculation of multiple indicators within the framework. Detailed guidance and supportive information are provided to assist in developing a comprehensive building description.

The level or levels of assessment can be determined based on the project's needs and priorities. It is possible to assess only one level or progress up to a specific level. Combining certain levels is also an option. The level definition can be applied to different indicators, allowing for assessment at various levels. However, the more levels that are addressed, the more accurate the understanding of the project's performance will be, including any gaps between design and the reality of the completed building. The framework also provides opportunities to further optimise performance in most indicators. This can be achieved by using input data with higher granularity, considering additional design and performance aspects, testing and comparing additional scenarios, or utilising more advanced calculation methods. Table 19.9 presents the main points addressed in each of the three levels of assessment in terms of project stages, assessment approach, reporting rules and steps, optional additional steps, and the need for a full building description.

Circularity implementation. The analysis of circularity implementation in this section focuses on the indicator level, which constitutes the third tier of the framework, following the thematic areas and macro-objectives, consequently. The examination involves assessing the alignment of 16 indicators in Level(s) V1.1, integrated within the six macro-objectives, with the 10-Rs principles. The findings of this assessment are summarised in Tables 19.10 and 19.11.

Table 19.10 provides an in-depth analysis of the direct relationships between the indicator scope, criteria, guidelines, and objectives within the 10-R framework. In contrast, Table 19.11 delves into the secondary impacts that indirectly contribute to circularity. In both tables, each of the 16 indicators is evaluated for its relevance to the 10-Rs circularity principles, with the results detailed in the final column in each table. Only the principles that are pertinent to each indicator are mentioned.

It is important to note that the examination results represent a consensus among three researchers in the field. However, these findings aim to provide a broad overview of the indicator framework's alignment with circularity principles without specifying their specific relationship to one or more of the three assessment levels of the framework. This is because all three assessment levels complement one another and ultimately support the same overarching logic and goal.

The sub-group working on Level(s) comprised three researchers in the field. The opinions expressed by these researchers shared notable similarities while also exhibiting some low to moderate differences on certain indicators. The primary points of contention revolved around the indirect relationships of specific indicators with circularity. Nevertheless, these differences predominantly arose due to varying subjective interpretations of sustainability and circularity concepts, and the inherent, undefined interplay between them without clear delineation of their scope. However, it is important to note that these differences in opinions were expected and were effectively addressed through extensive discussions and the exchange of perspectives to refine the results and determine which indicators had a direct association and which had an indirect connection to the 10-R principles of circularity.

The indicators that exhibit the strongest direct links to circularity implementation are the four indicators within Macro Objective 2, "Resource-efficient and circular material life cycles." These indicators concentrate on design and engineering to promote lean and circular material flows, extend product service life and material utility, and minimise environmental impacts. However, it is important to recognise that the majority of the remaining circularity-relevant indicators in the other Macro Objectives are influenced by the indicators within Macro Objective 2.

A more detailed explanation on the indicators that establish direct circularity association (Indicators 2.1, 2.2, 2.3 and 2.4) and their indirect impact on the framework's other indicators is provided in the subsequent paragraphs. This is followed by paragraphs explaining LCA and LCC indicators in Macro Objectives 1 and 6,

Table 19.9 Important aspects addressed in each of the three levels of assessment in Level(s) framework

	Level 1 Conceptual design	Level 2 Detailed design and construction	Level 3 As-built and in-use
Project stages	• L1a. Project definition and brief • L1b. Concept design	• L2a. Outline design (spatial planning and permitting) • L2b. Detailed design (tendering) • L2c. Technical design (construction)	• L3a. As-built design • L3b. Commissioning and testing • L3c. Completion and handover • L3d. Occupation and use
Assessment type	Qualitative assessment using checklists and reporting formats	Quantitative assessment using the provided reference calculation methods and the common units of measurement	
Reporting rules and steps	• Complete a Level(s) project plan, following steps 1–3 • Specify which design concepts have been addressed • For renovation projects, report on the baseline survey, using the format provided	• Complete a Level(s) project plan, following steps 1–3 (if not done before) • Complete the building description • For renovation projects, report on the baseline survey, using the format provided • Report on the results of the assessment of each indicator using the respective formats • Report on the method used and the main assumptions for each indicator using the respective formats	• Complete a Level(s) project plan, following steps 1–3 (if not done before) • Complete the building description (if not done before) • Report on the results of the assessment of each indicator using the respective formats • Report on the method used and the sampling strategy used for each indicator using the respective formats
Optional additional steps	• Select and report on the results of steps that go further	• Select and report on the results of recommended optimisation steps in indicators' manuals	• Select and report on the use of any of the recommended optimisation steps in indicators' manuals • Report on the results of surveys of occupant satisfaction
The need for a complete building description	No	Yes	Yes

Table 19.10 Criteria which are directly associated with circularity (circular principles as reflected in the employed framework)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
1. Resource use and environmental performance	MO1. Greenhouse gas emissions along a building's life cycle	1.1 Use Stage Energy Performance (kWh/m^2/year)	REDUCE: • The primary goal of this indicator is to promote the reduction of energy consumption and the associated environmental impacts, such as greenhouse gas (GHG) emissions, during a building's operational stage • Reducing energy consumption during the usage stage is closely linked to resource efficiency. Lower energy use translates to reduced resource consumption for energy production
		1.2 Life Cycle Global Warming Potential (CO2 eq./m^2/year)	REDUCE: • The indicator aims to reduce the building's life-cycle GWP and embodied carbon levels • Products with lower GWP often require fewer resources, such as raw materials and energy, during their production and use • Contemplating adaptive reuse and renovation in this indicator helps reduce the additional resources required for these activities and therefore reduces the lifecycle GWP compared to a new building

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
	MO2. Resource efficient and circular material life cycles	2.1 Bill of Quantities, Materials and Lifespans	<u>RETHINK:</u> • The indicator aims to achieve material savings by considering shared elements <u>REDUCE:</u> • The indicator aims to achieve material savings by reducing floor-to-ceiling heights to minimise structural material use and save resources • The indicator aims at reducing the material footprint by incorporating passive thermal devices and renewable energies to lower the energy consumption, cost and carbon emissions • The indicator aims at optimising the use of fit-out materials that cater to occupants' needs while avoiding unnecessary materials that might end up as waste • By using materials efficiently, minimising waste production during construction, and designing for deconstruction, the industry can reduce its impact on resource consumption <u>REUSE:</u> • The indicator aims to enhancing material efficiency by optimising the load-bearing capacity of structural elements (beams, columns and floor plates) to facilitate a building's future adaptive reuse • It promotes the compliance with design for disassembly requirements and future element reuse, reducing the need for new resources <u>REPAIR:</u> • The indicator aims at enhancing material durability to extend the building life service by designing for easy repair • The indicator allows to record material and component service lifespans, and schedule replacement and repair • Repairing and maintaining existing structures can extend their lifespan and reduce the need for demolition, reconstruction and new construction <u>REFURBISH:</u> • The indicator aims at enhancing material durability to extend the building life service and support potential refurbishments • The indicator suggests using recycled content from reclaimed resources to support building refurbishment projects <u>REMANUFACTURE:</u> • The indicator suggests using recycled content from reclaimed resources in product remanufacturing and integration into new or renovated building projects <u>REPURPOSE:</u> • The indicator suggests using recycled content from reclaimed resources supporting product repurpose to be used in the same or different industry

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
		2.2 Construction and Demolition Waste	<u>REDUCE:</u> • The indicator aims to shape the outline Waste Management Plan (WMP) and thus allowing to reduce the quantities of CDW generated <u>REUSE:</u> • The indicator aims to promote and allow users to systematically plan for the reuse of materials and waste <u>REPAIR:</u> • The indicator aims to promote and allow users to systematically plan for elements repair and maintenance <u>REFURBISH:</u> • The indicator aims to promote and allow users to systematically plan for elements and building systems refurbishment <u>REMANUFACTURE:</u> • The indicator aims to promote and allow users to systematically plan for elements recovery and therefore facilitating their remanufacturing <u>REPURPOSE:</u> • The indicator aims to promote and allow users to systematically plan for safe elements recovery and therefore facilitating their repurposing for different applications <u>RECYCLE:</u> • The indicator aims to promote and allow users to systematically plan for facilitated recycling <u>RECOVER:</u> • The indicator aims to promote and allow users to systematically plan for possible material and energy recovery from CDW

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
		2.3 Design for Adaptability and Renovation	RETHINK: • The aim of this indicator is to motivate designers to think about multiple alternatives and appraise the ones that facilitate potential adaptability and renovation REDUCE: • By promoting the design of buildings with extended lifespan, a great reduction in resource consumption, waste generation and environmental impact occur REUSE: • Extending the lifetime of buildings entails facilitates multiple uses and adaptive reuse REPAIR: • Applying the principles of DfA enables facilitated access to elements to repair, maintenance and replacement REFURBISH: • DfA allows to extend the lifetime of building by facilitating refurbishment and renovation

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
		2.4 Design for Deconstruction	REFUSE: • This indicator allows to achieve circularity by enabling the recovery of components for reuse in multiple cycles possibly in multiple buildings or building systems RETHINK: • The intentional design of buildings for deconstruction implies an upfront lifecycle thinking on how to use building components and products to their highest extent REDUCE: • DfD aligns with the reduce principle of circularity by minimising the amount of resources needed and waste generated during a building's or product's life cycle REUSE: • This indicator promotes circularity by enabling the recovery of building elements for future reuse REPAIR: • DfD facilitates easy repair and maintenance through access zones REFURBISH: • Easy recovery of building elements and products facilitate their refurbishment • Easy access to damaged elements that need replacement of maintenance provide proper conditions for efficient building refurbishments REMANUFACTURE: • DfD principles enable facilitated elements recovery and use of discarded products or products part to manufacture new products with similar function REPURPOSE: • DfD principles enable facilitated elements recovery and use of discarded products or products part to manufacture new products with different functions RECYCLE: • DfD encourages easy separation and recycling of materials and components and continuous circulation into the production process

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
	MO3. Efficient use of water resources	3.1 Use Stage Water Consumption (m^3/occupant/year)	RETHINK: • The indicator supports appraising lower water consumption alternatives over water-intensive processes or products considering a full lifecycle perspective REDUCE: • The indicator contemplates reducing water consumption during the use stage for more efficient use of this critical resource, especially in areas with water scarcity • Reducing water consumption will reduce the embodied environmental impacts of delivering water to the point of demand
2. Health and comfort	MO4. Healthy and comfortable spaces	4.1 Indoor Air Quality	N/A
		4.2 Time Out of Thermal Comfort Range	N/A
		4.3 Lighting	REDUCE: • Applying design strategies as to allow more natural light to enter spaces reduces energy consumption for lighting and the associated GHG emissions
		4.4 Acoustics	RETHINK: • Acoustics performance is directly related to material used and structural architecture of the building

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
RE3. Cost, value and risk	MO5. Adaption and resilience to climate change	5.1 Life Cycle Tools: Scenarios for Projected Future Climatic Conditions	RETHINK: • The information provided by life cycle tools for climate scenarios can help appraise among multiple design options the alternative that better suits its environment minimising resource consumption and environmental impact REDUCE: • If the building is designed to meet future climate change, its lifetime will be extended and the probability of maintenance and repair will be lower reducing resource consumption and environmental impact
		5.2 Increased Risk of Extreme Weather	RETHINK: • The consideration of the increased risk of extreme weather can help appraise among multiple design options the alternative that better suits its context minimising therefore resource consumption and environmental impact REDUCE: • If the building is designed to meet future climate change particularly the risk of extreme weather, its lifetime will be extended and the probability of maintenance and repair will be lower thus reducing resource consumption and environmental impact
		5.3 Sustainable Drainage	RETHINK: • The indicator implies a creative approach to how sustainable drainage systems can mitigate the increased risk of flooding caused by urbanisation

(continued)

Table 19.10 (continued)

Thematic Area	Macro objective	Indicator	Association with circularity (employed framework)
	MO6. Optimised life cycle cost and value	6.1 Life Cycle Costs (€/m^2/year)	REDUCE: • LCC analysis considers the total costs related to resource consumption over the lifecycle of a product, which can help to optimise and reduce resources consumption
		6.2 Value Creation and Risk Factors	RETHINK: • The appraisal of product selection based on their future value help minimise risks, costs and resources REDUCE: • If an asset is designed to maximise its value and value retention over time, the probability of its lifetime to be extended will be higher. This will indirectly contribute to the reduction of resource consumption and environmental impact

Table 19.11 Criteria which are indirectly associated with circularity (circular principles as reflected in the employed framework)

Thematic Area	Macro Objective	Indicator	Association with circularity (employed framework)
1. Resource use and environmental performance	MO1. Greenhouse gas emissions along a building's life cycle	1.1 Use Stage Energy Performance (kWh/m^2/year)	RECYCLE: • Energy efficiency can indirectly impact recycling. Products that consume less energy during their usage stage might have a reduced carbon footprint, making them more environmentally friendly in terms of recycling processes. However, recycling energy-intensive products can pose greater challenges

(continued)

Table 19.11 (continued)

Thematic Area	Macro Objective	Indicator	Association with circularity (employed framework)
		1.2 Life Cycle Global Warming Potential (CO_2 eq./m^2/year)	REUSE: • The indicator contemplates future adaptive reuse, which, in comparison to new construction, will result in lower embodied and operational GHG emissions and GWP • Products with low GWP may have a minimal environmental footprint over their lifecycle, making them more likely to be reused REPAIR: • The indicator contemplates future adaptive reuse, which, in comparison to new construction, will create a circular path of preserved and recovered materials to be repaired REFURBISH: • The indicator considers future adaptive reuse of existing buildings and materials to be refurbished, aiming to reduce both embodied and operational GHG emissions and GWP REMANUFACTURE: • The indicator contemplates future adaptive reuse, which, in comparison to new construction, will create a circular path of recovered materials to be remanufactured • Products with low GWP are better candidates for remanufacturing because they have a smaller carbon footprint REPURPOSE: • The indicator contemplates future adaptive reuse, which, in comparison to new construction, will create a circular path of recovered materials to be repurposed RECYCLE: • The indicator contemplates future adaptive reuse, which, in comparison to new construction, will create a circular path of recovered materials to be recycled. Recycling products with low GWP can help reduce the overall carbon emissions in the product lifecycle

(continued)

Table 19.11 (continued)

Thematic Area	Macro Objective	Indicator	Association with circularity (employed framework)
	MO2. Resource efficient and circular material life cycles	2.1 Bill of Quantities, (BoQ) Materials and Lifespans	RECYCLE: • Compiling a BoQ properly support facilitated and efficient recycling of construction and demolition waste RECOVER: • Compiling a BoQ properly facilitate the streaming of non-recyclable or non-reusable components of construction and demolition waste for energy recovery
		2.2 Construction and Demolition Waste	The elements listed in Table 19.1 under indicator 2.2 can be categorised as having both direct and indirect impacts on circularity
		2.3 Design for Adaptability and Renovation	REDUCE: • Creating buildings and products that can be easily adapted and renovated rather than replaced, can reduce the need for new resource consumption and minimises waste REUSE: • Applying reusable products and material in buildings promote their adaptability and lifespan extension RECYCLE: • Designing buildings for adaptability and renovation often involves the use of recyclable materials and components which ensure that materials can be recycled at the end of their life, reducing waste and conserving resources
		2.4 Design for Deconstruction	RECOVER: • DfD minimises CDW to be sent to energy recovery. However, it facilities the process by efficient and effective separation of recoverable and unrecoverable waste for the last to be streamed for energy recovery

(continued)

Table 19.11 (continued)

Thematic Area	Macro Objective	Indicator	Association with circularity (employed framework)
	MO3. Efficient use of water resources	3.1 Use Stage Water Consumption (m^3/occupant/year)	REDUCE & REUSE: • Employing technologies such as rainwater harvesting and grey water filtering supports the reduce and reuse principle REDUCE & REPAIR: • Repairing water infrastructure such as leaky pipes or malfunctioning water systems, can help reduce water waste during the Use stage
2. Health and comfort	MO4. Healthy and comfortable spaces	4.1 Indoor Air Quality	N/A
		4.2 Time Out of Thermal Comfort Range	REDUCE: • Applying strategies such as passive energy technologies for heating and cooling provides thermal comfort while reduces energy consumption and GHG emissions
		4.3 Lighting	N/A
		4.4 Acoustics	N/A
3. Cost, value and risk	MO5. Adaption and resilience to climate change	5.1 Life Cycle Tools: Scenarios for Projected Future Climatic Conditions	N/A
		5.2 Increased Risk of Extreme Weather	RETHINK: • The consideration of the increased risk of extreme weather can help appraise among multiple design options the alternative that better suits its context minimising therefore resource consumption and environmental impact REDUCE: • If the building is designed to meet future climate change particularly the risk of extreme weather, its lifetime will be extended and the probability of maintenance and repair will be lower thus reducing resource consumption and environmental impact

(continued)

Table 19.11 (continued)

Thematic Area	Macro Objective	Indicator	Association with circularity (employed framework)
		5.3 Sustainable Drainage	REDUCE: • It indirectly allows to reduce the use of freshwater in the building REUSE: • Sustainable drainage practices like rainwater harvesting and greywater recycling can promote water reuse for irrigation or non-potable uses
	MO6. Optimised life cycle cost and value	6.1 Life Cycle Costs (€/m^2/year)	REDUCE: • The indicator can contribute to achieving a reduced environmental impact because higher initial capital costs may be required to achieve lower life cycle running costs • The development of a maintenance and replacement plan by applying circularity design and material concepts can support more cost effective management of assets and subsequently, reduced overall building-associated costs through the whole lifecycle REUSE: • The indicator encourages the reuse of materials when it is cost-effective RECYCLE: • The indicator encourages the recycle of materials when it is cost-effective
		6.2 Value Creation and Risk Factors	RECYCLE: • A value can be created when contemplating recycling of waste

respectively, which are also of great importance to circularity particularly the (R2) Reduce strategy, despite being well known for sustainability assessments.

Indicator 2.1. Bill of quantities, materials and lifespans. The scope of this indicator encompasses data for all construction products and materials procured for constructing new buildings or renovating existing ones. With regard to circularity, this indicator offers recommendations for the following project aspects:

1. Achieving material savings by considering shared elements (**Rethink R1**) based on building typology, such as common sidewalls, and by reducing floor-to-ceiling heights to minimise structural material use (**Reduce R2**).
2. Enhancing material efficiency by optimising the load-bearing capacity of beams, columns and floor plates to align with client needs. These decisions influence the future options for adaptability and renovation (indicator 2.3) facilitating adaptive reuse of the building (**Reuse R3**).
3. Reducing the material footprint by incorporating passive thermal devices and renewable energies to lower the energy consumption, cost and carbon emissions (**Reduce R2**).
4. Enhancing material durability to extend the building life service by designing for accessibility for **repair (R4)**, disassembly (indicator 2.4), and potential **refurbishment (R5)** to support adaptability (indicator 2.3).
5. Optimising the use of fit-out materials that cater to occupants' needs while avoiding unnecessary materials that might end up as waste (**Reduce R2**), as calculated in indicator 2.2 Construction and demolition waste.
6. Ensuring compliance with design for disassembly requirements and future element **reuse (R3)**. The indicator also suggests using recycled content from reclaimed resources (supporting product **refurbishment (R5)**, **remanufacture (R6)** and **repurpose (R7)**) and integrating it into new or renovated building projects.

While this indicator does not rely on specific inputs from other indicators, the information gathered for it provides reporting requirements to several other Level(s) indicators, notably:

- 1.2. Life cycle global warming potential and/or any Life Cycle Assessment (LCA) by supplying material and product life service information as inputs to LCA analysis, controlling and **reducing (R2)** environmental impacts and carbon footprints through links between BoQ with LCA inventories or environmental databases like EPD.
- 2.2. Construction and demolition waste and materials by converting the BoQ to bill of materials (BoM), aiming to minimise and **reduce (R2)** waste production and natural resource usage.
- 6.1. Life Cycle Costs (LCC) analysis by providing material and product life service information, enabling BoQ to BoM conversion for costs breakdowns of each material or product, critical for cost control and **reduction (R2)**.

Decisions made in this indicator regarding material selection significantly impact the efficiency of other circularity design indicators, specifically, 2.3 Design for adaptability and renovation and 2.4 Design for deconstruction for which material and product lifespans supply crucial inputs.

Indicator 2.2. Construction and demolition waste and materials. In line with the waste hierarchy, this indicator assesses the total volume of waste and materials generated from construction, renovation, and demolition activities. This assessment subsequently helps facilitate and enable systematic planning for waste **reduction (R2)** as well as the **reuse (R3)**, **recycling (R8)**, or recovery of components for **repair (R4)**, **refurbishment (R5)**, **remanufacturing (R6)**, and **repurposing (R7)** of materials and waste through the separate collection of CDW during construction, renovation, and demolition activities. For unrecoverable waste, the indicator helps streamline unrecoverable waste for material and energy **recovery (R9)**.

This indicator relies on critical inputs from indicator 2.1. Bill of quantities, materials and lifespans. It also closely relates to indicators 2.3 "Design for Adaptability and Renovation" and 2.4 "Design for Deconstruction," as the design concept significantly influences waste management throughout construction, utilisation, and end-of-life stages.

Indicator 2.3. Design for adaptability and renovation. The projected service life of a building holds significant implications for the extent of functional utility achievable through the initial investment of materials and resources in its construction. Deliberate considerations in designing a building for future adaptability indicate a primary focus on optimising resource utilisation to maximise the building's functionality over an extended period **(Rethink R1)**.

Incorporating contemplations of future flexibility and adaptability from the early design stages holds tremendous potential in effectively addressing emerging changes over the building's lifecycle. Consequently, this approach contributes to the **reduction (R2)** of environmental impacts and material consumption throughout the entire lifecycle of both the building and its constituent elements.

The concept of Design for Adaptability (DfA) enables more efficient utilisation of space and building structures by providing the essential prerequisites to extend the lifespan of the main building structure and components. This extension facilitates multiple applications through adaptive **reuse (R3)**, **repair (R4)**, and **refurbishment (R5)**. In essence, this indicator plays a pivotal role in mitigating CDW (Indicator 2.2), which typically arises from premature demolition when a building no longer aligns with evolving user and environmental requirements.

DfA goes hand in hand with DfD (indicator 2.4) as both indicators share some important design concepts such as accessibility to services for easy maintenance, **repair (R4)** and replacement of components.

Indicator 2.4. Design for Deconstruction. The indicator evaluates the capacity of a building's design to enable the efficient recovery of materials for future reuse or recycling. It involves assessing the ease of disassembling essential building components, followed by evaluating the ease of reusing and recycling these parts, as well as their associated sub-assemblies and materials.

This indicator allows to achieve circularity by enabling the recovery of components for **reuse (R3)** in multiple cycles possibly in multiple buildings or building systems **refuse (R0)**.

Ensuring easy accessibility to the different elements allows for easy **repair (R4)** and recovery of components that can be **reused (R3)**, **refurbished (R5)**, **remanufactured (R6)**, **repurposed (R7)** and **recycled (R8).**

The intentional design of buildings for deconstruction implies an upfront lifecycle thinking on how to use building components and products to their highest extent **(Rethink R1)** which is essential to **reduce (R2)** the environmental impacts and material use and resource consumption subsequently impacting the amount of waste generated from multiple building activities during construction, operation and maintenance and end-of-life phases (indicator 2.2).

Furthermore, the circularity indicators namely design for adaptability and renovation (indicator 2.3) and design for deconstruction (2.4) have an important indirect impact on the indicators in macro objective 4 by enabling facilitated possibilities to meet the healthy and comfort requirements to users by allowing a certain level of flexibility and upgradability to meet any emergent needs to meet these requirements along the lifecycle of a building.

Indicator 1.1 Use stage energy performance. This indicator measures the energy performance of a building based on the calculated (in design stage) or actual energy consumption (in operational stage) in order to meet the various energy requirements associated with its use. Reporting on this indicator can provide useful insights on the implication of circularity practices on production and use stages related to material use, replacement and refurbishment. By balancing the relationship between circularity and environmental impacts, the most beneficial circularity design and material selection options can be appraised to **reduce (R2)** the environmental impacts since the early design decisions by proactive thinking about the whole lifecycle performance.

Indicator 1.2 Life cycle Global warming potential. This indicator measures the greenhouse gas (GHG) emissions and the global warming contribution associated with the building at different stages along the life cycle from cradle through to grave. Cradle to grave consideration allows contemplating the most beneficial design solutions to balance the levels of embodied carbon and use stage carbon emissions. It helps identify design and material aspects that contribute the most to GHG emissions along a building lifecycle. It therefore, helps improve the design concepts and material selection by recommending relevant circularity aspects to reduce the embodied carbon and use stage emissions. Applying the circularity design and material concepts (Macro objective 2) since the design stage has great influence on **reducing (R2)** embodied carbon levels by contemplating future adaptive reuse of the building itself during the operational stage and creating circular path of recovered materials through reuse, recycling and disposal in the end-of-life deconstruction stage.

Indicator 6.1 Life cycle costs. Life Cycle Costing is a technique that enables comparative cost assessments to be made over a specified period of time, taking into account initial capital costs and future operational and asset replacement cost. It is particularly relevant to achieving an improved environmental performance (relevance with Macro objective 1 indicators 1.1 and 1.2) because higher initial capital costs may be required to achieve lower life cycle running costs **(Reduce R2)**. This indicator allows stakeholders to understand the relationship between upfront capital costs and use stage costs. The development of a medium to long-term maintenance and replacement plan by applying circularity design and material concepts (Macro objective 2 indicators) can support more cost-effective management of assets and subsequently, reduced overall building-associated costs through the whole lifecycle. In the conceptual design stage, this indicator recommends implementing a lifecycle thinking to appraise specific design and material decisions (relevance to Macro objective 2 indictors and indicators 1.1 and 3.1) based on their long-term impact on the overall lifecycle costs.

Indicator 3.1 Use stage water consumption. In addition to the previous indicators, indicator 3.1 Use stage water consumption also establishes an important direct connection to circularity. This indicator measures the total consumption of water for an average building occupant, with the option to split this value into potable and non-potable water. From a lifecycle perspective, this indicator helps appraising lower water consumption alternatives over water-intensive processes or products **(Rethink R1)**. Reducing water consumption will reduce the embodied environmental impacts of delivering water to the point of demand **(Reduce R2).**

19.3.6 SBTool

Introductory remarks. SBTool (Sustainable Building Tool) is a constantly evolving international framework for the assessment of buildings' environmental performance, under the responsibility of iiSBE (international initiative for a Sustainable Built Environment) since 2002. It is the successor (in essence, the evolution) of GBTool, which constituted the computational implementation of the GBC (Green Building Challenge) assessment method. The contribution of researchers and organisations of several countries has been one of the basic pillars for the development of the method and its evolution over time. One important aspect is that SBTool is a generic rating framework or toolbox that only becomes efficient after contextualising the scope, weights and benchmarks [31]. It has been reported to have been used in several countries and regions [31]. Fully functional, adjusted to the local conditions and priorities versions of the method are available for, among others, Italy (Protocollo ITACA), Portugal (SBTool-PT) and Czech Republic (SBTool-CZ).

The process of contextualisation consists of the selection of the most relevant *criteria*, the allocation of weights to each *criterion* to reflect local priorities, and the definition of benchmarks based on local conditions. This tool was specifically designed to allow users to reflect on different priorities and to adapt it to the environmental, socio-cultural, economic and technological context for its application [32]. The result is a framework that can measure the sustainability level of buildings, concerning the context in which it is located.

The family of iiSBE frameworks entails specific tools for buildings, neighbourhoods, and other applications allowing to assign sustainability scores in those different scales. The tools' structure consists of a hierarchy of parameters with the following main characteristics: all the examined parameters (for each scale a different set of problems are examined) are classified into major *performance issues* (referred to also as *issues* from now on); each issue includes several *performance categories*, which, in turn, are consisted of a number of *performance criteria* (referred to also as *categories* and *criteria*, respectively, in the following). The latter represent the level of the tool's structure where the assessment takes place via the examination of the respective indicator and assessment scale.

SBTool for Buildings 2022 [25], which is examined in this work, is consisted of seven *issues* (i. Site Regeneration and Development; ii. Energy and Resources Consumption; iii. Environmental Loading; iv. Indoor Environmental Quality; v. Service Quality; vi. Social Cultural and Perceptual Aspects; vii. Costs and Economic Aspects), 20 *categories*, and more than 100 potentially active *criteria* (depending on the scope of the analysis selected, on the phase of the life cycle of the building, on the building uses and on other factors). The methodology also dictates that in the context of the contextualisation, KPIs need to be determined [26]. The evaluation performed by SBTool can be applied to the four fundamental phases of the construction cycle: pre-design, design, construction or operations, and up to three different occupancy types separately or in a single project can be taken into account. It also considers new or renovation projects.

As previously mentioned, the assessment takes place at the *criteria* level. Each *criterion* is assigned a score ranging from -1 to + 5 (with the exception of those characterised as mandatory, for which the minimum potential score is higher than 1, to a degree decided by the third party contextualising the tool). In this assessment scale, the benchmark of score "0" corresponds to the minimum acceptable performance (established by legislation, standards, or existing performance levels) and 5 represents a value for excellent or ideal performance (where 3 identifies a best-practice value). In other words, each "score" is the outcome of a comparison between the building under consideration and national / regional references. Databases from many sources are used to calculate the score of each criterion. For the calculation of the scores of higher structural levels (*performance categories* and *issues*, total score), the approach used in the SBTool is to weigh the scores of the individual *criteria* and apply a weighted aggregation process. The weighting variables are set at the national/ regional level, in order to achieve the tool's adjustment to the local conditions. The approach adopted enables international comparisons of buildings from various countries [32].

Obviously, the process of weighing and benchmarking are fundamental stages of the process of contextualisation for further assessment on a local/national level. Different weighting systems are used in different adapted versions of the generic tool; in the one reviewed in this study, the weighting takes place at the criteria level.

The application (adaptation) of SBTool is divided in 4 steps:

1. Selection of criteria (local authorities or applicant, among others: selection of issues, criteria and indicators)
2. Weight definition
3. Benchmark definition

4. Indicators assessment

The framework is materialised in two interconnected Microsoft Excel workbooks. The first one (file A) is used to set locally relevant weights, benchmarks, laws, and standards for generic building types in their own region; in other words, this workbook forms the frame, the basis and the context for each local assessment, it is the centre of the methods' contextualisation and adjustment to local conditions (the input in the first file, where the region, occupancy type, weights and benchmarks are determined, are in the local context). The second workbook (file B) is used to compile information about a single project during the assessment. The second file contains particular project weights and benchmarks that are used to perform project information, performance targets, and simulations. A single file A can correspond to any number of files B; for example, file A for office buildings in a given region can be used for the evaluation of any number of office buildings (each one corresponding to its own file B) in this area.

The assessment results contain an extended set of data regarding the performance of the examined building [29]. Specifically, the results of the assessment are represented by a spider web diagram that describes the sustainability level achieved in each one of the *issues* and an overall score of the sustainability performance of the building. Other important aspects of the examined building's performance are summarised in the results report, such as the individual scoring by *issue*, and the project information. It is important to note that not only the derived values relative to the zero benchmark are provided, but also absolute results are shown. Also, occupancy-specific outcomes are provided [29]. In the results report, data regarding central components of the assessment (e.g. relative weights of the active *issues*) is also presented.

Circularity implementation. The implementation of circularity criteria is developed with a detailed evaluation of each indicator in the SBTool framework. This issue is crucial and is at the core of this report. The intention is to understand HOW this circularity is put forward, in practice, or implemented within the framework of analysis.

The *criteria* listed in SBTool are associated with the circular economy 10-R framework of circular economy strategies and are classified in Tables 19.12 and 19.13. Table 19.12, consists of the *criteria* that have been found to have a direct association with CE, while Table 19.13 shows the *criteria* that have an indirect relation. The association was established based on the description and evaluation of each *criterion* (aim, benchmark, indicators, etc.). Additionally, the tables mention which specific principles/strategies were associated with each one of the criteria, as well as the step of the building life cycle in which it is situated. A significant clarification in relation to the referred strategies is that general circularity principles (adaptability, resilience, etc.) have also been considered; in fact, they were "correlated" with one or more of the 10 strategies involved in the employed 10-R framework and appear accordingly in the following tables.

The same approach as in the other methods was employed in cases where disagreements among the members of the sub-group working on SBTool occurred regarding

Table 19.12 *Criteria* which are directly[10] associated with circularity (circular principles as reflected in the 10-R framework)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
A. Urban, site and infrastructure systems	A.1 Site regeneration and development	A1.1	Protection and restoration of wetlands	REPAIR / REFURBISH: restoring damaged wetland provides higher scores within the assessment scale of the criterion	Site
		A1.2	Protection and restoration of coastal environments	REPAIR/ REFURBISH: restoring damaged coastal environments provides higher scores within the assessment scale of the criterion	Site
		A1.3	Reforestation for carbon sequestration, soil stability and biodiversity	REPAIR/ REFURBISH: restoring damaged forested areas provides higher scores within the assessment scale of the criterion	Site
		A1.5	Remediation of contaminated soil, groundwater or surface water	REPAIR/ REFURBISH: the restoration of contaminated soil is promoted REMANUFACTURE: Strategies of treating contaminated soil or groundwater consist in the remanufacturing of contaminated matter	Site
	A.2 Urban design	A2.1	Maximising efficiency of land use through development density	REDUCE use of land (considering land as a resource) RETHINK urban environments for a more efficient use of urban land and services	Site & design

(continued)

[10] Direct association: direct reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the *criterion*.

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	A.3 Project infrastructure and services	A3.1	Supply, storage and distribution of surplus thermal energy amongst groups of buildings	RETHINK: the redistribution of surplus thermal energy from buildings in the zone to other buildings (aiming at the optimisation of its supply, storage and distribution for space heating amongst groups of buildings) is under consideration REDUCE: Rethink strategies can be focused on energy consumption reduction	Site & design & management
		A3.2	Supply, storage and distribution of surplus photovoltaic energy amongst groups of buildings	RETHINK: the redistribution of surplus electrical energy generated by PV in the zone to other buildings (aiming at the optimisation of its supply, storage and distribution amongst groups of buildings) is under consideration REDUCE Rethink strategies can be focused on energy consumption reduction	Site & design & management

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		A3.3	Supply, storage and distribution of surplus hot water amongst groups of buildings	RETHINK: the redistribution of surplus hot water generated from photovoltaic sources on site among buildings (aiming at the optimisation of its supply, storage and distribution amongst groups of buildings) is under consideration REDUCE: Rethink strategies can be focused on resources consumption reduction	Site & design & management
		A3.4	Supply, storage and distribution of surplus rainwater and greywater in groups of buildings	RETHINK: the redistribution to other buildings of the surplus rainwater and greywater generated from roof or site catchment areas or from sanitary waste is considered REDUCE: Rethink strategies can be focused on resources consumption reduction	Site & design & management

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		A3.7	Composting and re-use of organic sludge	REUSE: the existence of an effective composting facility in the project to handle the organic sludge produced and measures regarding its reuse in or off site are assessed RECYCLE: if composting will be considered as a type of recycling	Site & design & management
		A3.8	Provision of split grey / potable water services	REDUCE the use of potable water REUSE greywater	Site & design & management
		A3.10	On-site treatment of rainwater, stormwater and greywater	REDUCE the use of potable water REUSE & RECYCLE greywater/rainwater	Site & design & management
B. Energy and resource consumption	B1. Total life cycle non-renewable energy	B1.1	Embodied non-renewable energy in original construction materials	REDUCE resources consumption (the non-renewable embodied energy, as estimated by an acceptable LCA method, is assessed)	Materials
		B1.2	Embodied non-renewable energy in construction materials for maintenance or replacement(s)	REDUCE resources consumption (the non-renewable embodied energy, as estimated by an acceptable LCA method, is assessed)	Materials

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		B1.4	Consumption of renewable energy for all building operations	REDUCE resources consumption (criteria: renewable energy for building operations)	Design & management
	B3. Use of materials	B3.1	Degree of re-use of suitable existing structure(s) where available	REUSE/REDUCE of existing structures for new constructions. Reduce embodied energy and construction costs	Design
		B3.3	Material efficiency of structural and building envelope components	REDUCE: Reduce the need for new materials, reduce embodied energy and costs. (Increase efficiency of materials)	Design & materials
		B3.4	Use of virgin non-renewable materials	REDUCE: Reduce consumption of non-renewable resources and encourage the use of recycled/refurbished/remanufactured products	Design & materials
		B3.5	Efficient use of finishing materials	REDUCE resources consumption (elimination or reduction in use of finishing materials, whether virgin, re-used or recycled)	Design & materials
		B3.6	Ease of disassembly, re-use or recycling	REDUCE/RECYCLE: Promotes recycling, reusing, refurbishing, and repurposing of building components	Design & materials

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	B.4 Use of potable water, stormwater and greywater	B4.2	Use of water for occupant needs during operations	REDUCE water consumption	Design
		B4.3	Use of water for irrigation purposes	REDUCE/RECYCLE: Reduce potable water consumption, encourage reuse and repurpose of greywater and rainwater for irrigation	Design & management
		B4.4	Use of water for building systems	REDUCE: Reduce the use of potable water, encourage reuse and repurpose of greywater and rainwater	Design & management
C. Environmental loadings	C.3 Solid and liquid wastes	C3.1	Solid waste from the construction and demolition process retained on the site	REDUCE: Reduce solid waste from construction diverted to the waste management system RECYCLE/REUSE: Recycling and reuse of construction waste	Materials & construction
		C3.5	Liquid effluents from building operations that are sent off the site	REDUCE Liquid waste sent off site for treatment	Construction
	C.4 Impacts on project site	C4.3	Recharge of groundwater through permeable paving or landscaping	REPAIR/REFURBISH: Recharging restoring groundwater	Site & design
E. Service quality	E.2 Functionality & efficiency	E2.7	Spatial efficiency	RETHINK: Optimise spatial use of building	Design
		E2.8	Volumetric efficiency	RETHINK: Optimise spatial use of building	Design

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	E.4 Flexibility and adaptability	E4.1	Ability for building operator or tenant to modify facility technical systems	REPURPOSE/REMANUFACTURE of spaces in the building by the possibility to relocate HVAC, lighting and control systems	Design
		E4.2	Potential for horizontal or vertical extension of structure	REPURPOSE/RETHINK: flexibility of the structure design to be extended when needed. Reduce resources consumption when extension is needed	Design
		E4.3	Adaptability constraints imposed by structure or floor-to-floor heights	REPURPOSE/REMANUFACTURE of spaces in the building by the possibility to adapt to other uses	Design
		E.4.4	Adaptability constraints imposed by building envelope and technical systems	REPURPOSE/REMANUFACTURE of building envelope and HVAC and electrical systems in the building by the possibility to adapt to other uses	Design
		E4.5	Adaptability to future changes in type of energy supply	REPURPOSE/REMANUFACTURE of spaces in the building by the possibility to update energy systems	Design

(continued)

Table 19.12 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	E.5 Optimization and maintenance of operating performance	E5.2	Adequacy of the building envelope for maintenance of long-term performance	REDUCE the need for maintenance by ensuring durable design of building envelope	Design
		E5.4	Existence and implementation of a maintenance management plan	RETHINK/REDUCE: Ensure the reduction of energy and water consumption over time by developing a maintenance plan	Design & management
G. Cost and economic aspects	G.1 Cost and economics	G1.3	Life-cycle cost	REDUCE/RETHINK: Life cycle assessment is implied in circular economy	Design, construction & management

Table 19.13 *Criteria* which are indirectly[11] associated with circularity (circular principles as reflected in the 10-R framework)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
A. Urban, site and infrastructure systems	A.1 Site regeneration and development	A1.6	Shading of building(s) by deciduous trees	REDUCE: reduce energy needed for cooling of buildings RETHINK The use of trees for carbon sequestration	Site
		A1.7	Use of vegetation to provide ambient outdoor cooling	REPAIR / REFURBISH: restoring damaged wetland provides higher scores within the assessment scale of the criterion	Site
		A1.10	Provision and quality of children's play area(s)	REDUCE: Indirect relation with the reduction of fuel consumption/CO_2 emissions by reducing transportation needs	Site
		A1.12	Provision and quality of bicycle pathways and parking	REDUCE: indirect relation with the reduction of fuel consumption/CO_2 emissions by reducing transportation needs	Site
	A.2 Urban design	A2.2	Reducing need for commuting transport through provision of mixed uses	REDUCE: indirect relation with the reduction of fuel consumption/CO_2 emissions by reducing transportation needs	Site
		A2.3	Impact of orientation on the passive solar potential of building(s)	REDUCE energy consumption via passive solar systems	Design

(continued)

[11] Indirect association: no reference/description in the intent, indicator, benchmarks, and generally, in the structure and content of the *criterion*. However, we see a clear connection of the type: if this *criterion* is met, then, as a consequence, a circularity principle will be served.

Table 19.13 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		A2.5	Impact of site and building orientation on natural ventilation of building(s) during warm season(s)	REDUCE energy consumption from the need of mechanical ventilation systems	Design
		A2.6	Impact of site and building orientation on natural ventilation of building(s) during cold season(s)	REDUCE energy consumption from the need of mechanical ventilation systems	Design
	A.3 Project infrastructure and services	A3.9	Provision of surface water management system	REDUCE the impact of water sewage systems RETHINK: improve flood resilience capacity of the site	Design
		A3.13	Provision of on-site parking facilities for private vehicles	REDUCE: indirect relation with the reduction of fuel consumption/CO_2 emissions by reducing transportation needs	Design
B. Energy and resource consumption	B1. Total life cycle non-renewable energy	B1.3	Consumption of non-renewable energy for all building operations	REDUCE: reduces resources consumption	Design & management
	B2.Electrical peak demand	B2.1	Electrical peak demand for building operations	REDUCE: reduce resources consumption, often obtained from fossil-fuel generated electrical power	Design

(continued)

Table 19.13 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		B2.2	Scheduling of building operations to reduce peak loads on generating facilities	REDUCE: Related with indicator B1.1	Management
C. Environmental loadings	C.1 Greenhouse gas emissions	C1.1	GHG emissions from energy embodied in original construction materials	REDUCE: Reduction of GHG emissions considering the entire life cycle of materials	Materials
		C1.2	GHG emissions from energy embodied in construction materials used for maintenance or replacement(s)	REDUCE: Reduction of GHG emissions considering the entire life cycle of materials	Materials & management
		C1.3	GHG emissions from primary energy used for all purposes in facility operations	REDUCE: Reduction of GHG emissions from calculated energy use in the building	Materials, construction & management
	C.2 Other atmospheric emissions	C2.1	Emissions of ozone-depleting substances during facility operations	REDUCE: reduction of emissions, which are considered as an impact, consequence of the implementation of other circularity indicators	Design & management
		C2.2	Emissions of acidifying emissions during facility operations	REDUCE: reduction of emissions, which are considered as an impact, consequence of the implementation of other circularity indicators	Design & management
		C2.3	Emissions leading to photo-oxidants during facility operations	REDUCE: reduction of emissions, which are considered as an impact, consequence of the implementation of other circularity indicators	Design & management

(continued)

Table 19.13 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
	C.3 Solid and liquid wastes	C3.2	Solid non-hazardous waste from facility operations sent off the site	RECYCLE: considering future recycling of construction waste	Materials & construction
	C.5 Other local and regional impacts	C5.1	Impact on access to daylight or solar energy potential of adjacent property	REDUCE of resources consumption considering solar power potential	Site & design
E. Service quality	E.1 Safety and security	E1.3	Risk to occupants and facilities from flooding	Related to resilience as a general circular economy principle. Hence, associations with principles of the employed framework are implied: REDUCE resources consumption for repair REUSE/REPAIR facilities	Site & design
		E1.4	Risk to occupants and facilities from windstorms	Related to resilience as a general circular economy principle. Hence, associations with principles of the employed framework are implied: REDUCE resources consumption for repair REUSE/REPAIR facilities	Site & design
		E1.9	Maintenance of core building functions during power outages	REDUCE: related to resilience	Management
	E.3 Controllability	E3.1	Effectiveness of facility management control system	REDUCE (indirect impact on energy consumption)	

(continued)

Table 19.13 (continued)

Issue	Category	Criterion		Association with circularity (employed framework)	Level (site, material, design, construction, management)
		E3.2	Capability for partial operation of facility technical systems	REDUCE (indirect impact on energy consumption)	Design & management
		E3.3	Degree of local control of lighting systems	REDUCE (indirect impact on energy consumption)	Design & management
		E3.4	Degree of personal control of technical systems by occupants	REDUCE (indirect impact on energy consumption)	Design & management
	E.5 Optimization & maintenance of operating performance	E5.5	On-going monitoring and verification of performance	REDUCE: ensure the reduction of energy and water consumption over time	Management
F. Social, cultural and perceptual aspects	F.2 Culture and heritage	F2.4	Use of traditional local materials and techniques	REDUCE: could encourage reduction of the use of high embodied energy materials, raw-materials consumption	Design & construction
G. Cost and Economic aspects	G.1 Cost and economics	G1.2	Operating and maintenance cost	REDUCE water and energy consumption	Management

the existence and type of association of each criterion with the 10-R framework. As also indicated in all other methods, the outlined associations in the following tables are those that were estimated to exist for each criterion by at least one member of the sub-group working on SBTool.

The sub-group working on SBTool consisted of five members. In the analysis of each of the *criteria* many differences were found between the members of the sub-group, mainly in the indirect association with circular economy due to the subjectivity of interpretation of the *criteria*. In SBTool, there is no direct mention of circular economy or consideration of CE in the evaluation of the *criteria* but is implied in the formulation of the tool since it considers criteria for the entire life cycle process of buildings.

The *criteria* that were more evidently related to CE to all the members of the group, were the ones that considered life cycle assessment and that were oriented to optimisation, flexibility and adaptability, reduction and efficiency strategies. Finally, just over a quarter of the total number of criteria considered are presented in Table 19.12 indicating the direct association.[12] For instance, within the Flexibility and Adaptability *category*, all five *criteria* were found to be directly associated with circularity. A similar approach emerged in the Use of Materials *category*, where all five *criteria* (with the exception of one underdeveloped criterion, aligned with the principles of optimisation and minimisation, which was not considered in the present analysis anyway) are directly contributing to the circular economy concept. The following *categories* were also represented by a large number of *criteria* with a direct association in Table 19.12: Use of Potable Water, Stormwater and Greywater (all three *criteria* available), Project Infrastructure and Services (seven out of 11 available), Total Life Cycle Non-Renewable Energy (three out of 4 available). As well as some specific single *criteria* of the following categories are present in Table 19.12: Urban Design, Solid and Liquid Wastes, Impacts on Project Site, Optimization and Maintenance of Operating Performance, Life-cycle cost and others. Regarding the seven examined *issues*, it is evident that some of them, like A. Urban, Site and Infrastructure Systems and B. Energy and Resource Consumption are more strongly represented in Tables 19.12 and 19.13 than for example G. Cost and Economic Aspects. It is also important to note that this domination could be also related to the number of accompanied *credits* in each *issue.*

The *criteria* that were defined with an indirect relationship and approximately account for just over one-sixth of the total number of *criteria*, are the ones related with the GHG, energy consumption and waste reduction since there was a discussion in the differentiation between circularity and sustainability. This is demonstrated in categories such as Greenhouse Gas Emissions and Other Atmospheric Emissions (all three *criteria* in each category), Controllability (all four *criteria*), and Electrical peak demand (all two *criteria*). In the above-mentioned Urban Design *category* there are also *criteria* with indirect association, which account for the majority of those available for assessment (four out of five *criteria*). Site Regeneration and Development is characterised by the same number of direct and indirect associations concerning circularity, four for each type out of twelve possible. The remaining *criteria* are found individually within their respective *categories.*

The concept of "Reduce" dominates in indirect associations, while in direct associations, it occurs, but not so often, typically in combination with other concepts of the employed framework. Additionally, there are some *criteria* that can be included as CE strategies but do not meet the requirements of proposed methodology, as they could not be related to the strategies of the 10-R framework, but could be included in a new aspect, resilience, as seen in the case of the Service Quality *issue.*

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[12] The numbers of *criteria* referred to in this section are based on the maximum scope of application of the examined version of SBTool for new buildngs; the underdeveloped *criteria* were not included in the analysis, while no separate or in any sense special consideration was provided for *criteria* applicable for specific cases (large projects, etc.).

In the *issue* A. Urban site and infrastructure, the most common associations are with the strategies of “Repair” or”Refurbish”, regarding site regeneration and “Reduce” or ‘Rethink” when it comes to *criteria* related to resources consumption for the urban adaptation of buildings. Also, regarding the *issues* B. Energy and resource consumption, C. Environmental loadings and G. Cost and economic aspects, the association with CE is mainly regarding the reduction of resources consumption.

19.4 Conclusions

In this chapter, a first approach to the investigation of the way circularity principles and concepts are implemented into the structure of well-known buildings’ sustainability assessment methods is attempted. Under this light, observations related to the sustainability and circularity relationship, as well as the latter’s representation in the examined methods can be drawn.

A first conclusion lies in the difficulty of establishing clear expert opinions of what is actually circular within a sustainability-oriented context when specific issues and criteria are examined. This difficulty was expected, also based on the various approaches existing for the relationship between sustainability and circularity and its complex nature, as analysed in the respective section of the chapter. Indeed, as noted in the respective sections, disagreements among the members of each expert group examining a method arose. In fact, an absolute consensus in every case was not reached, at least easily. Indicative of the various expert opinions expressed is the fact that the specific principles found to be associated with each criterion by the individual members of each expert group were not the same in all cases.

Of course, differences in the expressed opinions, in terms of whether a type and a scale (and which one) of association exists for specific issues, can be detected in the results derived by each group. However, the central issues do present a degree of homogeneity in the way they were approached in each method. At this point it has to be highlighted that the whole content of the examined level of each method (*criterion*, *issue*) was taken into consideration; this explains the fact that while a criterion in one tool seems to be associated with the employed CE framework, a criterion with a similar title in another tool does not. Differentiations among the evaluation implementation and obstacles encountered for the examined methods arose also due to the fact that their structures are varying, and that the examination took place at the lowest autonomously scored level. For example, for DGNB this means the *criterion* level, with each *criterion* encompassing a number of different indicators, while for SBTool it corresponds to the *criterion* level, with each *criterion* being based on one indicator (i.e., in fact having a narrower scope). Some differentiations were based on the approaches adopted in each method; for example, in DGNB CE bonuses are explicitly related to specific *criteria.*

Another challenge that arose during the process consisted in associating widely accepted building circularity principles (such as adaptability and resilience) or other concepts (e.g. upcycling) with specific circularity strategies of the employed framework. Relevant expert comments and explanations can be found in the "circularity implementation" section of each method, in the tables and or in the text. One possible explanation for this difficulty could be related to the fact that the employed 10-R framework is not oriented towards the building sector exclusively; however, it is important to note that the scope of the analysis considered both building products and buildings as products, mitigating this issue for the majority of cases. Clear matching in such cases may warrant further research and discussion. Furthermore, the development of frameworks capable of comprehensively addressing the complexities of the built environment may be a future goal.

It is interesting to note that the age of the tools may also, to some degree, be reflected in the language used in its assessment. Early tools such as BREEAM were created when the waste hierarchy consisted of three levels, reduce, reuse and recycle. On the other hand, Level(s)' more explicit alignment with 10-R principles could be related to its more recent formation, and its adoption of the expanded waste hierarchy from the literature. In the context of the afore-mentioned example including the oldest and the most recent methods among the assessed ones in this work, it is worth noting that i) the head of the Building Research Establishment is reported in stating that BREEAM will be aligned with Level(s) and ii) BREEAM have recently expanded their tool to be more explicit in measuring circularity. The latter fact shows the flexibility which all these tools exhibit, allowing them to adapt and improve on their sustainability measurements.

Finally, in the majority of the criteria estimated to have an association with circular economy, more than one level (site, material, design, construction, management) was found to be implicated. This fact reveals the complexity of the involved issues and scopes.

It's worth noting that alternative approaches could have been adopted in the context of this work, employing a more "narrow" or "broad" interpretation of whether and to which degree circularity is represented in each criterion. In any case, the presented results should be treated as indications and preliminary findings, as well as a potential basis for future work. This might include the broader participation from stakeholders and researchers, as well as expanded examination of the different methods by a larger and more diverse group of experts, with almost equivalent number of examiners for each method. Furthermore, the scope of the study could be extended to encompass other sustainability assessment methods, other aspects (e.g., existing buildings), and other scales (e.g., neighbourhood or urban scale).

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Part V
Stakeholders and Circular Value Chain Management Editorial

Diana Bajare and Gabriel Zsembinszki

In the constantly changing landscape of sustainable development, the role of stakeholders and the integration of circular value chain management stand as central focal points. As we explore further into the complex interconnections between stakeholders and circular value chain management, it becomes increasingly evident that collaboration, engagement, and overcoming obstacles are critical to driving the transition to a circular economy. Within this framework, the principles of the circular economy serve as guiding stars, illuminating the roles stakeholders play, their challenges, and the opportunities they present. From exploring the significance of locality in enabling circular solutions to defining project lifecycle stages and identifying decision-making activities, each facet offers valuable insights into the complex relationship between stakeholders and circular value chain management. It also delves into the realm of project life cycle stages, illuminating the decision-making activities underpinning the journey toward sustainable development. As the narrative develops, the focus shifts to specific contexts where stakeholders face unique challenges and regulatory landscapes in their efforts to implement a circular economy, particularly within the construction sector. For instance, the barriers and opportunities in construction highlight the urgent need for transformative action. At the same time, case studies from diverse regions provide inspiring examples of effective strategies and best practices in circular economy management. Moreover, education and digitalisation have emerged as powerful tools for fostering relationship-building and shared learning, catalysing the adoption of circular and sustainable approaches in the construction sector. By examining various case studies and best practices, it emphasises how the dissemination of knowledge and initiatives aimed at building capacity have the potential to

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drive significant systemic change. Through a comprehensive assessment of stakeholder opinions, influences, and interrelationships, valuable information is obtained on the costs and benefits of implementing the circular economy in the construction value chain. By fostering collaboration, innovation, and shared learning, we can pave the way toward a more resilient, inclusive, and sustainable future where the circular economy is a cornerstone of progress and prosperity for all.

Chapter 20
Stakeholders' Role, Inter-Relationships, and Obstacles in the Implementation of Circular Economy

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Abstract The building sector contributes around 39% of global carbon dioxide emissions and consumes nearly 40% of all the energy produced. Over the whole life cycle, the building sector yields over 35% of the EU's total waste generation. These

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facts substantiate the necessity to implement circular economy in the built environments, in order to mitigate global warming and climate change emergency. This chapter highlights the state-of-the-art knowledge and research gap with respect to the stakeholders' influences, inter-relationships, and obstacles for circular economy implementation on building stocks. In this chapter, a robust critical literature review of key documentations such as research articles, industry standards, policy reports, strategic roadmaps, case studies, and white papers has been rigorously conducted together with expert interviews. The state-of-the-art review addresses multi scales of CE practices adopted within the built environments. This chapter spells out current challenges and obstacles often encountered by various stakeholders. Case studies related to circular economy implementation have been drawn in order to promote such the CE practices across value chains in different regions and counties; and to overcome the barriers for circular economy implementation.

Keywords Circular economy · Stakeholder analysis · Value chain · Interrelationship · Buildings

20.1 Principles of the Circular Economy

The circular economy aims to minimize waste, maximize resource efficiency, and uphold sustainable development. It is based on several fundamental principles that guide the transition from a linear "take-make-dispose" model to a more regenerative and restorative system. The Circular Design Guidelines (CDG) have been introduced by IDEO and the Ellen MacArthur Foundation (EMF) as tools to help people wanting to start contributing to the planet in transition into a circular economy [1]. The guidelines could be stimulated by an issue related to an increasing global population and the amount of consumption of resources that has resulted in negative impacts on the environment. This is caused by a one-way (linear) production and consumption model, where goods are produced from raw materials, sold, used, and then burned or disposed of as wastes. Circular design (CD) acts as the pivotal point in implementing circular economy (CE) strategies. In this case, IDEO and EMF start to support people who share common goals to contribute to the transition to CE using the CDG. The CDG was published in 2017 [1].

The core principles of the circular economy are as follows:

- **Design out waste, toxicity, and pollution**: The circular economy promotes the design and production of products and services, focusing on reducing waste,

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pollution, and the use of non-renewable resources. It involves incorporating durability, modularity, reusability, and recyclability principles into product design and manufacturing processes [2].

- **Keep products and materials in use**: This principle emphasizes the importance of prolonging the lifespan of products and materials by promoting reuse, repair, and refurbishment. It encourages businesses and consumers to extend the useful life of products through sharing, leasing, and remanufacturing, thereby reducing the need for new resource extraction and minimizing waste generation [1].
- **Regenerate natural systems**: The circular economy recognizes the importance of preserving and restoring natural resources and ecosystems. It aims to minimize environmental impacts and promote sustainable practices, such as adopting renewable energy sources, regenerative agriculture, and ecosystem restoration initiatives [3].
- **Foster collaboration and stakeholder engagement**: The circular economy emphasizes the need for collaboration and cooperation among stakeholders at all levels. This includes engaging businesses, governments, consumers, research institutions, NGOs, and communities to drive collective action, share knowledge, and develop innovative solutions to systemic challenges [1].
- **Shift to a systems perspective**: The circular economy encourages a holistic and systemic approach to resource management. It promotes a shift from a linear supply chain perspective to a more integrated and interconnected system where materials and resources circulate in closed loops. This involves considering the entire lifecycle of products, from sourcing and production to consumption and end-of-life treatment [3].
- **Use digital technology and data for optimization**: Digital technologies, such as the Internet of Things (IoT), big data analytics, and blockchain, can be crucial in optimizing resource use, improving efficiency, and enabling transparency in the circular economy. These technologies can facilitate the tracking and tracing of materials, allow sharing platforms, and support decision-making for resource management [4, 5].

By applying these principles, the circular economy aims to create a more sustainable and resilient economic system that reduces environmental impacts, promotes social well-being, and ensures long-term prosperity. It seeks to decouple economic growth from resource consumption and waste generation, ultimately leading to a more regenerative and restorative approach to economic development.

In addition, the complexity of circular economy practices for existing ageing building stocks is much more critical than those for new buildings. This is because the modification or renovation actions applied to existing building stocks can occur at any stage (such as after ten years of service, 20 years of service, or 50 years of service), which can typically happen due to a change of use. These aspects have raised the complications and impart uncertainties in decision-making and effective technical solutions that could seamlessly enable the transition to net zero. Figure 20.1 displays the uniqueness between circular economy implementation practices for new and existing building stocks. When dealing with existing or ageing building stocks, the

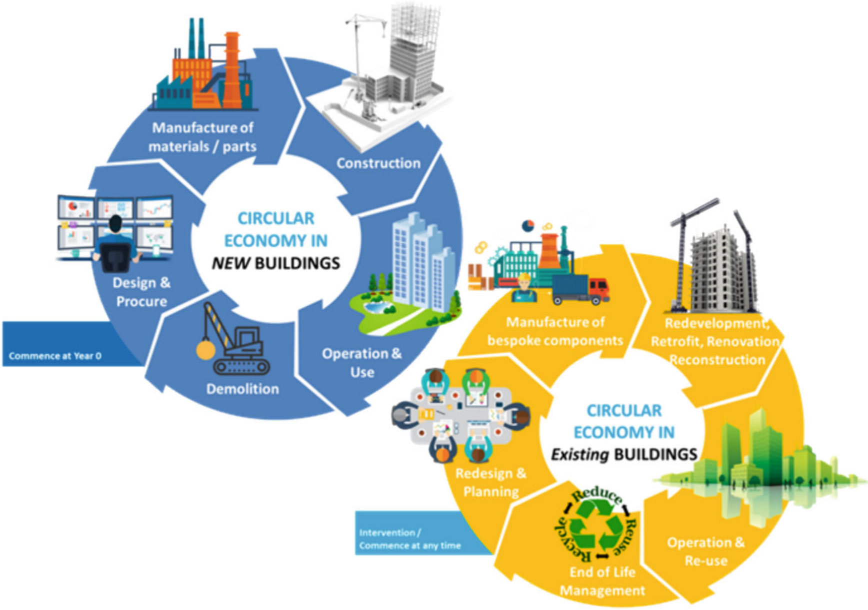

Fig. 20.1 Comparison of lifecycle and circular economy implementation between new and existing building stocks

sophisticated and refined scope of circular economy implementation can be observed. The decision-making mechanisms and influences among stakeholders could be more delicate and bespoke. It is thus very challenging to establish practical policies in order to promote and incentivize the adoption of circular economy practices underpinning net zero.

Reaching net-zero emissions will need transformative strategies for the global economy. Notably, emissions by energy generation also comprise 83% of CO_2 emissions across land-use systems. Indeed, McKinsey [6] reported that 'Effective decarbonization actions include shifting the energy mix away from fossil fuels and toward zero-emissions electricity and other low-emissions energy carriers such as hydrogen; adapting industrial and agricultural processes; increasing energy efficiency and managing energy demand; utilizing the circular economy; consuming fewer emissions-intensive goods; deploying carbon capture, utilization, and storage (CCS) technology; and enhancing sinks of both long-lived and short-lived greenhouse gases' [6]. An approach to achieving a status of NZEBs (Net Zero Energy Buildings) for new buildings and existing buildings is to promote the development, implementation, and automation of circular economy strategies by creating a cohesive network of market actors using Industry 4.0 Technologies via digital transformation, by assuring active stakeholder engagement, and by implementing a series of diverse outreach activities (see Figs. 20.2 and 20.3). These strategies can be further automated to optimize energy consumption within the building stocks to reach net zero emission (or beyond) by

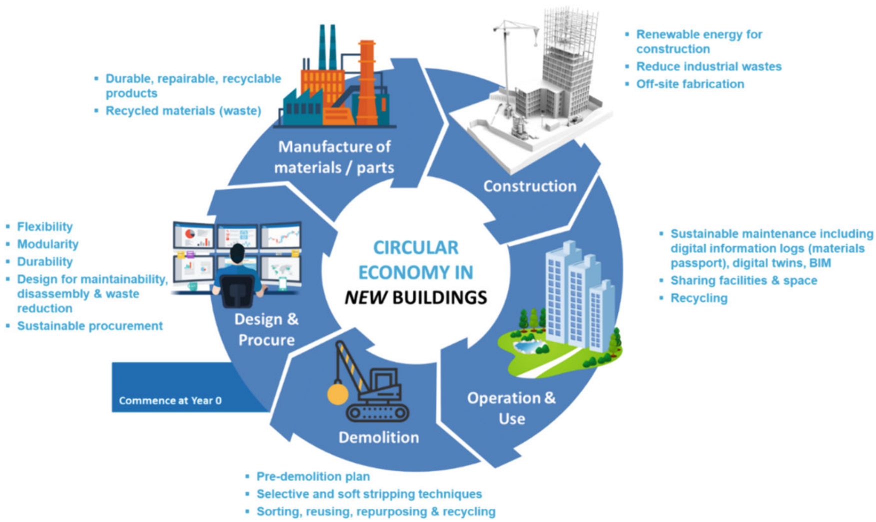

Fig. 20.2 Circular economy perspectives for the new building sector

adopting digital twins and artificial intelligence. To overcome market barriers beyond NZEBs, new strategies are required to simplify the whole process of design, retrofit, and renovation. To reduce emissions in the construction and commissioning stages, pre-simulations could be undertaken using a digital twining platform that is capable of the analyses for appropriate strategies for near zero energy buildings (NZEB) or zero energy buildings (ZEB) or even energy-positive buildings (EPB), life cycle costing and attractive zero-emission/zero-pollution co-benefits [7].

20.2 Stakeholder Roles in Driving the Transition to CE: Collaboration, Challenges, and Opportunities

Stakeholders are crucial in driving the transition to CE by collaborating and coordinating their efforts. They display inter-relationships that can significantly influence progress or present obstacles. Stakeholders can foster innovation, establish sustainable value chains, and contribute to developing a regenerative and circular economic system through their respective roles.

Key roles of different stakeholders:

- **National and Local Governments and Policy Makers**:
  - Develop and enforce regulations, policies, and frameworks that promote circular economy principles.
  - Provide incentives, funding, and support for research and development of circular technologies and practices.

Fig. 20.3 Circular economy perspectives for the existing building sector

- Collaborate with other stakeholders to drive systemic change and create an enabling environment for the circular economy [8].

- **Businesses and Industries**:
  - Adopt circular business models and practices to minimise waste, promote resource efficiency, and extend product lifecycles.
  - Design products for durability, reparability, and recyclability.
  - Collaborate with suppliers, consumers, and other businesses to establish closed-loop supply chains and value networks.
  - Invest in innovative technologies and processes to enable the circular economy.
  - Contractors/subcontractors
  - Use innovative solutions and efficient technologies for resource efficiency, waste reduction, and circular business models.
  - Creates and implements the organization's waste management policy
  - Creates and maintains site conditions for waste management on-site.
  - Supplies of recyclable waste to recycling facilities.
  - Creates a supportive organizational culture.
  - Responsible for the knowledge and skills of staff, i.e., providing education and training.

- **Consumers and End Users**:
  - Make sustainable purchasing decisions by choosing durable, repairable, and eco-friendly products.

- Embrace sharing, renting, and second-hand markets to reduce consumption and extend product lifespans.
- Practice responsible waste management through recycling, composting, and proper disposal.
- Demand transparency and information about the environmental impact of products and services [8].

- **Research Institutions and Academia**:
  - Research to advance circular economy knowledge, technologies, and best practices.
  - Develop innovative solutions for resource efficiency, waste reduction, and circular business models.
  - Provide expertise, training, and education to support the adoption of circular principles by businesses and other stakeholders.
- **Non-Governmental Organizations (NGOs) and Civil Society**:
  - Raise awareness about the benefits of the circular economy and advocate for its implementation.
  - Promote sustainable consumption and behaviour change among consumers.
  - Map, monitor, and provide feedback on the progress and implementation of circular initiatives.
  - Collaborate with other stakeholders to drive policy changes and influence corporate practices.
  - Develop and revise international standards for circular economy innovation to be inclusive and agile.
- **Waste Management and Recycling Industry**:
  - Collect, sort, and process waste materials for recycling, upcycling, and energy recovery.
  - Invest in infrastructure and technologies to improve waste management and recycling capabilities.
  - Collaborate with businesses and governments to establish efficient collection systems and closed-loop material flows.

Governments and policymakers are responsible for creating regulations, policies, and frameworks that support the transition to CE. They work with other stakeholders to develop and enforce these regulations, provide incentives, and support research and development. However, challenges can arise due to political resistance, conflicting priorities, and limited awareness or understanding of the circular economy concept.

Businesses and industries drive the implementation of circular economy principles. They adopt sustainable production methods, design products for longevity and recyclability, and prioritize resource efficiency. Collaboration with government bodies, suppliers, consumers, and waste management entities is essential for establishing efficient material flows and promoting resource reuse, recycling, and upcycling. Business challenges include high upfront costs, technological obstacles, resistance to change, and a potential lack of market demand for circular products.

Consumers and end users have a significant impact on the circular economy through their purchasing decisions. They can drive positive change by supporting sustainable products and services, embracing reuse and recycling, and demanding environmentally friendly options. Consumer interactions with businesses and governments, such as expressing their preferences through purchasing power and providing feedback on product design and disposal systems, are crucial. Challenges for consumers include limited awareness of the circular economy, concerns about affordability, convenience factors, and resistance to behavioral changes.

Research institutions and academia contribute to the circular economy by conducting studies, developing innovative technologies, and sharing knowledge and expertise. Collaboration with businesses, governments, and non-governmental organizations allows for the development and dissemination of best practices, research projects, and training and education. However, limited funding, research gaps, and the time required to translate academic findings into practical applications can present obstacles.

Non-Governmental Organizations (NGOs) and Civil Society organizations play a significant role in advocating for the circular economy, raising awareness, driving behavioral change, and monitoring progress. They engage with governments, businesses, and consumers to promote sustainable practices, influence policies, and provide feedback on implementation. Challenges for NGOs and civil society include limited resources, conflicting interests among organizations, and differing priorities, making coordination and consensus challenging.

The waste management and recycling industry is vital in the circular economy. They collect, sort, process, and reintroduce materials into the value chain. Collaboration with businesses, governments, and consumers helps establish efficient collection systems, invest in recycling infrastructure, and promote circular waste management practices. However, challenges include insufficient infrastructure, lack of standardized processes, and difficulties in managing complex waste streams, which can impact achieving high recycling rates.

Finally, International, Regional, and National Standardization organizations are responsible for creating standard methods and processes for the circular economy, which will support the correct implementation of these processes and ensure a coordinated effort to transition to a circular economy. They develop such standards with regulators, academia, industry, and consumers. The European Standardization Organization (CEN) already has a designated subcommittee to develop a standard for circular economy in the construction sector.

These stakeholders are interconnected and reliant on each other for successful circular economy implementation. Collaboration, dialogue, and alignment of goals are crucial to overcoming obstacles and driving systemic change toward a sustainable and circular future. While the core stakeholders in the circular economy can be similar across different countries, the specific organizations, industries, and individuals may vary depending on the local context and priorities. The particular organizations, associations, and individuals may vary depending on the local context. Additionally, the level of maturity and engagement in circular practices can differ among countries, influenced by factors such as policy frameworks, infrastructure development, cultural norms, scale of activities, and economic conditions.

Based on the critical literature review and desktop study, the stakeholders have been grouped by commercial purpose into industry and non-industry stakeholders. Table 20.1 defines the detailed stakeholders of existing building sectors across Europe. Consequently, the survey through the interview has been conducted to gain further crucial information for later data analyses, including (i) ranking for influence, (ii) inter-relationship correlation, and (iii) barrier identification.

20.3 Stakeholder Engagement and Collaboration in Circular Value Chain Management

In Circular Value Chain Management, various stakeholders play distinct roles that contribute to optimizing and coordinating material and resource flows within the circular economy. These stakeholders include suppliers, raw material providers, manufacturers and producers, distributors and retailers, consumers, waste management and recycling industry, reverse logistics, and circular service providers.

Stakeholders	Circular value chain management
Suppliers and raw material providers	These stakeholders are responsible for supplying the necessary raw materials, components, and resources for production. In the circular value chain, they play a crucial role in sourcing sustainable and recyclable materials that can be reused or regenerated in the value chain
Manufacturers and producers	Manufacturers and producers transform raw materials into finished products. In the circular economy, they adopt design principles that promote product disassembly, reusability, and recyclability. They also explore opportunities for remanufacturing or refurbishment to extend the product's lifespan
Distributors and retailers	Distributors and retailers facilitate the efficient movement of products from manufacturers to consumers. In the circular value chain, they can contribute by promoting products with longer lifespans, offering repair services, or implementing take-back programs for recycling or proper disposal
Developers/contractors	Developers/contractors are responsible for defining the goal and incorporating circularity requirements in construction projects. Their role is crucial in making decisions and actions that will affect the consumer
Consumers	Consumers and end users are critical in circular value chain management through their purchasing decisions and behaviors. In the circular economy, consumers can actively participate by making conscious choices, opting for durable and repairable products, and engaging in sharing or rental platforms

(continued)

(continued)

Stakeholders	Circular value chain management
Waste management and recycling industry	The waste management and recycling industry is responsible for collecting, sorting, and processing waste materials for reuse, recycling, or energy recovery. They collaborate with manufacturers, retailers, and consumers to establish efficient waste collection systems and transform discarded materials into valuable resources
Reverse logistics and circular service providers	These stakeholders handle the reverse flow of products, materials, and components in the value chain. They manage product take-back, repair, refurbishment, and remanufacturing activities. Their role is crucial in enabling the return of products or components to the value chain for further use or recycling. Besides, standards organizations and regulators play a role in characterizing and valorizing waste

A deeper knowledge of stakeholder participation in the CE context enables more informed decision-making when integrating CE into organizational processes and the supply chain. This may also assist practitioners in reconsidering and assessing their stakeholder engagement activities. Implementing circular stakeholder engagement strategies is critical for transitioning to CE in industrial enterprises [9]. To effectively engage and collaborate with different stakeholders with varying roles in the transition to CE, several approaches can be adopted.

Firstly, establish a multi-stakeholder platform where representatives from various stakeholder groups can exchange knowledge, share experiences, and discuss challenges and opportunities related to the circular economy. This platform facilitates collaboration, builds trust, and encourages collective action [3].

Open and transparent communication channels should be fostered among stakeholders. Regular meetings, workshops, and conferences allow stakeholders to interact, understand each other's perspectives, and find common ground. Clear and consistent communication helps align goals, address concerns, and build partnerships.

Identifying shared objectives and interests among stakeholders is crucial. Collaboratively defining goals and outcomes that align with the principles of the circular economy creates a shared vision, fostering cooperation and a sense of purpose.

Encourage stakeholders to actively participate in the co-creation and co-innovation of circular solutions. This involves different stakeholders in designing and developing strategies, policies, and projects related to the circular economy. By including diverse perspectives, innovative and effective solutions can be created.

Partnerships and collaborations among stakeholders should be encouraged. Leveraging the strengths and expertise of each stakeholder group through collaborative projects, joint ventures, and knowledge-sharing initiatives accelerates the implementation of circular economy practices.

Recognizing and promoting best practices implemented by different stakeholders is essential. Highlighting successful circular economy initiatives and examples

Table 20.1 Key stakeholders in building sectors are classified by the life cycle stage (*Data Source* expert discussion with CircularB project members)

Stage of the life cycle:	Who are the stakeholders for residential and non-residential buildings?	What are the key contributors to CO_2e?	What are emerging CE strategies/tools/	Stage of the life cycle:
Planning & design	Owners/investors Financial institution Local councils/ urban planners Architects/ engineers	Energy	Deep renovation Urban wind Photovoltaic technology (PV) Solar thermal energy LCA/Digital twins/BIM Design for reuse/ repurpose	Living cost Financial burden No incentives to improve No governmental directives Risk-averse attitude
Construction/ retrofit/renewal/ refurbishment/ renovation	Construction companies manufacturers engineers experts/ researchers/ standardization organizations	Materials (1. Concrete; 2. Steel; 3. Plastics) Machineries Water Waste Energy	Material circularity (e.g. material passport/BIM) Component circularity (e.g. digital twins) Renewable energy grid Waste reduction (e.g. BREEAM)	Limited technologies options/no incentives No legislation/ standards/ specification
Operation/use	Asset owners Residences (dwellers) Maintainers Experts/ researchers	Water Waste Energy	Resource efficiency Energy efficiency Waste management	Limited methods for service life assessment Human behaviors No incentives
End of life	Asset owners Demolition companies Waste managers Experts/ researchers	Waste (building materials, electrical appliances, furniture) Energy	Material circularity Net zero target Material recycling	Toxicity Uncertainties Limited recycling technologies Limited Standards and specifications
Intervention phase (dealing with residues)	Exporter of wastes Environmentalists	Residuals	Energy recovery factor (ERF)	Landfill Toxicity

inspires others, creates positive models, and motivates stakeholders to adopt similar approaches.

Support capacity-building initiatives that enhance stakeholders' knowledge and skills in circular economy principles and practices. Providing training programs, workshops, and educational resources enables stakeholders to contribute effectively to the circular economy.

Advocate for supportive policies and regulations by collaborating with stakeholders. Engage with policymakers and decision-makers to influence the development of frameworks that incentivize circular business models and sustainable practices.

By adopting these approaches, stakeholders can foster collaboration, leverage their respective roles and expertise, and work together to implement the circular economy successfully.

20.4 Strategies for Overcoming Stakeholder Obstacles in the Implementation of the Circular Economy

Limiting obstacles in implementing the circular economy that may arise from stakeholders requires proactive engagement, effective communication, and addressing their concerns. Here are some strategies to mitigate the barriers:

Stakeholder Identification and Analysis: Conduct a comprehensive stakeholder analysis to identify and understand key stakeholders who may impact the implementation of the circular economy. This analysis should consider their interests, concerns, and potential obstacles they might pose [10]. Organizations can tailor their engagement strategies by gaining insights into stakeholder perspectives. The analysis should also consider the scale of the ecosystem within which the stakeholders operate.

Stakeholder Engagement: Engage stakeholders from the outset of the circular economy implementation process. Encourage open dialogue, active participation, and collaboration to build shared ownership and trust [9]. Involving stakeholders in decision-making processes and seeking their input can help address concerns and foster a sense of inclusion and commitment.

Awareness and Education: Raise awareness about the circular economy and its benefits among stakeholders through targeted communication, educational, and training initiatives. Provide resources, training programs, and case studies to enhance stakeholders' understanding of circular economy principles and practices [11]. Effective communication can help overcome resistance or misconceptions arising from limited awareness.

Addressing Concerns: Actively listen to and address stakeholders' concerns through transparent and honest communication. Provide evidence-based information on the potential benefits and risks of circular economy initiatives, assuaging any apprehensions [12]. This can help alleviate stakeholders' fears and build support for implementing circular practices.

Incentives and Support: Provide incentives and support mechanisms to encourage stakeholders' active participation in circular economy initiatives. This may include financial incentives, grants, or access to resources and expertise [13, 14]. Tailoring incentives to stakeholders' needs can encourage their buy-in and commitment to circular practices [15].

Collaboration and Partnerships: Foster collaboration and partnerships among stakeholders to jointly develop and implement circular economy initiatives. This can involve forming multi-stakeholder platforms, partnerships between businesses and NGOs, or public–private collaborations [16]. Collaborative efforts can leverage diverse perspectives, resources, and expertise to address complex challenges associated with the circular economy.

Continuous Monitoring and Evaluation: Establish mechanisms for continuous monitoring and evaluation of circular economy initiatives, including feedback loops with stakeholders. Regularly assess progress, gather stakeholder insights, and adapt strategies accordingly. This iterative approach allows for timely adjustments, addressing emerging obstacles and maximizing the effectiveness of circular economy implementation.

By actively engaging stakeholders, addressing their concerns, and fostering collaboration, the implementation of the circular economy can be facilitated. Incorporating the diverse perspectives of stakeholders contributes to developing more robust and inclusive circular strategies. In addition, it is essential to consider these interventions in terms of uniqueness (or appropriateness) for the scale and specificity of the region/ecosystem to which it will be applied to.

20.5 Exploring the Significance of Locality in Enabling Circular Solutions in the Built Environment

20.5.1 Exploring the Significance of Locality in Enabling Circular Solutions in the Built Environment

Meanwhile, an emerging interest is in harnessing local knowledge, resources, and stakeholders to achieve tailored and effective circular solutions in the built environment. This can be traced to the broader research on sustainability and socio-technical transitions, which tells us the importance of understanding and working with the 'local context' to achieve the desired outcomes [17]. To gain a circular built environment, understanding and working with the local context, including stakeholders, knowledge, and resources, is essential (e.g., [18]). Therefore, while previously described literature and case studies predominantly emphasize the importance of clear centralized guidance, models, and regulations, there is also an emerging recognition that 'local context' is crucial for implementing practical and customized circular solutions in the built environment [19]. However, currently, there is a lack of conceptual discussion and empirical evidence to define and address 'locality' in the context of circular economy in the built environment [20].

This section discusses two key aspects of 'locality' for effective development and implementation of circular solutions in the built environment: space (both physical and social) and knowledge. It also connects with the broader circular economy literature, which sees cities as the locus of circular transitions by suggesting that cities localize space and expertise. Therefore, this section serves as a starting point for structuring research that aims to enhance our understanding of:

– The role of space and knowledge co-production in achieving a circular built environment.
– The relevant local stakeholders involved in circularity initiatives.
– City-level governance of locality to support a circular built environment.

20.5.2 Locality of Physical Space

The physical/material aspects of the built environment have numerous location-specific features that are critical to consider when developing and deploying circular solutions in the built environment. First, the built environment consists of immovable buildings and infrastructure predominantly consisting of bulk mineral materials with relatively low-cost unit prices and high transportation costs [21]. For these reasons, any innovation in material flows requires considering the physical aspects of space [22]. For example, the availability and distance of raw and used materials, the terrain type, and building density are all important parameters that can affect the optimum circular solution for building materials in a given location [21]. This also means that different spatial features can determine whether narrowing, slowing, or closing material flows would be more advantageous in a given location [23]. Notably, such location-specific determinants become even more influential with decreasing spatial scale as the alternatives to access raw and secondary materials decrease with the decreasing spatial scale.

20.5.3 Locality of Social Space/place

A socially focused understanding of space (i.e., place) refers to the specific set of social relations and social constructions that participate in the (re)production of social structures, social actions, and relations of power and resistance that shape actions and direct behavior in a given locality [24]. The literature on circular economy implies the importance of understanding and working with socio-spatial relationships in a given locality for effective development and implementation of circular solutions in the built environment. Such a consideration of socio-spatial relationships is important for at least two reasons.

First, they can act as enablers or barriers during circular solution development and practical implementation by encouraging or discouraging acceptance/adoption. Socio-spatial relationships determine various actors' resources, incentives, interests, and visions. Thus, depending on how much these are aligned or misaligned determines whether the developed circular solutions could be established in practice.

Second, socio-spatial relationships are important to understand and work with to develop and deploy circular solutions that can bring genuine benefits to the affected local people and places instead of exploiting them for the benefit of only a few powerful actors. Since the circular economy is as political and economic as it is operational and technical, there needs to be an in-depth consideration of the impact of circular solutions on the social and economic structures, actions, and power dynamics in a given locality [25–27].

20.5.4 Locality of Knowledge and Circular Economy

Broader sustainability research suggests that harnessing the knowledge of people affected by sustainability transitions is essential in addressing the complex challenges of such transitions (e.g., [28]). Co-producing knowledge to define, develop and implement sustainability visions and solutions has been increasingly recognized as the recipe for achieving the desired positive societal impact through sustainability transitions. In this context, knowledge co-production can be defined as "iterative and collaborative processes involving diverse types of expertise, knowledge, and actors to produce context-specific knowledge and pathways towards a sustainable future" [29].

Arguably, this line of thinking also applies to implementing a circular economy in the built environment, thus highlighting the criticality of harnessing local knowledge in developing and devising circular solutions in the built environment. The built environment has a unique and intimate relationship with society as it provides people's livelihood. As mentioned in the previous section, people have unique/local social and material experiences in the built environment, which manifest through their local knowledge of living, interacting, and travelling in specific ways. In re-inventing the economics of the built environment to make it more circular, such knowledge needs to be harnessed as a valuable resource to develop effective solutions with positive societal impact. As stated by Fratini et al. [30] (p.4), "knowledge and power are inevitably interlinked in the governance of urban transformation", and thus, delivering a just green transition through a circular economy requires severe locality consideration of knowledge.

20.5.5 Localizing Role of Cities and Circular Economy

In referencing prior research and delving into the pivotal role of cities within the context of the circular built environment, it is imperative to underscore their significant role in localizing this transition. The prevailing discourse within the broader circular economy literature posits that cities serve as the epicenter of the circular transition, primarily owing to their formidable accumulations of resources, capital, and talent, as previously articulated. Additionally, cities exhibit a distinct advantage in this transition due to their pre-existing infrastructure and governance mechanisms, which are poised to regulate and facilitate the necessary economic activities.

As mentioned before, broader literature on circular economy has identified cities as the locus of circular transition due to high concentrations of resources, capital, and talent [1]. In line with this argument, and following the discussion in previous sections, it could be argued that cities deserve special attention because of their role in localizing space and knowledge, especially in the case of implementing a circular economy in the built environment. As stated by Rizzo and Sordi [31], if one considers circularity as the nexus between resource flows and sociocultural processes of urbanization (which involves urban planning and construction), then cities become particularly relevant in understanding how physical space, citizens, and their knowledge interact and play out.

Regarding land use/physical space planning, cities can support closing resource loops by optimizing the locations of interdependent actors in various value streams [22]. There have been several examples of this globally [32, 33]. A similar approach to the built environment can support the implementation of a circular economy in the built environment, for example, by facilitating the matching of material demand and supply (e.g., [34]) and addressing the lack of physical space for waste sorting and recycling [35].

From a socio-economic-cultural perspective, reasonable consideration of socio-spatial relationships and knowledge co-production is crucial to address multiple interests in an urban context holistically. In recognition of this, broader research in the circular economy started to adopt more holistic concepts, such as 'circular development,' instead of 'circular economy' [36]. This advocates for merging land-use considerations with socially-and knowledge-driven considerations such as market capacity building, partnership building, and new regulations. However, it is currently unclear how circularity in the built environment could be best supported by such a holistic approach at the city level.

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Chapter 21
Defining the Project's Lifecycle Stages and Their Related Decision-Making Activities

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Abstract Large infrastructure projects are significant for societal and economic development, involving different types of infrastructure and many stakeholders. This chapter outlines the stages of the project life cycle, emphasizing the importance of stakeholder engagement at all stages for successful project outcomes. The stages include initiation, planning, execution, monitoring and control, and closure, each with defined objectives, outcomes, and decision-making activities. Due to the complexity of infrastructure projects, effective stakeholder relationship management is essential. The chapter emphasizes the need for continuous communication, strategic engagement, and proactive risk management to align project objectives with stakeholder interests. Case studies and literature reviews show how stakeholder participation improves project performance, sustainability, and societal impact. The findings highlight the importance of integrating stakeholder perspectives to achieve effective project management and meet performance indicators, ultimately leading to successful project implementation and long-term societal benefits. In order to characterize the role of stakeholders, mutual relations and obstacles to the implementation

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of the circular economy outside the European Union, the case of Albania, which will soon become a potential member state of the European Union, is analyzed. The problems with the involvement of interested parties in the implementation of the infrastructure project and the benefits and obstacles are similar for both the member state of the European Union and the countries that are just about to become one.

Keywords Infrastructure projects · Project lifecycle · Stakeholder engagement · Project management · Risk management · Sustainability

21.1 Identification of the Project Lifecycle Stages

Large infrastructure projects have gained significant importance in recent years for societal and economic development [1]. The availability of infrastructure is strongly correlated with economic growth and plays a vital role in socio-economic development [2]. These projects encompass various types of infrastructure, including complex (e.g., transportation, transmission) and soft (e.g., cultural, healthcare) infrastructure [3, 4]. The scale of these projects is extensive, covering broad geographical regions and involving multiple stakeholders [3]. Stakeholders are individuals or groups who can significantly impact the project or are affected by its activities. In the project closure stage, stakeholders play a significant role as they may have been actively involved throughout the project or may be affected by its completion [5].

However, large-scale infrastructure projects face challenges due to their complexity, involving multiple stakeholders with opposing requirements [6]. These complexities and insufficient stakeholder involvement can lead to time and cost overruns [7]. Research indicates that a significant number of projects fail to achieve stakeholder satisfaction or meet planned goals [8, 9]. Recognizing the need for improved stakeholder engagement, scholars emphasize the importance of involving stakeholders throughout the project lifecycle [10].

The analysis of project information plays a crucial role in identifying and addressing problems, dysfunctions, and issues that arise during project implementation. However, when a project is successfully completed, the project structure is dismantled, and team members regroup to undertake new projects, this information is usually lost. It should serve as a valuable learning experience for future projects and be appropriately documented and archived.

For a project to positively impact the organization or community where it is implemented, it must align with the established strategy, deliver added value, and be continuously monitored to ensure that the achieved results align with the expected outcomes. Evaluating project performance also involves considering the perspective of stakeholders who can influence or are affected by the project. Clear roles, effective communication channels, and well-defined reporting mechanisms are essential to ensure the organization's and project's economic success.

Organizing and coordinating a project involves aligning its activities with stakeholder interests to achieve efficient project management and fulfil the project objectives. This part of Chapter aims to address the integrated approach of stakeholders. It proposes harmonizing project outcomes with stakeholder objectives.

To achieve the objectives and fulfil the performance indicators of a project, effective management of stakeholder influences is crucial for the project manager and the project team. Stakeholders play a significant role in the success of a project and should not be disregarded by the project management team. However, managing stakeholders can be complex, particularly when they have diverse nationalities and cultural backgrounds, which can pose challenges in the communication process. Stakeholders may have different, even opposing, goals, creating additional difficulties in managing stakeholders.

During the actual development of the project, stakeholders hold varying levels of authority and responsibility, which can fluctuate throughout the project lifecycle. Their active or passive involvement, ranging from occasional participation in studies and analysis to providing financial or legal support, can significantly impact the project's success.

Strategic project management approaches should be employed to effectively engage stakeholders in the project and ensure efficient communication. By recognizing the influence and importance of stakeholders, project teams can navigate the complexities of stakeholder dynamics and optimize their contributions to project success.

The project lifecycle consists of several stages that encompass the planning, execution, monitoring, and closure of a project. Each stage has specific objectives, deliverables, and decision-making activities. The following are commonly recognized project lifecycle stages: **Initiation, Planning, Execution, Monitoring and Control, and Closure**.

Initiation: This stage involves defining the project's purpose, goals, and objectives. It includes conducting feasibility studies, identifying stakeholders, and determining the project scope. Decision-making activities in this stage include project selection, prioritization, and obtaining approvals.

The findings by Prebanić and Vukomanović [11] led to the development of a framework model for stakeholder engagement in infrastructure projects, highlighting the importance of multiple management levels and project success criteria. The research also revealed the need to consider trade-offs between long-term societal success and short-term efficiency in project delivery and the immaturity of stakeholder engagement practices in construction infrastructure projects. The complexity of infrastructure projects and the role of public clients as initiators of engagement activities were identified as influential factors. The framework model provides practical implications for project managers to enhance their competencies and suggests potential changes in procurement and tender processes to enable early and comprehensive stakeholder involvement. Further research is needed to refine the framework and explore its applicability to different types of infrastructure projects and contexts.

Stage I: Sustainable Project Development—Main Activities Should Be Implemented

The project's initiation stage involved extensive stakeholder involvement to ensure alignment with diverse interests and needs.

- **Stakeholder Identification**: A comprehensive stakeholder analysis must be conducted to identify and categorise key stakeholders, including local residents, transportation authorities, environmental organisations, business associations, and government agencies. This step will help identify the range of interests, concerns, and expertise within the stakeholder landscape.
- **Defining Project Objectives**: Stakeholder consultation workshops should be organised to define the project purpose, goals, and objectives. During these workshops, stakeholders will be invited to provide input on the desired outcomes, environmental considerations, and community impact. This collaborative approach ensures that stakeholder perspectives will be integrated into the project's vision and mission.
- **Gathering Stakeholder Input**: Various engagement techniques, such as interviews, focus groups, and surveys, will employed to gather stakeholder input. Through these interactions, stakeholders will express their views on the project's potential benefits, potential risks, and preferred strategies. Their input will provide valuable insights for identifying project constraints and opportunities.
- **Assessing Feasibility and Viability**: Feasibility studies should be conducted with the active participation of stakeholders. Technical experts should collaborate with stakeholders to assess the environmental, economic, and social feasibility of alternative project options. Stakeholders will provide data, local knowledge, and contextual information that will influence the selection and evaluation of potential project scenarios.
- **Securing Stakeholder Support**: Throughout the initiation stage, continuous communication and collaboration will secure stakeholder support. Regular stakeholder meetings should be organised to share project updates, address concerns, and clarify expectations. Stakeholders should actively participate in the approval process, providing feedback and endorsing the project proposal.

This example demonstrates how stakeholders could be involved in the initiation stage and contribute to a more inclusive, sustainable, and contextually appropriate infrastructure development project. By actively engaging stakeholders, the project team will be able to align the project's purpose, goals, and objectives with the diverse interests of the stakeholder community.

Planning: In the planning stage, project managers develop a detailed project plan that outlines the approach, activities, resources, timelines, and budget. Decision-making activities include defining project milestones, identifying potential risks, and establishing communication and procurement strategies.

Stakeholder involvement in project planning is crucial. Engaging external stakeholders early on is important, rather than just during the implementation phase. This ensures their input on critical decisions and allows a better understanding of their perspectives, values, and interests. By involving stakeholders in the planning process, project managers can address potential conflicts, incorporate diverse viewpoints, and enhance the credibility and success of the project.

The study by Heravi et al. [12] examined the current level of stakeholder involvement during the project's planning process. Stakeholders often provide the needed resources and can control the interaction and resource flows in the network. They also ultimately have a substantial impact on a construction organization's survival. Therefore, appropriate management and involvement of key stakeholders should be an essential part of any project management plan.

A series of literature reviews were conducted to identify and categorize significant activities involved in the project planning stage. For data collection, a questionnaire survey was designed and distributed amongst nearly 200 companies involved in Australia's residential building sector. The analysis results demonstrate the engagement levels of the four stakeholder groups involved in the planning process and establish a basis for further stakeholder involvement improvement.

Stage II: Project Planning—Main Activities Should Be Implemented

- **Defining Project Approach and Activities**: To ensure an ideal and desired project outcome, stakeholders, including local community representatives, environmental groups, and energy regulators, should actively participate in workshops and focus group discussions. These collaborative interactions define the project's approach and activities, considering crucial factors such as environmental impact assessments, land use planning, and community engagement strategies. By involving stakeholders, valuable insights can be gained regarding local sensitivities, environmental concerns, and community expectations, enabling a project that aligns with the interests and needs of all involved parties.
- **Resource and Timeline Planning**: The input of stakeholders, including representatives from engineering firms, construction contractors, and equipment suppliers, is essential in determining the resources required and timelines for the project. Through meaningful discussions and leveraging stakeholders' expertise and knowledge, estimates can be made regarding resource requirements, construction timelines, and potential bottlenecks. This collaborative approach allows for developing a realistic project schedule and

resource allocation plan, ensuring the project progresses efficiently and effectively.

- **Budget Development**: To achieve an ideal budget for the project, stakeholders from finance and accounting departments, project sponsors, and financial institutions should be consulted during the budget development process. By involving these stakeholders, valuable insights can be gathered regarding the costs associated with land acquisition, infrastructure development, equipment procurement, and ongoing operational expenses. Their financial expertise and market analysis contribute to informed budget decisions and support cost-effective project planning, optimally allocating financial resources.
- **Risk Identification and Mitigation**: In order to mitigate potential risks and achieve a desired outcome, stakeholders such as risk management experts, environmental consultants, and local community representatives should actively participate in risk identification workshops. Various risks related to land use conflicts, wildlife protection, regulatory compliance, and community acceptance can be identified through these collaborative discussions. Engaging stakeholders in risk mitigation strategies and contingency planning can proactively address potential project risks, minimising their impact on the project's success.
- **Communication and Procurement Strategies**: Effective communication and transparent procurement processes are essential for an ideal project outcome. Stakeholders from communication and procurement departments, local authorities, and community representatives are crucial in developing communication and procurement strategies. Their input is vital in determining effective communication channels, engaging with local communities, and establishing fair and transparent procurement practices. Furthermore, stakeholders can contribute to identifying potential local suppliers, fostering regional economic benefits, and ensuring that procurement practices are conducted with integrity and fairness, promoting positive stakeholder relationships and project success.

This example demonstrates how stakeholder involvement in the planning stage of a building project facilitated comprehensive project design, minimized conflicts, and enhanced the project's overall feasibility and success.

Execution: The execution stage involves the implementation of the project plan. Activities include coordinating resources, managing stakeholders, and monitoring project progress. Decision-making activities in this stage include addressing changes, resolving conflicts, and ensuring the project stays on track.

According to the research of Bizon-Górecka and Górecki [13], the relationships between stakeholders significantly impact the project's efficiency, timeliness, and quality. Managing these relationships should be a key element of project risk management. The investor plays a central role in the project and bears legal and financial responsibilities. The investor's representative, or supervision inspector, ensures compliance with the construction design and building permit and is responsible for the timely execution of the project. The designer develops the construction design following regulations, norms, and technical expertise. The site manager, as the immediate representative of the contractor, oversees the construction works and ensures compliance with construction laws. These stakeholders work together to ensure a harmonious and successful construction process.

Stage III: Construction Project Execution—Main Activities Should Be Implemented

By analyzing different case studies, valuable insights can be gained into how stakeholder involvement during the execution stage of construction projects can lead to improved project outcomes, enhanced sustainability performance, and stronger relationships among project participants. Understanding the strategies and approaches stakeholders employ in these projects can inform the best practices and inspire future initiatives in the construction sector

- **Coordinating Resources**: Stakeholders can actively collaborate to optimise resource allocation and streamline construction activities. Regular meetings and communication channels will ensure timely materials, equipment, and skilled labor availability.
- **Managing Stakeholders**: Effective stakeholder management will foster positive relationships and address concerns. Stakeholders, including community representatives and regulatory authorities, will provide input on environmental compliance, safety measures, and community impact management.
- **Monitoring Project Progress**: Stakeholder involvement will be vital for monitoring project milestones and ensuring adherence. Progress review meetings will engage stakeholders, enabling feedback on construction quality, compliance, and project timelines.
- **Addressing Changes and Resolving Conflicts**: Stakeholders will be critical in addressing and resolving conflicts. Their expertise and input from architects, engineers, and regulatory agencies will facilitate prompt decision-making and necessary modifications.
- **Ensuring Project Compliance:** Stakeholders from quality assurance, safety, and regulatory departments will actively ensure project compliance with standards, regulations, and certifications. Their involvement will support quality control, safety protocols, and sustainable construction practices, aligning the project with environmental and social requirements.

Monitoring and Control: During this stage, project performance should be continuously measured, and progress should be monitored against the project plan. Decision-making activities include analyzing data, identifying variances, and taking corrective actions to address deviations from the plan.

A study examined the stakeholder engagement and participation in monitoring and evaluating processes in local government project delivery in Ghana [14]. Six main stakeholders were identified, including the client, contractors, consultants, material suppliers, local authority service providers, and the beneficiary community. However, the study found that only three stakeholders, namely the client, contractor, and consultant, actively participated in the monitoring and evaluation at all stages of the project implementation. This indicates a high engagement level but a poor participation level in monitoring and evaluating.

The lack of stakeholder participation in monitoring and evaluating has contributed to various challenges in local government project delivery in Ghana. These challenges include procurement issues leading to payment delays, non-compliance with project specifications, project delays, inadequate health and safety practices, client dissatisfaction, and corruption in the construction sector.

Stage IV: The Monitoring and Control Stage of the Project—Main Activities Should Be Implemented

- To achieve ideal project transparency and stakeholder engagement, regular stakeholder reporting should be conducted during the monitoring and control stage. Stakeholders, including project sponsors, regulatory authorities, and community representatives, should receive periodic updates on project status, milestones achieved, and any deviations from the planned schedule. Their active participation in review meetings will allow for valuable feedback, address concerns, and ensure alignment with project objectives and compliance requirements.
- **Performance Measurement**: Collaboration with stakeholders will be crucial in establishing meaningful performance measurement metrics and indicators during the monitoring and control stage. A comprehensive project performance assessment will be achieved by involving stakeholders in defining key performance indicators (KPIs), such as cost, quality, safety, and environmental impact. Stakeholders will provide valuable insights into appropriate measurement criteria and benchmarks, facilitating accurate monitoring and evaluation of project progress.
- **Risk Management**: The active involvement of stakeholders is essential in effective risk management during the monitoring and control stage. Through risk review meetings with stakeholders from various departments, including project management, safety, environmental, and legal, emerging risks will be identified, assessed, and addressed promptly. Risk response strategies should be developed by leveraging stakeholders' expertise and perspectives, ensuring proactive risk mitigation and informed decision-making.

- **Quality Assurance**: Stakeholder involvement is vital for maintaining high-quality standards during the monitoring and control stage. Engaging stakeholders such as quality control inspectors, contractors, and end-users in quality inspections, audits, and reviews will validate compliance with quality standards. Stakeholders' input will seek to identify potential issues or deficiencies and implement corrective actions, guaranteeing project deliverables meet stakeholder expectations and ensuring overall project success.
- **Change Control**: Stakeholder involvement is crucial in effective change control processes during the monitoring and control stage. As changes or deviations occur, consulting stakeholders, including project sponsors, designers, and end-users, allow for a comprehensive evaluation of their impact and the proposal of suitable alternatives. Collaborating with stakeholders will inform decision-makers, minimize disruptions, and ensure project progress remains aligned with stakeholder needs and expectations.

This example demonstrates how stakeholder involvement in an infrastructure development project's monitoring and control stage contributed to stakeholder reporting, performance measurement, risk management, quality assurance, and change control. The stakeholder collaboration supported effective project oversight, timely decision-making, and adherence to project objectives

Closure: The closure stage marks the completion of the project. It includes formalizing project deliverables, conducting final inspections, and obtaining client acceptance. Decision-making activities in this stage involve transitioning project outputs to operations, conducting lessons learned, and performing project reviews.

Caibula et al. [5] concluded that a project's closing phase is vital in evaluating its success based on various criteria, including meeting deadlines, efficiently utilizing allocated resources, and overall performance. During the closing phase, a comprehensive analysis of the implemented project must be conducted, considering four key elements: activities undertaken, achieved results compared to initial plans, resources invested, and the impact on direct and indirect beneficiaries.

To ensure the successful completion of a project, careful identification and analysis of project stakeholders are essential. Stakeholders encompass individuals and entities from the project's community's internal and external environments. The stakeholder identification and analyzing process involves analyzing their level of influence, interests, interdependencies, and potential connections with other stakeholders.

This analysis process, conducted at the project's outset, enables the project manager to allocate appropriate attention and focus to each stakeholder, thereby maximizing project outcomes during implementation and closure. Stakeholder identification and analysis are qualitative research processes aimed at understanding and analyzing their roles in shaping project policies and methodologies. The importance of efficient stakeholder management is emphasized the higher the complexity of a project, as ineffective relationship management can negatively impact project implementation and potentially lead to project failure.

Stage V: The Closure stage of the Project—Main Activities Should Be Implemented

- **Project Evaluation**: Stakeholders, including project team members, management representatives, and end-users, must be involved in project evaluation activities during the closure stage. Evaluation workshops and surveys should be conducted to gather feedback on project performance, outcomes, and lessons learned. Stakeholders will provide insights into the project's strengths, weaknesses, and opportunities for improvement.
- **Knowledge Transfer**: Stakeholders will be crucial in knowledge transfer during the closure stage. Lessons learned sessions and documentation reviews will be conducted with stakeholders from various departments, such as design, engineering, marketing, and customer support. Stakeholders will share their experiences, best practices, and recommendations for future projects. Their input will contribute to organisational learning and the retention of valuable project knowledge.
- **Stakeholder Satisfaction Assessment**: Stakeholders, including project sponsors, customers, and end-users, should be engaged in assessing stakeholder satisfaction during the closure stage. Surveys, interviews, or focus group discussions should be conducted to gauge stakeholder perceptions of project success, alignment with expectations, and overall satisfaction. Stakeholder feedback will help identify areas for improvement and provide insights for future stakeholder engagement strategies.
- **Transition Planning**: Stakeholders from different departments, such as operations, maintenance, and customer service, collaborated during the closure stage to ensure a smooth transition from the project phase to ongoing operations. Stakeholder input will seek to develop transition plans, including activities such as training, documentation handover, and support processes. Stakeholders contributed their expertise to facilitate a seamless transition and ensure the project's deliverables should be effectively utilised.
- **Celebrating Achievements**: Stakeholders should be involved in celebrating project achievements and recognising contributions during the closure stage. Appreciation events, project showcases, or award ceremonies should be organised to acknowledge the efforts and accomplishments of project team members, stakeholders, and collaborators. Stakeholders' involvement in these celebrations will foster a sense of pride and enhanced stakeholder relationships.

This example demonstrates how stakeholder involvement in the closure stage of a project development project contributed to project evaluation, knowledge transfer, stakeholder satisfaction assessment, transition planning, and celebrating achievements. The stakeholder collaboration facilitated organizational learning, knowledge retention, and positive stakeholder experiences

The involvement of stakeholders in the project's lifecycle stages and related decision-making activities can vary depending on the project management methodology or framework being used. Different methodologies have their approaches to stakeholder engagement, which can influence when and how stakeholders are involved in the project.

Here are some reasons why specific stages and activities for involving stakeholders may vary based on the project management methodology or framework:

- **Emphasis on stakeholder collaboration**: Some methodologies, such as agile or collaborative project management approaches, prioritise continuous stakeholder collaboration throughout the project. These methodologies often involve stakeholders in iterative feedback cycles, regular meetings, and collective decision-making processes. This allows for more frequent and immediate stakeholder input and involvement.
- **Sequential nature of traditional methodologies**: Traditional project management methodologies, such as the waterfall approach, follow a sequential and linear progression of project stages. Stakeholder involvement in these methodologies may be more concentrated during specific stages, such as project initiation, requirements gathering, or project review meetings. The decision-making activities related to stakeholder involvement are aligned with these particular stages.
- **Tailoring to project complexity**: Different projects have varying levels of complexity, and the chosen project management methodology or framework may be tailored accordingly. PRINCE2 or PMBOK may be employed for complex projects, providing specific stages for stakeholder identification, analysis, and engagement. These methodologies emphasise structured stakeholder management processes to ensure effective communication and stakeholder alignment.
- **Flexibility and adaptability**: Some project management methodologies, such as hybrid approaches or customised frameworks, offer flexibility in adapting to the project's specific needs. Stakeholder involvement and decision-making activities can be tailored based on the project's unique characteristics, stakeholder requirements, and the organisation's preferences. This allows for a more customised approach to stakeholder engagement throughout the project's lifecycle.
- **Organizational culture and practices**: The chosen project management methodology or framework may align with the organisation's culture and practices. Some organisations have established frameworks or methodologies that prescribe specific stages and activities for stakeholder involvement. These organisations may have their guidelines, templates, or best practices that dictate how stakeholders are engaged and involved at different stages of the project.

The specific stages and activities for involving stakeholders and related decision-making activities may vary depending on the project management methodology or framework being used. Factors such as the methodology's approach to stakeholder collaboration, the sequential or iterative nature of the methodology, the project's complexity, the flexibility of the chosen approach, and the organization's culture and practices all influence how stakeholders are engaged and when their input is sought throughout the project's lifecycle.

21.2 Stakeholders Role, Inter-Relationships and Obstacles in the Implementation of Circular Economy in Albania

21.2.1 Connection of the Construction Sector with Other Economy Sectors

The construction sector is interconnected with other sectors of the economy in terms of using inputs and cooperation with different sectors throughout the construction process and even after finishing construction. The development of the construction sector or its slowdown affects the performance indicators of other sectors. Any economic changes may also affect other sectors, including the construction sector, and vice versa [15]. The construction sector is connected to the transport sector (for the extraction/transport of raw materials), the production sector of construction materials as well as the trade sector of construction materials that are imported, such as iron, cement, inert materials of production points, electrical materials, plumbing materials, paving and cladding tiles, doors and windows, with apartment and office furniture, and also with heating and cooling equipment and appliances, kitchen appliances, waterproofing materials, etc. [16]. When the construction sector is working efficiently, there are high demands for the above-mentioned materials and equipment, so other sectors of the economy are put to work. This implies that as construction activity increases, there is a greater demand for trading these materials and equipment. The opposite happens when the construction sector is stagnant.

The economic environment includes some macroeconomic indicators. Economic factors have an impact on construction businesses and their performance. An important economic factor that can affect the economic performance of construction companies is the change in demand, which can occur due to several factors, ranging from economic (such as varying growth or interest rates) to demographic (migrations or lower/higher natality).

The construction sector is also influenced by social factors or social pressure, such as the credibility of construction companies. Buyers do not know every detail or information about the quality and type of materials used in the construction of a building. Therefore, a construction company's reliability, credibility, or good name plays an important role in buying or selling buildings. Everyone wants to feel confident about the quality of the construction work carried out in the buildings. Therefore, many construction firms work to change themselves by creating a good image and perceived credibility with all interest groups.

In almost the majority of cases, buyers' decisions to purchase a residential premise or to invest in real estate are influenced by the proximity to the main facilities that people need in their daily lives, such as transport facilities, proximity to schools/ hospitals/ commercial complexes/ sports centers, etc.

The decision to purchase a specific residential premise can affect the development of the whole neighborhood/area and contribute towards opening new businesses necessary for people to live a comfortable life on their premises. In this context, different economic sectors are interconnected in contributing towards a better life for citizens, creating a closed loop in which every chain link contributes to the next one.

21.2.2 Stakeholders in the Construction Sector and Their Important Role

A crucial step in integrating the circular economy principles in the construction sector is understanding the different stakeholders' roles, interactions, needs, and the influence they can exert on the process.

There are different types of stakeholders in the construction sector, which can be grouped as construction businesses (including workers, designers, architects, engineers, investors, employees, investors), suppliers, governmental institutions (including legal authorities, line ministries, municipalities, regional development agencies), public (including citizens, NGOs, civil society organizations, researchers, media, academics, owners, consumers, external experts, external/public auditors). In the case of Albania, not every group of stakeholders is invested in talking about CE or taking concrete steps towards implementing the CE approach in the construction sector. The CE approach is mostly mentioned, analyzed, and advised by external experts/researchers, including economy, technology, and environmental experts. The collaboration between these different groups of stakeholders within the process of CE implementation is necessary for the application and integration of the CE principles in the construction sector: to reduce waste and minimize resource depletion by recycling and reusing building materials, to optimize the use of materials and reduce the environmental impact of projects and in the choices of materials during the entire life cycle.

Governmental institutions can play a very important role in incentivizing construction businesses towards the CE approach; in Albania, some steps were made in drafting policies and strategies regarding managing waste (even construction and demolition waste (CDW)), but these efforts remain new and are not inclusive in terms of creating the right habitat for the CE approach to evolve, or do not present clear and strong opportunities for construction businesses. The Albanian Government has drafted the Strategy for Integrated Waste Management (2020–2035) published in 2020 [17], which was developed on the vision or perception of the concept of "zero waste" so that waste is collected and treated as raw materials and management is done under the concept of circulation systems. The key objectives are waste prevention, separate collection of waste, and large-scale recycling. Another legislative tool that aims to regulate the process of administration of construction waste is the Albanian Regulation No. 1 for the Treatment of Construction Waste from Creation to its Disposal [18], which predicts the separation of construction and demolition waste and their recovery.

21.2.3 Regulatory Efforts and Albanian—EU Projects to Apply CE to the Construction Sector

In cooperation with the European Union, the Albanian Government notified in 2022 that thirty-five million euros be provided for integrated waste management and six million euros for the "Europe for Nature" program, which consists of the protection of nature identified as one of the leading environmental priorities by the Albanian Government [19]. IPA III includes two major projects: the CE focuses on integrated waste management, and the second program focuses on nature and protected areas [19]. Thirty-five million euros have been provided for the first circular economy program to strengthen Albania's steps in the European action of green growth for a clean Albania as part of the worldwide challenge for integrated waste management. A challenge that is part of the most advanced European countries has identified the roadmap of how the consumer society should manage the waste it produces. The IPA program implements models for integrated waste management and the closure of illegal landfills in the waste management areas for the two counties (Kukës and Gjirokastra) where the program is focused. These two models are focus on the feasibility study carried out by the European Union funds for integrated waste management from the waste producer to the final point of solid waste treatment with a particular emphasis on source separation, recycling, and environmental education. Overall, IPA III program focuses on waste management, not specifically on the construction sector or even CDW. Waste management has been an utmost Governmental priority in recent years. In the Circular Economy approach, Albanian authorities have few to no specific economic instruments to promote recycling and prevent waste generation. The main challenges relate to the implementation of the waste management legislation, where significant financial resources are needed for infrastructure, and sufficient administrative capacity is unavailable both at the national and a local level. At the local level, separate waste collection is not correctly done, and recycling is mainly carried out sporadically by the private sector. There are more than hundred-ninety illegal dumpsites that need to be safely rehabilitated or closed to comply with EU standards.

Regarding the activities and operations of the construction business, the Government must monitor the changes that occur due to outside factors or influences that impact the operation of the business, considering that these factors significantly affect the work and performance of the construction business. Despite the development in Albania, a lot needs to be done if construction companies are to adopt CE principles in their processes. The Government must take measures to minimize the impact of threats imposed by the environment (economic, social, and political) and create a favorable environment for the construction business to increase sustainability and longevity in the market with the products and services that the construction companies themselves offer.

In Albania, some construction businesses have made some steps forward in using simple CE concepts in their supply chain of construction, but it is worth mentioning that these businesses are classified as "large businesses". "Contact" Construction Company uses the ISO 9001 standard in the design and implementation of construction works. Furthermore, the information on its official website declares that it carries out construction works respecting the environment with low construction intensity and green spaces. "Kastrati" Group, another large construction company, claims to strive to maintain the highest standards of integrity in all its endeavors by delivering premium-quality products and services to the benefit of all stakeholders and supporting long-term economic growth, social stability & progress. "BALFIN" Group, an another company that operates in the construction sector, declares that it works to meet its objectives by adhering to its values: Accountability, Partnership, Innovation, and Consideration. In compliance with these values and the internal Code of Conduct, as well as according to international best practices, BALFIN Group has established four pillars of corporate responsibility: Education, Health and Well-Being, Environment, and Poverty Alleviation. In fact, companies of BALFIN Group have long since been active with projects benefiting society. Considering their respective sectors and the geographical reach of their activity, they are focused on several directions and act as representatives of Group's Corporate Social Responsibility. Their projects are built around these pillars. "Orion" Construction Company has built its vision and mission on three pillars, two of them being related to environment and ecological solutions, such as green spaces, natural light and ventilation, and ecological materials, to guarantee absolute quality, longevity and to respect the environment, materials used for refinishing and plastering in the projects which are certified as ecological materials, solar panels, recyclable and eco-compatible materials together with renewable energy.

"Matrix" Construction Company claims that their projects provide more green spaces, use environmentally friendly materials, and provide alternative solutions for energy management.

All these construction businesses are considered as large companies in the Albanian economy; hence these tentative towards circular economy approach require financial resources and innovative technologies, which are hard to implement by small businesses.

Overall in Albania, the construction sector is poorly studied in terms of CE concepts and implementation of CE approach, concluding in a lack of information for inter-relationships of different stakeholders and obstacles in the implementation of CE.

21.2.4 Obstacles in the Implementation of CE in the Construction Sector

When analyzing the construction sector and the overall situation of the Albanian economy, several types of obstacles can be identified: economic, political, institutional, technological, and informational. By overlooking the system, not only in the construction sector, but in general, citizens and workers lack information on the CE approach, its concept, and its elements. Small construction businesses cannot afford to use CE technology, presenting one of the most important obstacles in this context: financial obstacles to upgrading technology. Furthermore, when detailing the legislative framework, it can be observed that even the legislative authorities consider the CE approach in its simplest form: waste recycling. No further steps have been taken legislatively to advance the CE concept in different areas of Albania's economy. Political obstacles are crucial, as each Government defines the key strategies for the upcoming years and does not apply a long-term vision, which is needed for the CE application. During these recent years in Albania, strategies were drafted by considering the Sustainable Development Goals (SDG) and European integration of Albania in the EU [17]. Even though these strategies cite the SDGs and are generally in line with the EU acquis, in general, despite some paragraphs that mention and include these goals, little effort is made to implement them. As policies and strategies are considered key in pushing the construction sector towards using the CE approach, their lack poses one of the greatest obstacles to the Albanian economy.

The lack of communication between different stakeholders such as: governmental institutions, construction businesses, economy/technology/CE experts, citizens, construction workers, municipality, external/public auditors, etc., is a key obstacle in implementing the CE approach in Albania. Furthermore, the absence of digital ways of interacting with stakeholders contributes negatively to the lack of communication between these different groups. Each chain link presents numerous challenges, from identifying the different stakeholders to managing their relationships.

Joint action is needed between key stakeholders that aim to apply CE in this sector. This can be done by organizing and attending different workshops or activities where stakeholders can present their challenges, barriers, ideas, and possible solutions. Today in the era of digitalization, where the data can flow and the information is widely distributed, the right information should be shared at the right time and to the people concerned and involved. All stakeholders should be identified very carefully to ensure the success of a construction project. While it can be straightforward to identify the internal stakeholders of a project, the external ones can be more complex and insidious, as many parties are involved, and also because of the interconnection of the construction sector with other economic sectors. In order to identify these stakeholders, action is needed to detail the interconnection of the construction sector with other sectors (such as transport/technology/financial sector, etc.) and raise capacities or awareness regarding the stakeholders' importance and their actions.

Understanding how and when to communicate with each of them is paramount. Often, in Albania, there are ways of communicating that are unsuitable for the work being carried out, producing improper involvement of stakeholders in the project and creating a significant obstacle to implementing new approaches like CE in the construction sector.

Concerning cultural obstacles, Albania has a long history of recycling to use CE principles during years before capitalism. The integrated management of waste and their differentiation in an organized way is estimated to have legal beginnings in Albania in the 1960s, but it is thought to be an earlier process. The industrialization of the country, the need for raw materials, the tendency to provide alternative sources for raw materials, the reduction of costs, and the general interest are estimated to have been some of the main reasons why in Albania in those years there was integrated waste management; where recycling and resource allocation by the population as a whole was foreseen. Furthermore, especially after the 1980s, a new type of activity developed that can be considered the beginning of Albania's circular economy. Under pressure from the lack of raw materials and low profitability, various enterprises began to produce small (fine) products using the waste from their basic production. After the fall of communism and the beginning of democracy in Albania, the culture of recycling diminished, especially during the first years of democracy. As Albania entered a new phase, consumption multiplied while recycling/waste management or other CE principles faded. Culturally, these principles were considered part of the past in these years. Nowadays, things have changed, and people are more prone to recycling and protecting the environment, but the approach of considering CE principles as something that culturally belongs to the past or the communism phase is still present.

When taking into consideration financial and cultural obstacles, which are of great importance, especially in countries similar to Albania (regarding economic challenges and also the lack of information on the CE approach), the limited access to financial markets is a hurdle, especially for small and medium enterprises, which hinders their participation in the process of transforming the economy in a sustainable way. Also, financial decision-making processes do not adequately consider long-term challenges, such as climate change or environmental issues. Albanian public opinion is not yet sufficiently informed on the relevance of environmental threats to the economy's stability and the financial system. As mentioned before, although our strategies cite numerous SDGs, we are far from reaching these goals.

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Chapter 22
Circular Value Chain Management—Barriers and Opportunities

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Abstract This section is devoted to analyzing the construction industry as one of the significant industries within the economy of any country with a high potential for circularity. According to Huovila and Westerholm [1], the buildings and construction sector is an essential contributor to environmental impacts and wealth

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creation in society, with social consequences. Globally, construction uses 36% of the energy, produces 39% of emissions, up to 40% of waste, and uses 50% of all the extracted materials. This undoubtedly emphasizes the significance of the industry and the necessity to transform it from a linear business model development towards a circular one to maintain the higher added value of the resources already currently in the economic cycle and significantly impact the consumption of primary resources. This section will provide an overview of different obstacles in the industry, followed by gaps in awareness and knowledge of the stakeholders and various case studies carried out during the research to highlight the potential solutions for shifting the mindsets and business models operating within the construction sector. The section also provides high-quality examples of successful study courses that can be integrated into different study programs to prepare highly-professional specialists in the construction industry or provide general knowledge on the industry and it's potential for circularity for any other stakeholders.

Keywords Circularity · Construction industry · CDW · Stakeholders · Barriers

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22.1 Identification of the Barriers and Opportunities in the Construction

The construction sector (buildings and infrastructure) is a key sector for the EU economy and represents a major source of employment. It accounts for 9% of the EU's GDP and provides 18 million direct jobs [2]. The construction industry is widely recognized for its significant environmental impacts, encompassing resource consumption, waste generation, and greenhouse gas emissions [3]. As a result, the transition towards a circular production and consumption system is imperative to mitigate these adverse effects. However, the construction sector faces formidable challenges in implementing circular practices due to the intricate nature of its value chain and the lack of clarity surrounding the principles of the circular economy (CE).

To address this complexity and facilitate the adoption of circular practices in the construction sector, this systematic literature review aims to analyses the barriers, drivers, and stakeholders that influence the implementation of CE [4–7]. The identified barriers and drivers are categorized into several factors, including economic, informational, institutional, political, and technological aspects. These categories encompass a comprehensive range of challenges and opportunities in the sector. Compared to other industrial mass markets, the peculiarity of Construction sectors should be focused on, i.e., very long-term life cycles of the "products."

Among the identified factors, political and technological barriers emerge as particularly prominent obstacles to implementing CE principles in the construction sector. This emphasizes the critical need for a governance policy incorporating regulatory measures and tax incentives. Additionally, prompt and sufficient information and integration of construction products at their end-of-life or demolition stage must be integrated wisely into the waste management system, allowing space for a circular value chain.

The review also underscores the importance of raising awareness and improving communication regarding CE principles within the construction sector. Enhancing the understanding and dissemination of CE concepts is essential for stakeholders to embrace and support the necessary changes.

Effective collaboration between the government and construction stakeholders is paramount for a successful transition towards CE. This collaboration can be facilitated through the establishment of public–private partnerships and the implementation of targeted communication strategies. By working together, these stakeholders can jointly address the challenges posed by the construction sector's value chain and capitalize on the opportunities presented by circular value chain management.

The construction sector faces significant environmental challenges that require adopting circular practices. The barriers and drivers identified highlight the need for a comprehensive approach that addresses economic, informational, institutional, political, and technological aspects. By overcoming these barriers and leveraging the opportunities, the construction sector can transition towards CE and mitigate its environmental impact while fostering sustainable development.

Several classifications of barriers and drivers for implementing CE have been proposed in the literature. For instance, de Jesus and Mendonça [8] classified them as complex factors (technical and economic) and soft factors (institutional and social). Guldmann and Huulgaard [9] grouped the barriers into four levels: market and institutional, value chain, organizational, and employee levels. Kirchherr et al. [10] defined barrier categories (cultural, regulatory, market, and technological) as nested. Hart et al. [11] adopted cultural, regulatory, financial, and sectoral barriers. Other classifications include financial, structural, operational, attitudinal, and technological barriers [12] and financial, institutional, infrastructural, societal, and technical barriers [13]. Govindan and Hasanagic [14] proposed different classifications, with five clusters for drivers (policy and economy, health, environmental protection, society, and product development) and seven clusters for barriers (governmental, technological, knowledge and skill, management, CE framework, culture, and social, and market). This analysis shows that there is no unified approach, no common interpretation of barriers exists, and that CE integration in the construction field is linked with various obstacles from different stakeholder groups and PESTLE factors.

The review of Munaro and Tavares [4] highlighted a more significant number of CE barriers and drivers in the construction sector and a shared responsibility between the government and project professionals as agents of change. The political issues were the most representative in the review and focused on developing a governance plan that promotes the CE. Many local authorities focus on short-term economic benefits and consider rapid industrial development their main political contribution [15]. Also, compliance with environmental regulations is inefficient due to a lack of budget and qualified employees. Decision-makers are regularly re-elected and do not necessarily have the ambition to establish long-term strategies for circularity or to maintain established strategies [16]. Municipal decision-making on waste and resource strategies is often fragmented between departments and other municipalities [17]. Since material flows extend beyond city limits, and material standards and regulations are usually determined at the national or regional level, it is difficult for municipal decision-makers to enact circularity without broader political integration [18].

According to the literature review, several **main barriers** can be drawn:

- **Lack of awareness and understanding**: Many organisations may not fully comprehend the circular value chain management concept and its potential benefits. This lack of awareness can hinder their willingness to adopt circular practices.
- **Technological challenges**: Implementing circular value chain management often requires advanced technologies for tracking, tracing, and recycling materials and the adaptability, reuse, and deconstruction of whole buildings. Adopting these technologies may present technical and financial challenges for organisations or society.
- **Regulatory barriers**: Existing regulations and policies may not always support or incentivise circular practices. Organisations may face legal and regulatory barriers that restrict or discourage the adoption of circular value chain management.

- **Limited collaboration and coordination**: Circular value chain management often involves multiple stakeholders across different value chain stages. Lack of collaboration and coordination among these stakeholders can impede the effective implementation of circular practices.
- **Financial considerations**: Transitioning to a circular value chain may require upfront infrastructure, technology, and training investments. Some organisations may face financial constraints or perceive a lack of short-term economic incentives, making it challenging to initiate circular initiatives.
- **Consumer behaviour and demand**: Shifting consumer behaviour and demand towards circular products and services can be a barrier. If customers are not sufficiently aware or willing to support circular initiatives, organisations may struggle to create a demand for circular products in the market.

While barriers exist, organizations that successfully overcome them can leverage the numerous opportunities offered by circular value chain management, leading to improved sustainability, resource efficiency, and competitive advantage.

Government regulations and fiscal actions are imperative to achieve an effective Design for Disassembly (DfD) and play an essential role in the current national and global sustainability agenda [19]. A policy emphasizing circular measures has synergistic potential with global climate change agreements. It has to be taken into account that different countries have different policies. For instance, some countries forbid potentially recyclable materials from being disposed of in landfills. In contrast, others are more flexible with restrictions, although they can leverage an increase in landfill disposal tax, which may also impose waste minimization activities and create business opportunities [20]. For example, the disposal of potentially recyclable materials is not allowed in the Nederland (without taxes). Local government agencies can raise awareness of the benefits of circular alternatives to encourage companies to change their modes of operation. This may require establishing a circular management group or appointing a coordinator who can maintain an overview of the state or city strategy [16]. Creating partnerships between actors in different sectors should also be encouraged, providing access to networks, organizing workshops or meetings, or establishing centers [16]. Support can also be provided by accessing the infrastructure and technologies available in other developed countries and from training organizations to instruct the culture of sustainability among them [21].

Although the literature considers technological issues as relatively minor challenges [10], the integration of design in circular processes is a challenge due to the lack of knowledge of the appropriate technologies and how to apply them, especially in the integration of receiving systems and reverse logistics [18]. This emphasizes that organizations lack the technological know-how to support the implementation of sustainability-oriented innovation [21]. The use of Building Information Model (BIM) associated with DfD can improve collaboration between stakeholders, the visualization of the deconstruction process, identify recoverable materials, develop a construction/deconstruction plan, analyses performance, and simulate End-of-Life (EOL) product alternatives [19, 22]. Cruz-Rios and Grau [23] pointed out the symbiotic relationship between the pre-fabrication, DfD, and product-service system (PSS) model to allow the return, repair, and remanufacturing of building materials. Material Passports are one tool that will involve different stakeholders and information during the stages of the building's life cycle and track standardized information on the environmental performance of the products and materials [24].

Reward measures for circular projects or penalties on waste generation rates must be incorporated into public policies [25, 26]. These measures will stimulate the development of new recycling technologies to consider the systematic planning of recycling facilities and the environmental compatibility of recycled products, which depend on the distances to the recycling plants [26]. A greater understanding of the cost–benefit of applying the CE principles to each stakeholder is essential. If the real cost of consuming greenfield areas, virgin, and finite resources were paid, there would be a financial justification for investing in support systems for reuse, recycling, and energy recovery [17]. The lack of structural solutions to direct fractions of the waste stream to the relevant beneficiaries causes uncertainty regarding the continuity of the supply of material resources. Achieving the effect of economies of scale becomes impracticable and often leads to an increase in the secondary material price [27]. The lack of public subsidies for secondary materials could be offset by the mandatory application of LCC for a building and tax exemptions for certified buildings with an ecological character [27]. Paiho et al. [16] questioned that the initial investment costs needed to switch to circular systems could be a challenge for both companies and municipalities, who may have vested interests in maintaining current linear production processes such as waste incineration companies, in addition to the risk in investing in new infrastructure.

Inertia and reluctance to diverge from everyday business practices suggest that discussions about CE are often restricted to a company's corporate social responsibility and/or environmental divisions [10]. The lack of a close connection between sectors delays the circular transition required for all sectors. For example, the real estate developer, who does not intend to own the building, can negatively influence the circularity decisions of the construction, as well as the financial sector, which is mainly traditional and does not consider the EOL materials value [28].

According to the literature review, several **main opportunities** can be drawn:

- **Resource efficiency and cost savings**: Circular value chain management can lead to significant resource efficiencies and cost savings. Organisations can reduce their reliance on virgin materials and lower production costs by optimising material use, recycling, and reusing resources. However, this can be achieved only in combination with national policy that increases the price for extraction or consumption of primary resources and thus boosts the market for secondary raw materials. A fascinating discussion for policymakers could raise the question: what happens if the two targets diverge? For example, if recycled materials cost more than virgin materials or have a (slightly) higher CO_2 emission. Which target will prevail?
- **New business models**: Circular value chain management opens up opportunities for innovative business models such as product-as-a-service, sharing economy platforms, and remanufacturing. These models can generate new revenue streams and create a competitive advantage.

- **Enhanced brand reputation**: Embracing circular practices can enhance an organisation's brand reputation and appeal to environmentally conscious consumers. It can demonstrate a commitment to sustainability, leading to increased customer loyalty and market differentiation.
- **Access to new markets**: Circular value chain management can enable organisations to tap into new markets and customer segments. A growing demand for circular products and services creates opportunities for organisations to expand their customer base.
- **Collaboration and partnerships**: Circular value chain management often requires collaboration and partnerships across stakeholders. By forming strategic alliances, organisations can access shared knowledge, resources, and expertise, enabling more effective implementation of circular practices.
- **Regulatory support and incentives**: Governments and regulatory bodies increasingly recognise CE principles' importance. There may be opportunities for organisations to receive support, incentives, and favourable policies that facilitate the adoption of circular value chain management.

Different scientists conducted several systematic reviews to examine the barriers, drivers, and stakeholder roles in implementing the CE in the construction sector. The findings indicate that CE has gained significance in the sector, but collaborative efforts and interdisciplinary action between construction stakeholders and the government are necessary to drive sustainable changes. The studies highlight the need for a well-defined governance plan, an efficient construction and demolition waste management (CDWM) program, and improved awareness and communication regarding circular principles. Implementing CE effectively requires a clear understanding of how circular actions can impact sustainability, supply chains, business models, and information and communication technology (ICT) systems. Integrating CE thinking into the early design stages of buildings can contribute to selecting appropriate strategies and tools.

Based on the relationships identified among CE barriers, drivers, and stakeholders, practical implications suggest exploring synergistic opportunities to create value and profits within the construction value chain while fostering stakeholder integration and closing the materials loop.

The review emphasizes the importance of a comprehensive and integrative CE framework that combines top-down and bottom-up approaches. Balancing these approaches is crucial to provide a competitive advantage. Top-down approaches help standardize and streamline CE implementation in the sector. At the same time, self-organized processes enable the formation of business models, highlighting the ongoing need for a market-oriented approach. Internal stakeholders play a significant role in driving sectoral change. Command and control policies can motivate participation in symbiotic activities, incentivizing economic benefits from construction and demolition waste (CDW) reuse, offering financial subsidies, and pressures from stricter environmental standards.

22.2 Case Study Albania—Actual Situation of Albanian Economy in General and Construction Sector in Particular

In Albania, the construction sector is taking a primary role in the economy, as the area permitted for construction has increased significantly, and the real estate market has expanded, especially in Tirana, Albania's capital. During recent years in Albania, engineering works and new constructions have dominated the building sector, especially when it comes to residential buildings; another signal of this growth is given by the increasing number of constructions permits issued by the Albanian authorities each year. Continuous growth can be observed when analyzing the construction sector data (Table 22.1).

According to Albanian Institute of Statistics (INSTAT) in 2022, the area granted for construction in the capital was 2.6 million square meters, a record level since 2010 of which nearly 80% of permits were for residential construction (Table 22.2). Since 2017, the area of building permits has increased significantly, peaking in 2022 at the highest historical level since the 1990s. The same trend continued in the first months of 2023, when almost 652,136 m^2 area was granted for construction of new buildings. Tirana received 70% of all construction permits granted in the country in the corresponding period. Even though the population has shown a shrinking trend year after year, the residential construction sector is continuing its activity, where in 2022, the total area of the construction permits reached a record level in the last 6 years.

In recent years, the main income item of the Municipality of Tirana is the "*Infrastructure impact tax from new constructions*", which is subject to all entities that seek to be provided with a development permit and a construction permit for residential, administrative, production facilities, and other services. From granting building permits, the municipality collects about a third of the income it collects in total from taxes and fees. Based on the municipality's draft budget, this momentum is expected to continue. In 2023, from this item, the municipality expects to collect 5.6 billion ALL in revenue, which consists of 34% of the total revenue of the municipality. Even in 2024 and 2025, the construction momentum is expected to continue, as the municipality anticipates about 6.2 billion ALL in income for each year.

Figure 22.1 indicates the yearly growth of the construction sector in Albania for the last five years. During recent years, the construction sector in Albania has shown

Table 22.1 Indicators on construction sector, 2017–2022

	2017	2018	2019	2020	2021
Construction permits	819	1194	1094	961	1369
Construction area (000/m^2)	869	1443	2022	1608	2317
Approximate value of constructions (billion ALL)	49.1	59.0	80.8	76.6	99.2

Source INSTAT [29]

Table 22.2 Summary of construction permit issuance, 2017–2022

		2018	2019	2020	2021	2022
Construction permits	819	1194	1094	961	1396	1420
– Residential buildings	524	770	741	660	1063	1113
– Non-residential buildings	295	424	353	301	333	307
Construction area (000/m^2)	869	1443	2022	1608	2317	2667
– Residential buildings	533	910	1241	1189	1761	2071
– Non-residential buildings	336	533	781	419	556	596
Approximate value of construction (billion ALL)	49.12	59.02	80.84	76.60	99.24	113.14
– Residential buildings	26.01	29.32	44.57	41.50	61.16	72.79
– Non-residential buildings	11.15	18.78	26.22	16.40	19.28	24.98
– Civil engineering works	11.97	10.91	10.05	18.70	18.80	15.37

Source INSTAT [29]

consistent growth, except for the year 2020, when the pandemic situation impacted the whole economy and inhibited the growth of this sector. From 2021 to 2022, the construction sector has grown 15% more. INSTAT data refer to the construction sector growing over the past year, but the contribution to total employment was 7.6%, from 8.1% in 2022. Most of the work processes in the sector are based on the labor force, but the expansion of the sector has not affected either employment or budget revenues.

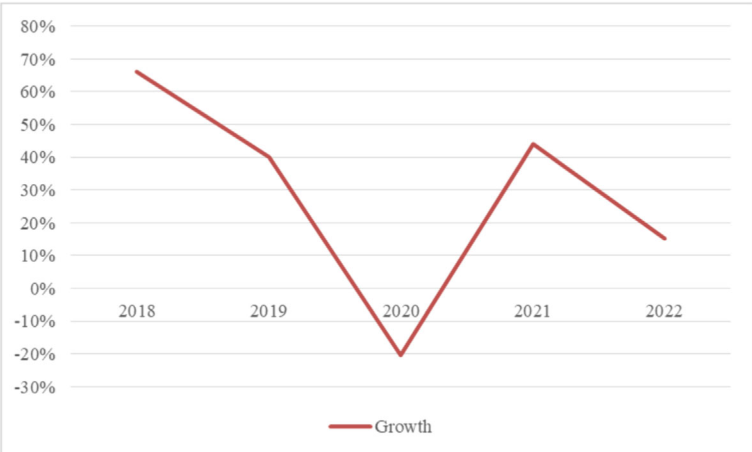


Fig. 22.1 The yearly growth of construction sector, 2018–2022 (*Source* INSTAT [29])

The construction sector suffers from high informality, which appears to have increased further in the past year. Studies by the International Labor Organization (ILO) estimate that construction has the highest informality among the non-agricultural sectors, with around 60%.

Although the supply has increased rapidly, the prices have followed the same trend, reflecting both an increase in construction costs and the high supply that has been driven by both credit (for average apartments purchased by the middle class) and informal money, which is mainly transferred into expensive apartments that are sold mainly in cash.

The Bank of Albania announced that in 2022 alone, real estate prices increased at a record pace of almost 40% compared to the previous year. On average, an apartment in Tirana costs from 800 to 900 euros/m^2 in the suburbs, 1500–2500 euros/m^2 in the areas near the center, up to 5000 euros/m^2 in the elite areas and the towers that are being constructed in the center of Tirana.

The Construction Cost Index, which measures the price performance of construction materials, labor costs, machinery, transportation, energy and other costs used in the construction of a typical dwelling (8–10 floors), reflects changes in the costs of construction work performed during the reference period compared with the base period (Q4/2020 = 100). It has six expenditure groups:

- Material Expenditures;
- Salary Expenditures;
- Machinery Expenditures;
- Transport Expenditures;
- Energy Expenditures;
- Other costs.

The Material Expenditure Index measures the performance of the prices of the main construction materials. This group consists of three subgroups: construction materials, electric and communication materials, and hydro-sanitary materials. The Labor Cost Index measures the performance of the wage bill for engineers, technicians and laborers. As seen from the data in Table 22.3, the Construction Cost Index has increased during 2017–2021.

The index of each group of expenses has increased, except for material expenses, which have decreased until 2020, but in 2021, they experienced an increase of 2.4%. The figures re-emphasize the importance of proper management of construction materials, with the aim of reducing costs and obtaining acceptable prices for consumers, by knowing that according to the Bank of Albania, the Fischer Index of housing prices increased by 9% on an annual basis on 2021. This change shows that, especially during the second half of 2021, the increase in housing prices has accelerated significantly until reaching index of total cost of 108.4 in 2022.

From year 2021 to year 2022 there exists a significant raise in all elements of Construction Index Cost, as described in the Table 22.4. Energy expenditures have increased with 14.21%, the biggest increase in all the elements, in the same line with energy price increase in the global markets during 2022.

Table 22.3 Construction Cost Index, 2017–2022

	2017	2018	2019	2020	2021	2022
Total cost	99.1	99.7	99.9	100.1	101.9	108.4
Material expenditures (a + b + c)	102.0	101.6	100.9	100.0	102.4	109.7
a. Construction materials	102.8	102.3	101.4	100.1	102.4	110.1
b. Electric and communication materials	100.1	99.3	100.2	100.0	102.7	107.9
c. Hydro-sanitary materials	98.7	99.2	98.7	99.7	101.6	109.5
Salary expenditures	99.7	100.7	101.7	100.3	102.2	106.1
Machinery expenditures	97.8	97.7	98.6	99.3	100.1	104.5
Transport expenditures	98.4	100.5	99.8	101.0	103.1	105.0
Energy expenditures	100.0	100.0	100.0	100.0	100.7	115.0
Other costs	95.7	98.0	98.8	100.4	102.4	109.1

Source INSTAT [29]

Table 22.4 Construction Cost Index change from 2021 to 2022

Total cost	6.38%
Material expenses	7.14%
Construction materials	7.50%
Electric and communication materials	5.08%
Hydro-sanitary materials	7.81%
Salary expenses	3.77%
Machinery expenses	4.40%
Transport exp	1.87%
Energy exp	14.21%
Other costs	6.50%

Source INSTAT [29]

22.3 Summary of Barriers and Tentative for Implementing CE Approach

As concluded from the analyzed data, the construction sector in Albania experienced significant growth, along with its costs, during the last six years, which leads to possessing a challenge in managing construction waste. In view of the challenge of incentivizing construction businesses towards the CE approach, the Albanian government, as a key stakeholder, has drafted the Strategy for Integrated Waste Management (2020–2035) published in 2020 [30]. It is the main planning document in the field of municipal, non-municipal, and hazardous waste management in Albania. This revised Strategy was developed on the vision or perception of the concept of "zero waste" so that waste is collected and treated as raw materials, and management is done under the concept of circulation systems, serving the criteria of using and preserving raw material resources in accordance with the concept of CE systems, to benefit from the standardized use and storage of raw materials. Under the new vision, the Strategy lays out the way to meet the obligations arising from all the changes in the EU Waste Directives, including the objectives of the Circular Economy Package. The key objectives are:

- waste prevention;
- separate collection of waste; and
- large-scale recycling.

According to the National Action Plan, part of this Strategy, until 2025 is targeted 30% recycling/reduction of construction waste, until 2030 is targeted 50% recycling/reduction, and 70% recycling/reduction is targeted in 2035. Regarding the concept of "zero waste", five ways of managing urban waste are defined: burning for energy, burning for disposal, recycling, depositing in landfills, and depositing outside landfills. Most of urban waste is deposited in landfills, which does not present a circular approach in managing waste. Waste management, not only construction waste, lacks the circular concept from which could benefit the whole society. Overall, this strategy, even though it declares that it has a circular approach regarding managing waste, in reality, is far from CE concepts. Incinerators, landfills, or even recycling waste are concepts not in full compliance with the circular approach, which should be implemented by businesses when choosing their inputs in the production process.

In this regard, another tool drafted by the government is the Albanian Regulation No. 1 for the Treatment of Construction Waste from Creation to its Disposal. This regulation aims to discipline the process of administration of waste from the construction field, establishing concrete rules and requirements for all entities that operate in the field of construction and the treatment of waste generated by it.

The most important provision in this regulation is the sorting of construction and demolition waste and their recovery. Municipalities are responsible for determining the sites for temporary treatment and storage plants. Based on this regulation, local government bodies, environmental inspectorates, and construction police must exercise continuous control over construction waste generators, storage sites, and their treatment plants. As an instrument to enforce the regulation, a financial guarantee (minimum 5% of the value of the construction works) is provided to be deposited with the local government to obtain a construction and demolition permit. The deposit is returned only if the requirements of the regulation regarding the management of the waste are met. No public data on these deposits were found during our research. INSTAT data indicates that in the last five years, managed urban waste has had a steadily decreasing trend. Inert, on the other hand, shows a stable trend with a slight decrease in 2021. Compared to managed urban waste, inert waste is more stable as it has grown more than urban waste in relative terms. For the last five years (2017–2021, as for 2022, there is still no data published from INSTAT), on average, inert made up approximately 7.2% of total managed urban waste.

Albanian economy possesses numerous challenges especially regarding the construction sector. International Monetary Fund paid special attention to the construction sector for the first time during the last statement on Albania and advised taking precautionary measures regarding the impact that the momentum of constructions and the expansion of the real estate market can have on the stability of the financial sector, as they call for close monitoring and management of potential risks from high credit growth in recent years, including increased foreign currency lending.

The data of the Bank of Albania show that the loan for housing has slowed down in 2022 after the increase in interest rates, which are approaching the level of 5%, or 1.5 percentage points more than a year ago. In October 2022, the new credit for the purchase of real estate was worth 2.95 billion ALL (Albanian Lek), the lowest value since January 2022 and 8.6% less than the same period a year ago. Real estate agents expect that there will be less demand for apartments from young families, as a result of inflation, rising interest rates and the high level of housing prices. Although construction businesses have been hit by rising costs and high supply, their hope is that a Fiscal Amnesty from the Albanian Government will keep the demand high.

In general, in Albania, some construction businesses have taken some steps forward in using environmentally friendly materials or providing alternative solutions for energy management. Even though, when analyzing the construction sector businesses, only the largest market players have made some progress in this context. Other construction businesses do not have the financial capacities in investing towards green construction or in using circular approach models. When taking into consideration the Albanian economy, there are a number of challenges in using the CE approach, including financial aspect, lack of technical and professional expertise, lack of support from governmental policies/strategies in terms of incentivizing using CE principles or governmental grants that could be used in this context. Albanian governmental institutions have not yet made legislative changes in order to push construction businesses in using CE approach. The only policies and strategies drafted until now are linked with waste management, including construction and demolition waste, yet these legal acts remain in the simplest form of circularity: recycling waste or incinerating it.

22.4 Comparison of Albania and Countries of EU in Terms of CE (in Construction Sector)

As mentioned in the previous section, the most important obstacles to implementing the CE approach to the construction sector in Albania are political, cultural, and financial barriers, which are also the ones with significant impact on the economy. European Court of Auditors (ECA) in 2023 has commented that overall, the EU has made very little progress in its transition to CE. Between 2015 and 2021, the average circularity rate for all twenty-seven EU countries increased by only 0.4 percentage points. According to the ECA report, EU measures and billions of euros have had little impact on EU countries' transition, particularly where the circular design of products and manufacturing processes is concerned [31].

As cited in the ECA report, the EU has made little progress towards achieving a CE approach in different industries. Meanwhile, in Albania, the situation is presented as much worse. In 2015, the EU Commission issued its first Circular Economy Action Plan, comprising measures to establish the supporting regulatory framework and policy orientation, allocate EU funding, and monitor the EU's transition to CE. In 2020, in response to the European Green Deal, the Commission issued a new action plan, building on the previous one and setting an aspirational target of doubling the EU's share of material recycled and fed back into the economy by 2030. By June 2022, nearly all EU countries had a national CE strategy or were in the process of developing one [31]. The EU adopted a broad range of directives on the CE, meanwhile in Albania, until 2023 there has not been drafted a national strategy for CE in different sectors of the economy. The only legislative framework regarding the concept of zero waste is that of managing waste (the concept of zero waste presented at is primitive steps like incinerating), where construction and demolition waste is mentioned as one of the kinds of waste generated in our country. Until 2023, no strategy or policy for CE has been developed in Albania, as well as there are no grants provided by the government in order to help construction businesses in implementing CE principles.

The EU Commission has started systematically mainstreaming the sustainability requirements for circular product and production design in its legislative proposals, which were finalized in the Green Deal Industrial Plan 2023, such as:

- A proposal for a sustainable product policy initiative;
- Under the circular electronics initiative, a proposal for a common charger solution and a system to reward consumers for returning their old devices;
- A proposal for a revision of the Industrial Emissions Directive, including the incorporation of CE practices into upcoming 'best available techniques' reference documents; and
- A review of the 2011 Restriction of Hazardous Substances Directive and guidance to clarify its links with the 2006 regulation on the registration, evaluation, authorisation and restriction of chemicals and eco-design requirements.

During last years, member states of EU have showed increasing focus on CE, but slow progress and issues with monitoring. On the contrary, in Albania, the governmental policies are still at early stages of being drafted, and far from implementation phase and monitoring phase.

ECA audit report states that progress in this context varied substantially among member states, and against this background, the EU's ambition to double the circularity rate by 2030 looks very challenging [31]. In conclusion, as EU member states present such difficulties in implementing a CE approach, for Albania it seems too optimistic to make progress in these terms. CE in Albania is widely influenced not only by political decisions, but also by the cultural and financial matters, making it quite difficult to make little progress in the upcoming years.

22.5 Relationship-Building and Shared Learning Through Training, Education and Digitalization to Promote the Implementation of Circular and Sustainable Approaches in Construction

One of the significant barriers to implementing CE in society is the general population's lack of awareness and understanding. Many people, even professionals, are unfamiliar with the concept of CE, which aims to minimize waste and keep resources in use for as long as possible. Without proper education and awareness, individuals may not recognize the importance of sustainable practices or how they can contribute to CE daily.

Education plays a pivotal role in addressing this barrier. Educational institutions, government agencies, and non-profit organisations can collaborate to launch comprehensive awareness campaigns. These campaigns should target various age groups and demographics, emphasising the benefits of CE, such as reducing environmental impact, conserving resources, and creating sustainable business opportunities. Individuals become informed consumers and active participants in CE initiatives by educating the public.

Traditional education systems often prioritise linear thinking and consumption patterns, hindering the transition to CE. Outdated curricula and teaching methods may not adequately prepare students with the skills and mindset required for sustainable, circular practices. To overcome this barrier, educational institutions can revamp their curricula to include CE principles. Integrating sustainability and circularity into various subjects, from science and engineering to economics and business, can equip students with the knowledge and skills to drive circular innovations in their future careers. Additionally, experiential learning opportunities, such as internships, summer schools, and projects focused on circular practices, can provide practical experience. Some examples will be provided in this chapter.

Resistance to change is another challenge when it comes to implementing CE principles. People are often accustomed to the convenience of disposable products and may resist adopting new habits or embracing product durability and reparability. Education can address this barrier by fostering behavioural change. Public campaigns and educational programs can emphasise the benefits of long-lasting products, reparability, and the satisfaction of reducing waste. Schools and communities can organise workshops and events that teach practical skills, such as upcycling and repair, making circular practices more accessible and appealing.

A shortage of professionals with expertise in CE principles and practices can impede the adoption of circular models in businesses and organisations. To address this barrier, educational institutions and vocational training centres can develop specialised programs and courses focusing on CE strategies, business models, and supply chain management. These programs can prepare new professionals with the knowledge and skills required to drive circular initiatives across industries.

Education plays a dual role in the transition to CE. It can be a barrier due to a lack of awareness, outdated curricula, and an opportunity through awareness campaigns,

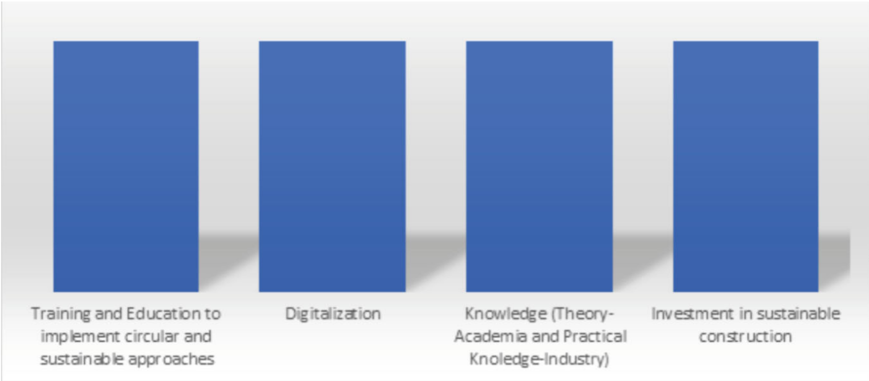


Fig. 22.2 The four pillars for implementation of CE

curriculum transformation, behavioral change education, and specialized training programs. By investing in CE education, society can foster a sustainable mindset and equip individuals with the tools to participate in circular practices actively, ultimately contributing to a more sustainable and resilient future (see Fig. 22.2).

22.5.1 Training to Promote Circular Economy and Sustainable Approaches

Together with three other components, the real-life learning tasks for a professional in the Circular Industry led to the "Four components of Competence-Based education" [32]:

- **Component 1**: Learning tasks—aim for an integration of skills and knowledge. Provide authentic, whole-task experiences based on authentic tasks that represent professional practice. The learning tasks are integrative in nature (like daily practice) and are aimed at transferring everything needed to carry out these learning tasks.
- **Component 2**: Supportive information—all information that is helpful for working on the learning tasks, especially the problem-solving and reasoning processes that are important for them.
- **Component 3**: Information—all information that is necessary for performing the learning tasks, such as step-by-step instructions while working on the learning tasks by a mentor and/or electronic system for workplace support.
- **Component 4**: Practice—provides additional practice in competency that need a lot of practice. Using these subtasks, the cognitive context of a task is repeated, and information is (repeatedly) practised in its correct context.

22.5.2 Study Course Program "Sustainable Management of CDW", the Case of Latvia

In the European Union, more than 800 million tons of CDW are generated every year in Latvia—about 300,000 tons of CDW (State Waste Management Plan for 2021–2028). Until 2035, the amount of municipal waste to be landfilled must not exceed 10% of the generated waste, accordingly, the importance of recycling increases significantly. However, up to 95% of CDW can be recycled or reused [25], and a large proportion of CDW is still landfilled, i.e., most commonly mixed with household waste. At the same time, sustainability factors and their integration into the business management model are increasingly important in policymaking and business.

Although the EU and national policy planning documents set ambitious goals for reducing the amount of waste to be disposed of, in Latvia, a large part of CDW ends up in a landfill. The existing regulations of the European Union and Latvia do not promote the management of CDW based on CE principles. The CDW circulation ecosystem does not create the preconditions for CDW inclusion in the circulation cycle. At the same time, sustainability factors and their integration into the business management model are increasingly important in policymaking and business. It should be noted that the lack of a sustainable construction waste management system in Latvia has caused a lack of understanding among stakeholders and issues at all stages of construction, i.e., in the development of procurement documentation, the collection and use of recycled waste for the production of new building materials, the design process and the entire construction stage.

According to Latvian legislation, CDW—is waste generated by construction because of construction or demolition [33]. Construction waste must be handed over to the operator who has received the appropriate permits for waste collection, transportation, and recovery. Each shipment of construction waste by legal persons must be registered in the waste transportation accounting system. In addition, recycling waste in the construction site must be foreseen within the construction projects in advance. Another important aspect is that backfilling is not waste regeneration itself, although materials that have been regenerated can be used to fill the spaces. Although the system is well established, the field of CDW faces a range of different problems. Some of the most common ones are listed below:

- The builder cannot present documents to prove that it has handed over construction waste to the waste management company;
- The construction waste is handed over to the company that did not receive a waste transportation permit or has received the permit but has not submitted financial security and cannot operate;
- Construction projects foresee the use of construction waste, but the construction project does not provide the conditions for the quality of the materials used;
- Transportation of construction waste is not registered in the waste transportation accounting system;
- Construction waste has been dumped in forests and meadows or any other illegal areas.

The discrepancies mentioned above are currently being addressed under the project financed by the Latvian Environmental Protection Fund: “Development of uniform guidelines and public education on proper management of construction waste and the use of materials obtained from recycled construction waste as valuable resources and raw materials in construction”, Reg. No. 1-08/185/2020, in accordance with the decision of the Latvian Environmental Protection Fund Council of February 24, 2021, protocol no. 3 § 1.3, and up to now, several activities have been implemented. Gaps in construction waste management were identified using various methods, and educational materials were developed for the sustainable development of the field for different stakeholders.

As success stories, we should mention the development of the Unified guidelines for understanding construction waste management, stakeholder surveys and interviews, as well as a new study program for interested stakeholders.

The Unified guidelines have been prepared to create a common understanding and provide information about construction and procedures for the management of waste generated during the demolition of buildings (hereinafter referred to as BBNA), for the activities to be performed, division of duties and responsibilities. The guidelines are intended for those working in the construction sector, waste management service providers, and the supervisory and controlling institutions of the construction processes and waste management sector. A separate section is dedicated to the management of household construction waste (hereinafter referred to as MBBNA). Guidelines consider construction waste circulation from the moment of the development of the construction project, which reflects the planned BBNA volumes and their management, until the final recycling, recovery or disposal of BBNA.

The general management principles of BBNA are as follows:

- BBNA takes into account the hierarchy of waste management activities;
- BBNA has to be managed in such a way that they do not pose a threat to the environment, human health, and real estate;
- The task of the involved parties is to ensure the BBNA defined in the regulatory acts achieving recycling and recovery goals;
- BBNA is managed according to waste management acts regulating the management sector.

To solve the situation, a study program in the scope of 6 ECTS was developed. The purpose of the study course is to create an understanding of construction waste—waste resulting from the construction, renovation and demolition of buildings, as well as leftovers and damaged materials resulting from the construction process or materials on the construction site that are used temporarily. Construction waste from residential buildings typically contains concrete, wood, metals, plasterboard, oils, chemicals, and roofing materials.

The aim of the course is to create theoretical and practical knowledge about the process of sustainable use and management of CDW, as well as to ensure that students acquire the necessary knowledge, skills and competencies in the process of sustainable use and management of construction demolition waste.

Study course results (knowledge, skills, competencies): To acquire a comprehension of the essence of construction waste sorting, recycling, and management processes.

Terms used:

- **Construction works**—a part of the construction process works that are carried out on a construction site or in a building to create a structure, place a pre-made structure or its part, rebuild, restore, restore, conserve, demolish a structure or install an engineering network;
- **Building**—a physical object (building or engineering structure) connected to the ground or a bed, which has been determined as a result of construction works;

As a result of the course, students are able to make responsible decisions for a sustainable choice in the process of construction, repair, building reconstruction or area improvement.

The content of the study courses is as follows (the thematic plan of the study course):

1. Waste management in construction. BREEAM, BIS and APUS.
2. Understanding the definition of construction waste and regulatory framework (in the country, municipalities).
3. Substances are hazardous to the environment and human health in construction waste—classification of hazardous substances and environmental impact.
4. Dismantling process planning and risks.
5. Procedures for the management of waste generated during construction and demolition of buildings (hereinafter referred to as BBNA), actions to be performed, obligations and distribution of responsibility.
6. Construction and demolition waste management organizations and their competencies.
7. Management of household construction waste (hereinafter referred to as MBBNA).
8. Distribution of duties and responsibilities of the parties involved.
9. Analysis of situations.
10. Classification, exceptions and by-products of construction and demolition waste (hereinafter referred to as BBNA).
11. Peculiarities of accounting for household waste when switching from volume to weight units.
12. Volumetric weight of BBNA types and individual material flows, its application.
13. Accounting of construction waste. Product life cycle and compliance.
14. BBNA management and examples of good management practices. Circularity and sustainability of CDW.
15. Experience of other countries (Austria, Finland, Israel, Estonia, etc.) Final exam.

The study course is based on the EU and Latvia regulatory base, scientific literature, and examples of good practice. Industry professionals are involved in the teaching process. The Table 22.5 shows the evaluation criteria and the achievable result. As it can be observed, various teaching methods and research elements are used in the learning process.

Table 22.5 The requirements of the study "Sustainable Management of Construction Demolition waste"

Requirements for study course acquisition and evaluation of results						
No.	Study course result	Assessment method/s	Evaluation criteria			
			Minimum level (40–64%)	Average level (65–84%)	High level (85–94%)	Brilliant (95–100%)
1	Understands the construction process	Discussion	Understands the nature of base terms	Understands the nature of concepts, but there are difficulties discussing them	Understands the nature of concepts and is able to argue on them	Understands the nature of construction processes and concepts at a level that can be explained to others
2	Understands the legal framework for the construction process	Test	Understands normative hierarchy	Understand rights, obligations and responsibilities	Is able to choose the requirements binding in the relevant local government	Knows how to apply normative acts at user level
3	Comprehensive knowledge of construction waste	Test	Understands the principles of the base	Understands principles but has difficulty discussing them	Have a good understanding and knowledge of key principles and issues	Understands the rubbish hierarchy that you can explain them to others
4	Understands the nature of the process of dismantling buildings	Analysis of the situation	Understands the principles of the base	Understands the nature of the process, but there are difficulties discussing them	Understands the nature of the process and is able to debate it	Understand and apply them practically, can explain them to others
5	Understands the nature of the assessment of responsible conduct	Test business game exam	Understands the principles of the base	Understands but does not apply knowledge in practice	Understands and is able to argue argumentatively	Understands the concepts and nature of responsible behavior at a level that can be explained to others

The initiators and authors of the course believe that the more all the stakeholders are informed about CDW, the faster this area of waste management will be settled, and the transition to CE will be integrated within the construction sector.

22.5.3 Case Study in Malta for Education in Circular Economy (CPD—Continuous Professional Development)

Training Course: Decarbonization in the Construction Sector.

A course organized by the Building Industry Consultative Council, Government of Malta with the contribution in CE. The course is organized every few months for different professionals in Malta, online and in person.

Module 2: Design for Sustainability is Specifically on CE and Sustainable Construction, Resources and Waste.

The course is Obligatory for energy performance certificate (EPC) Auditors in Malta and a CPD for all professionals (Engineering and Architecture, Energy Efficiency). It was carried out over various cycles during 2021–2023 to date. Examples are below.

CPD COURSE—Concepts for the Decarbonization of the Building Industry Mqf6 (Malta Qualification Framework Level 6)

The Building Industry Education and Training Research Centre together with the Building Construction Authority will soon start a new CPD course for professionals on decarbonization aspects (renovation and deep renovation). This course is part of the initiative of the Ministry for the Environment, Sustainable Development, and Climate Change in an effort to assist in Malta's Long Term Renovation Strategy 2050.

In collaboration with the BICC, the BCA has the obligation that every assessor gets the necessary training in 'energy performance of buildings' assessments to continue their professional growth in line with the country's long-term renovation strategy 2050 targets.

Given the above, the BCA is inviting current assessors to attend a sponsored course provided by the BICC—Award in concepts for the decarbonization of the building industry (Fig. 22.3). The course is based on a two-day seminar at Project House, Florian (26 and 27 January 2023). After completion of the course, assessors will be awarded the skill card that will become a mandatory requirement to act as a registered performance of building assessors.

Course overview: This comprehensive learning course on CE in Construction is designed to give participants a deep understanding of CE principles and their application within the construction sector. Through well-structured lessons, participants will

Fig. 22.3 Available courses for circular economy in Malta [34]

explore key concepts, regulations, and practical strategies to promote sustainability and circularity in construction projects.

The program aims to increase the learners' knowledge of CE principles, techniques, and practices applied to construction. This improved knowledge will allow construction workers to apply their existing skills to achieve relevant green circular techniques and standards.

Objectives:

- Understand how the key CE policy drivers impact each construction sector profession.
- List and describe the key phases, principles, and methods related to life cycle assessment and costings to support CE in the construction sector.
- Identify best practices in several standard construction methods and systems relevant to life cycle assessments and recognize work practices that fall below this standard.
- Describe some key challenges of implementing CE projects and how to apply specific solutions to meet those challenges.
- Outline the guidelines for the EU Construction and Demolition Waste management protocol with reference to minimizing the quantities of other resources being used.
- Understand why there is a need to talk and discuss with other trades to achieve circular buildings through collaborative teamwork.

Course content:

1. Introduction.
2. European & National Drive. EU CE Principles. Green Policies for Construction. National Regulations.
3. Introduction to CE. Introduction to Sustainability. Embodied Carbon in the built environment. Principles of CE.
4. CE and Construction. Circular interventions. Sustainable Development Goals. Green Certification Schemes and circularity.
5. Waste and Resource Management. Waste Management. Pre-demolition, pre-development audits. Demolition, reuse, recycle, repurpose.
6. Adaptable Materials and Systems. Circular materials and systems in buildings. Construction Techniques for Circular.
7. Water Management. Water Management Plan. Water Management on site.
8. LEAN and Modular Construction. Lean Construction. Modular Construction.
9. Life Cycle Assessment. Introduction to LCA, LCA and Level(s) Building Certifications.
10. Life Cycle Costing. Introduction to LCC. LCC Strategy.
11. Collaboration and Communications. Collaboration Roles and Responsibilities. Communication Tools.
12. Green Procurement. Introduction to GPP. Tendering and Circular Procurement. Certification and Eco Labels.

13. Certification in Construction. Environmental Product Declaration (EPD). Product Environmental Footprint (PEF). Ecolabels.
14. Using Building Circularity Tools. Building Circularity Tools (LCA & LCC). Calculation Methodology.

Module 1: Introduction to CE in Construction (https://constructionblueprint.eu/wp-content/uploads/2023/07/01.-Introduction-1.pdf).

22.5.4 Case Study Summer School—EPICENTRE. Educational Platform Life Cycle Assessment Structures

Project Call: EIT Raw Materials, implementation started at January 2024.

The study course will be developed by the Project Consortium: Aarhus University, Lulea University of Technology, Riga Technical University (Project leader), Tallinn University of Technology, Slovenian National Building and Civil Engineering Institute.

The "EPICENTRE" Ph.D., winter/summer school on Life Cycle Assessment/ Costing (LCA/LCC) and new business development addressed the lack of understanding and communication regarding LCA/LCC analysis and promoted sustainable practices in the Raw Materials sector to support the EU Green Deal. It will be implemented through a comprehensive and dynamic educational platform combining e-learning, simulations, and workshops to provide an innovative and engaging learning experience for candidates from industry and academia.

The EU has committed under the EU Green Deal to become the first carbon–neutral continent by 2050 by introducing innovation and relevant education. This is a three-year EIT project that will lead to the establishment of a four-level Pan-European PhD winter/summer school program. The program will focus on LCA/LCC and new business development, which are in high demand from EU industry partners. Emphasizing converting the acquired knowledge into actionable entrepreneurship. This program will prepare the talents with innovative solutions/ideas to apply for entrepreneurship funding in other EIT activities like Jumpstarter while also providing them with the necessary skills and knowledge in LCA/LCC and new business development. Our goal is to support the EU's efforts to achieve its carbon-neutrality objective by enabling the next generation of green entrepreneurs to develop sustainable business practices. The uniqueness of the course lies with one of the biggest challenges for the industry and those who perform the LCA/LCC analysis, which is the lack of understanding of a common "language" and methodologies and what information is required from the industry to perform proper LCA/LCC analysis to support the green transition. Industrial associate partners and start-ups will be sourcing real LCA/LCC case studies for the course to enable students to co-create through open innovation feasible solutions while supporting networking and match-making opportunities.

Background of the project EIT project (three years) will result in a four-level Pan-European Ph.D., winter/summer school on Life Cycle Assessment/costing (LCA/LCC) and new business development immensely demanded from EU industry partners with a sharp focus on converting gained knowledge to actionable Entrepreneurship as depicted below including preparing the talents to apply with their innovative solutions/ideas for entrepreneurship funding in other EIT activities like Jumpstarter, etc.

The program will focus on converting gained knowledge into actionable funnel entrepreneurship with a sharp emphasis on preparing talents to apply their innovative solutions/ideas for entrepreneurship funding in other EIT activities such as Jumpstarter.

The main goal is to equip the next generation of green entrepreneurs with the necessary skills and knowledge in LCA/LCC and new business development to promote sustainable business practices and support the EU's efforts to achieve its carbon neutrality objective. The uniqueness of the course lies with one of the biggest challenges for the industry and those who perform the LCA/LCC analysis, which is the lack of understanding of a common "language" and methodologies of how it is done. The course pedagogical approach is challenge-based and has strong support from the composite material and building industry (see letters of support).

After the course, the candidates will understand the process of performing the LCA/LCC analysis and thus will have the ability to communicate with different players about the information it requires. This will allow the industry to collect the necessary information significantly quicker and efficiently organize data collection to support their green transition. The increase in knowledge of LCA/LCC analysis will allow the industry to perform quicker analysis regarding the impact on the environment and choose more sustainable, non-toxic raw materials and manufacturing processes for the end products. This will allow EU innovations to move towards more sustainable choices.

The Ph.D., winter/summer school is designed to be suitable for candidates both from the materials industry and engineering/material academia. In addition, it is supported with case studies and financial both from industrial partners and leading universities.

The project differs from existing projects outside the KIC as it aims to provide a comprehensive and dynamic educational platform for LCA/LCC methodologies combining e-learning modules, simulations, digital tools, best practices for data collection/analysis, and hands-on workshops to provide a more engaging and effective learning experience.

The project aims to fill a critical gap in the sector's education and training programs by providing an innovative and dynamic platform for learning, assessing, and improving LCA/LCC methodologies. The RM sector faces various sustainability challenges, including environmental, social, and economic impacts of extracting, processing and using raw materials.

Project objective and scope: (1) Initiate triangle networking between EU academia, students, and industries (KICN02-10) on the development of LCA/LCC procedures and practices, meanwhile creating "safe" cross-disciplinary working environments to enable the development of disruptive open innovation solutions within the course, ready to meet the global market/business demands; (2) Create a comprehensive online education blended course for training in LCA/LCC for light structural materials, which will allow PhD students from all EU countries and particularly the Baltic RIS countries (KICN01-04) to use marketing channels such as university networks, science communities, trade unions other rooftop organizations, etc. web pages (https://phdcourses.dk).

The students will gain crucial expertise through challenge-based education; (3) Develop an open forum for discussion related to standardization and execution of LCA/LCC for a wide range of materials/products, thus involving all participants in networking (KICN02-01) and stimulating interdisciplinarity; (4) Establish LCA blended learning resources for educating professionals at partner universities, which will also be offered after the project ends; (5) Prepare young professionals who are ready to communicate using language used by LCA and LCC experts and use their new knowledge to enhance sustainability at EU companies (KICN01-17, KICN01-18), as well as empower them to move their ideas from knowledge to application via new business development.

22.5.5 Case Study—Digitalization, Latvia

There are many types of engineers specializing in different sectors with one goal to build a better world. Digitalization skills are one of the significant challenges that the construction sector has to overcome to improve the human capital of the sector, which is rapidly developing. Further, Artificial Intelligence (AI) or rather human-supervised and enhanced AI, is where the technology is moving.

During the COVID-19 pandemic, the development of digitalization progressed at the speed of light and provided a crucial role in education. Every day, millions of people were online working, educating and training. The digital transformation plans and online shared platforms that were planned for later on were implemented with the speed of light.

In the post-pandemic, there is a race to digitalization of the construction. Construction companies and consulting companies are using more and more digital and human-guided AI tools.

The construction sector is facing many challenges, such as a shortage of skilled personnel, project delays, productivity, and rising costs of materials, energy and transport. In these circumstances, digitalization in construction is complex and moving forward. Most used is Building Information Modelling (BIM) software and it is becoming a standard practice in the industry. Further, online document management systems cloud to manage large infrastructural projects from various aspects of digital documentation.

*Case Study Module 1: Introduction to Digitalization in Construction (*https://constructionblueprint.eu/wp-content/uploads/2023/07/01.-Introduction.pdf*)*

The aim of the program is to increase the learners' knowledge of digital tools, techniques and practices applied to the construction sector.

Objectives:

1. List and describe the key policy and legislative drivers relevant to digitalisation in the construction sector.
2. Identify the need and benefits of digitalisation for the construction sector.
3. List and describe the key digital tools, techniques and practices used to support the construction of quality buildings.
4. Identify best practice of a number of construction methods and details using digital tools and techniques to achieve quality buildings.
5. Identify best practices of a number of service methods and installations using digital tools, techniques and technologies to achieve quality buildings.
6. Understand how to communicate with other trades using collaborative digital tools and techniques to achieve quality buildings.
7. Understand how to apply digital problem-solving workflows and solutions on-site.

Available Case Study Courses for Digitalization: https://constructionblueprint.eu/training-curricula.

Course content:

1. Introduction.
2. European & National Drive. EU Digitalization Policies. National digitalization.
3. Introduction to Digital Tools. Communication Tools. Collaborative Tools.
4. Introduction to Digital Technologies. On-site Technologies. Off-site Technologies.
5. Data Protection. Cyber Security. Digital Data management and storage.
6. Introduction to BIM. BIM Fundamentals. BIM Principles. BIM Uses and Software.
7. BIM Uses in Construction. BIM Objects. Maturity levels. Use of BIM in each Phase.
8. BIM and Collaboration. Accessing info through the cloud. Accessing info with mobile devices (apps, QR, etc.). BIM review and problem solving. Quantification and Clash Detection.
9. Roles and Knowledge Transfer. Roles BIM and file structure. Digital Workflows. System thinking.
10. Introduction to Quality Checks. Quality Control and Checks. Building Compliance.
11. Quality Checks on Site. Building Fabric. Checks Building. Services Checks.
12. Automation and Artificial Intelligence. Automation. Artificial Intelligence and 3D Printing. Wearables and Extended Reality. Smart Controls.
13. Construction 2030. Quantum Computing and Blockchain. Digital in the Future. Future Choices.
14. Tools for Energy Efficiency. Energy Efficiency Tools. Energy Simulation Tools.

15. Tools for CE. Sustainable Construction. BIM checks for LCA. BIM checks for LCC.
16. Introduction to Digital Passports. Digital Logbooks. Digital Building Passports. Digital Renovation Building Passports.

22.5.6 Educational Case Studies: Sustainability Competency Requirements Within an Engineering Degree in the UK

The UK Engineering Council [35] sets the overall requirements for the Accreditation of Higher Education Programs (AHEP) in engineering, in line with the UK Standard for Professional Engineering Competence (UK-SPEC). AHEP sets out the standard for degree accreditation. It also outlines the purpose and application process for universities that wish to secure or maintain accreditation of their programs. The standard for engineering degrees has been developed through consultation with the engineering profession and includes input from employers and academics. Degree accreditation is undertaken by sector-specific professional engineering institutions under license from the Engineering Council. These institutions interpret the standards as appropriate for their own sector of the profession and use them when deciding whether degree programs meet the requirements to be awarded 'Engineering Council accredited degree' status. The learning outcomes for all engineering students and apprentices have been revised for the most recent fourth edition of AHEP (AHEP4). They now have a sharper focus on inclusive design and innovation, as well as the coverage of areas such as sustainability and ethics. The coverage of equality, diversity and inclusion is also strengthened to reflect the importance of these matters to society as a whole and within the engineering profession. To reflect a reality of modern society, there is now explicit treatment of security and the mitigation of security risks. With special attention to CE implementation, sustainability of engineering practice is an issue of concern for the profession and every Higher Education Academy (HEA) is encouraged to make use of the United Nations Sustainable Development Goals, and Engineering Council Guidance on Sustainability in program design and delivery. The Engineering Council guidance can be found at: www.engc.org.uk/sustainability.

According to the UK Engineering Council [35], the UN Sustainable Development Goals are part of engineering professional requirements (e.g. for Attribute 5: Sustainable Development according to the Institution of Civil Engineers). As part of the Engineering Council's institutions, all engineers need to understand and demonstrate their knowledge and experience around this attribute, whether they are applying for Incorporated or Chartered Membership. The following tables present the fundamental knowledge and understanding requirements in sustainability and CE. These sustainability requirements and learning outcomes are essential for the Approval and Accreditation of Qualifications and Apprenticeships (AAQA) across all engineering programs in the United Kingdom (Table 22.6).

Table 22.6 Sustainability requirements for engineering education and practices across the UK

Sustainability	Leaning outcomes, knowledge and understanding requirements		
The engineer and society	Engineering activity can have a significant societal impact and engineers must operate in a responsible and ethical manner, recognize the importance of diversity, and help ensure that the benefits of innovation and progress are shared equitably and do not compromise the natural environment or deplete natural resources to the detriment of future generations		
Professional level	**Incorporated engineer**		
Area of learning	Foundation degrees, higher national diplomas and equivalents	Bachelors top-up degrees and equivalents	Bachelor's degrees and Bachelors (Honors) and equivalents
Competency requirement	Evaluate the environmental and societal impact of solutions to broadly-defined problems	Learning outcome related to sustainability achieved at previous level of study	Evaluate the environmental and societal impact of solutions to broadly-defined problems
Professional level	**Chartered engineer**		
Area of learning	Bachelors (Honors) degrees and equivalents	Masters degrees other than the Integrated Masters and Doctoral programs and equivalents	Integrated Masters degrees and equivalents
Competency requirement	Evaluate the environmental and societal impact of solutions to complex problems and minimize adverse impacts	Evaluate the environmental and societal impact of solutions to complex problems (to include the entire life-cycle of a product or process) and minimize adverse impacts	Evaluate the environmental and societal impact of solutions to complex problems (to include the entire life-cycle of a product or process) and minimize adverse impacts

22.5.7 *Educational Case Studies: CESBA Med eLearning Platform (Malta)*

The CESBA MED Interreg Med project [36] tested 10 case studies from all over Europe. A common sustainability assessment framework at the urban and building scale was selected after the testing phase to support the development of energy efficiency plans for public buildings in the context of their surrounding neighborhood. The tool covers various indicators, including resource use and CE.

The CESBA eLearning platform developed by the University of Malta has the objective of improving stakeholder's skills by offering targeted training courses as an essential component of CESBA MED strategic overview. Two courses are offered according to the identified target groups and the two scales, the building scale and the urban scale. One course is intended for decision-makers (policymakers, investors, developers). The training course is targeted for decision-makers and consists of three modules. The second course is intended for all training material is available in English and in other five engineers and technical coordinators. The course is targeted for the users of the CESBA MED SNTools and consists of eight technical-level modules. At the end of this course, one may take a test and on successful completion, a certificate is awarded. The tool is available in different languages besides English (Italian, Spanish, French, Greek, Croatian). These courses are organized using Moodle which is an open-source e-learning platform, and were developed as part of the CESBA MED Project, with free access to any interested individual or organization from the MED area.

22.5.8 Educational Case Study—Turkish Circular Economy Platform

Since 2016, BCSD Turkey and EBRD have joined forces to create awareness and accelerate the transition to a circular economy in Turkey by providing tools and technical support that enable businesses to move away from the traditional ineffective way/concept to a more powerful way of doing business. The journey started with Turkish Materials Marketplace, which was instrumental in creating an ecosystem around the circular economy.

Through the course of the past four-year platform felt the need to create a space where anything and everything on circular economy is explained in detail. The main aim of the Turkish Circular Economy Platform [37] is to provide practical solutions, incentives, news and opportunities in the field of circular economy. The platform includes a knowledge hub, an e-commerce platform (Turkish Materials Marketplace), measurement tools, and offers training, financial opportunities, and consultancy services for companies that are truly looking to accelerate their transition to circular.

About BCSD Turkey

Business Council for Sustainable Development Turkey (BCSD Turkey) is the global network partner of the World Business Council for Sustainable Development (WBCSD).

BCSD Turkey was established in 2004 to contribute to better understanding, adoption and implementation of the basic principles of sustainable development in Turkey. Our purpose is to increase the awareness of businesses about sustainable development and to extend their influence. With this purpose in mind, BCSD focuses activities on the five main areas within the framework of the UN's Sustainable Development Goals, and we work with the leading companies of Turkey on sustainability.

About EBRD

The European Bank for Reconstruction and Development (EBRD) was established in 1991 as an international financial institution to support the countries of central and Eastern Europe in transitioning to a market economy after the collapse of communism in the region. EBRD is currently active in nearly 40 countries from central Europe to central Asia and the southern and eastern Mediterranean, plus the West Bank and Gaza. EBRD's shareholders are 69 countries from five continents, including the European Union and the European Investment Bank.

In 2015, the EBRD adopted the Green Economy Transition (GET) approach to put investments that bring environmental benefits at the heart of its mandate. The objective is to increase the financing of projects that advance the transition to an environmentally sustainable, low-carbon economy, and help prevent economies from being locked into a carbon-intensive, polluting pathway that depletes natural assets.

About CIRCO

CIRCO is a Dutch circular design program, helping companies to take the first step in the process for circular business.

CIRCO, is supported by the Government of Netherlands, providing circular design training programs to create circular products, services and business models for companies. Participants from Turkey's leading companies had the opportunity to learn the pressure cooker version of the "Creating Business Through Circular Design" methodology by the experienced instructors of CIRCO.

Some of the issues covered during the workshop were the role of product design in the circular economy, how important it is and how it provides circularity in business. All participants had an opportunity to experience the required steps to apply CIRCO's circular economy business models and design strategies for their own businesses and understand their role in the circular economy by practicing a re-design process of a product. We would like to thank all TMM members who participated in this special event, which is a rather short version of the original 3-day CIRCO methodology workshop.

Circular Business Design

CIRCO Circular Business Track powers the development of the Circular Economy, driven by design principles. Companies work together with designers to develop circular products, services and business models. They do so by sharing knowledge, experience and inspiration with their network.

"Creating business through circular design" is a project that inspires and facilitates the manufacturing industry to 'Go Circular', using a circular design approach. The mission of this track is to make the circular design the new default for production.

CIRCO Demo

There is a demo to explain to the basics of the track. The DEMO is a short, 1–2 h, interactive workshop as an introduction to the CIRCO methodology. The ones who are Interested in "Circular Business Model Design" can join and learn more details about this track.

About the Program

Circular economy is an interesting though still rather abstract concept. The DEMO demonstrates the CIRCO design process in a pressure cooker format, making circular business concrete and providing a circular dimension to your innovation process. Participants will get acquainted with a circular way of working and experience how to:

- Identify circular business opportunities;
- Apply circular business models;
- Use circular design strategies:
  - Learn about circular cases and the CIRCO cumulative experience;
  - Meet other companies and stakeholder starting their circular journey;
  - Get curious and inspired.

Creating Business Through Circular Design Workshop

"Creating Business Through Circular Design" was held on the 16th of November in collaboration with CIRCO and The Government of Netherlands, which is a pioneer in the field of circular economy.

The Consulate General of the Kingdom of Netherlands, organized a series of design events in Istanbul, presented as 'Co-Design' between 20 September-20 November under the theme of "Designing Our Liveable Cities Together". Within the program, a special workshop was organized by CIRCO for BCSD Turkey and TMM members.

The workshop was held in Palais de Hollande with the participation of The Consul General of the Kingdom of Netherlands, Bart van Bolhuis, BCSD Turkey team, CIRCO experts and TMM members.

Benefit of Participants

Participants explore new circular business opportunities for their companies through platform's circular design methodology with the help of three-day workshops.

At the end of day three, participants will have developed a new circular proposition, enclosing a business model, product (re) design and additional services/ processes. During the workshop participants will gather new knowledge about the circular economy in general, circular design and circular business models. Furthermore, interaction with the other participating companies during the process offer new insights and open opportunities for potential collaboration.

For which institutions is the event beneficial?

Manufacturing companies that aspire to develop a (more) circular and sustainable business are the most important candidates. In each track, up to 10 companies can participate.

A designer/business developer/engineer and someone from the business part of the organization, familiar with the market, customers and preferably other stakeholders can be participants from companies. Per company only two employees can enroll in the workshop.

Much added value derives from combining innovative circular product design with business models.

Daytime activities are organized in such a way that participants can find enough time to work as much as possible on their own circular case.

This is done in a mix of:

- Transferring relevant circular knowledge, design process components and tools;
- Working independently with two people from a company;
- Working together with other participating companies.

Daily Program of the workshop:

- **Day 1: Initiate**. This workshop delves deeper into the (design) principals of the circular economy. Together with other companies and designers, loss of valuable materials, products and components across the current value chain is mapped out and resulting circular business opportunities are identified and selected;
- **Day 2: Ideate**. The most interesting circular opportunity from the first workshop will be elaborated further using circular design strategies and business models. This results in a circular customer proposition with a business model, product (re) design and additional services.
- **Day 3: Implement**. Day three is all about implementation. Every company designs an implementation roadmap to bring its circular proposition to market. To finish off with a bang, participants pitch their new Circular Business proposition.

22.6 Barriers and Opportunities in the Field of CDW Management

22.6.1 Case Study—Circularity of Household-Generated Construction and Demolition Waste: Management Principles for Green Transition in Latvia

The research under the case study presents the study of principles of circularity of household-generated waste based on data analysis gained out of the survey to draw practical suggestions for professionals towards sustainable development in the short-term and long-term future. The systematic literature study is grounded in text analytics, and the best practices from Austria and Scandinavia were explored. The collected data on construction waste in Latvia was analyzed by applying statistical methods. The research results revealed a significant increase in building construction and demolition waste and their lack of circularity. The authors conclude that it is necessary to use best practices on how to apply circularity in building construction and demolition waste management, and how to develop the cooperation links between local building authorities and householders using digital solutions for the green transition.

Latvia does not collect separate statistics on the CDW collection generated by industry and the household sector. However, it is assumed that within the household sector, there might be a higher probability of a lack of information on appropriate and more cost-efficient management of this type of waste with minimal harm to the environment, which leads to the necessity of improvement in education.

To carry out the research and see which areas require significant improvement of awareness and education activities, a survey has been developed. This country-wide survey for Latvia covered permanent residents of Latvia between the ages of 18 and 75. The survey's sample size is 2005 respondents, of whom 67% have been directly involved in the construction, repair, improvement, and/or demolition of their own or family real estate. The survey was structured in a way to gain comprehension of the overall knowledge level of the society on the construction and demolition waste subject, as well as to identify the main gaps in the management of this particular waste stream. Overall, the survey consisted of 65 questions. The following section will provide an analysis of the obtained results of the survey and later form a set of conclusions and recommendations.

According to the results of a survey of the population of Latvia, slightly more than 2/3 of respondents (67%) have carried out repair or construction work in their household in the last 5 years, which resulted in discarded repair and/or construction waste. From the respondents, the distribution in detail was as follows:

1. Currently doing—5%;
2. Have carried out in the last year—25%;
3. Have carried out 1–2 years ago—16%;
4. Have carried out 3–5 years ago—21%.

However, almost 1/3 of respondents (32%) have not carried out any repairs, resulting in repair or construction waste. The results show that it is quite common to do some minor renovation or construction works in a timely manner in Latvian society.

When analyzing the type of repair works performed (Fig. 22.4), it can be summarized that the most common type of repair or construction work performed is cosmetic repair, such as painting, changing tiles or plumbing, etc. (78% of respondents did this). Other jobs or activities are mentioned relatively less frequently. Of course, for this type of activity, the households do not need to receive any approval from the building authority institution, which makes the process less bureaucratic and complex. On the other hand, it assumes that society is aware of all information publicly available on managing construction and demolition waste. To support the above-mentioned, most respondents (73%) who have carried out repair or construction work in their household in the last five years, which resulted in the generation of discarded repair and/or construction waste, did not carry out such work that required approval from the building authority. 17% of respondents made an agreement with the construction board for those works that required it, but 3% of respondents indicated that the works were only partially coordinated with the building board—not all works that required approval were agreed upon. 7% of respondents state that they do not know whether the works performed require approval from the building board (Fig. 22.5).

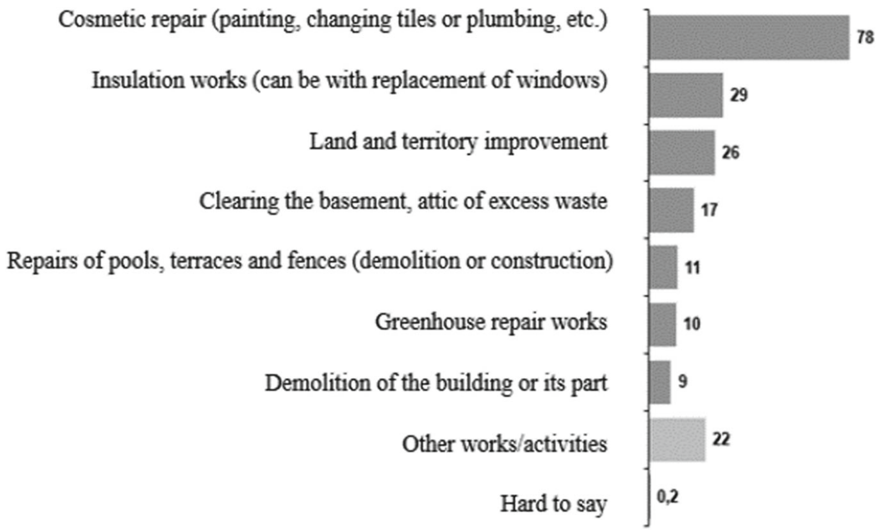


Fig. 22.4 Type of repair or construction work, Answer to the survey question "What type of repair or construction work did you/your household do?" Base: respondents who have carried out repair or construction work in their household during the last five years, which resulted in the generation of disposable repair and/or construction waste, n = 1350 Multiple choice question (% sum > 100)

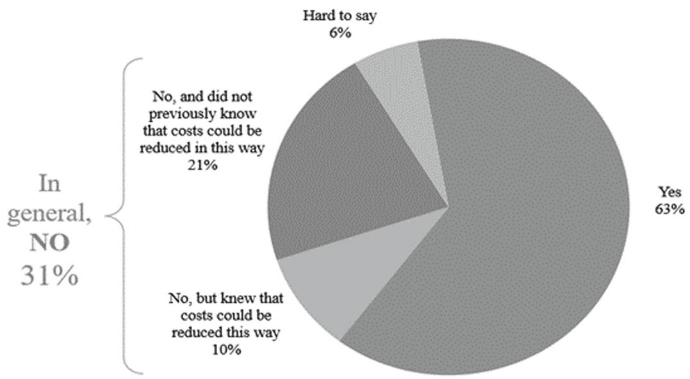


Fig. 22.5 The answer to the survey question "Did you sort the repair and construction waste for disposal, for example, to reduce costs?" Base: respondents who have carried out repair or construction work in their household during the last five years, which resulted in the generation of disposable repair and/or construction waste, n = 1350 Multiple choice question (% sum > 100)

Figure 22.6 provides a comprehensive visualization of the approach that the citizens chose for performing repair and construction works at their individual real estate. In addition, this figure represents the scale of the construction or repair works carried out, showing that in most cases, the responses covered really small scale-works that do not require certain approval, and this also means that these particular households did not have a chance to receive more explicit information on the management of construction and demolition waste that could be received by the ones who undergo the official process due to the scale of the works. Meaning that the households either must be educated enough to know where to look for required information, or the municipalities must have this information provided to the inhabitants to make sure that they discard construction and demolition waste in the most resource-efficient manner while still complying with all applicable regulations.

The survey carried out by the authors also addressed the question of waste generation. From the analysis of the responses, it has been concluded that more than half of the respondents (57%) indicate that they generated up to 1 m^3 or ten large bags of

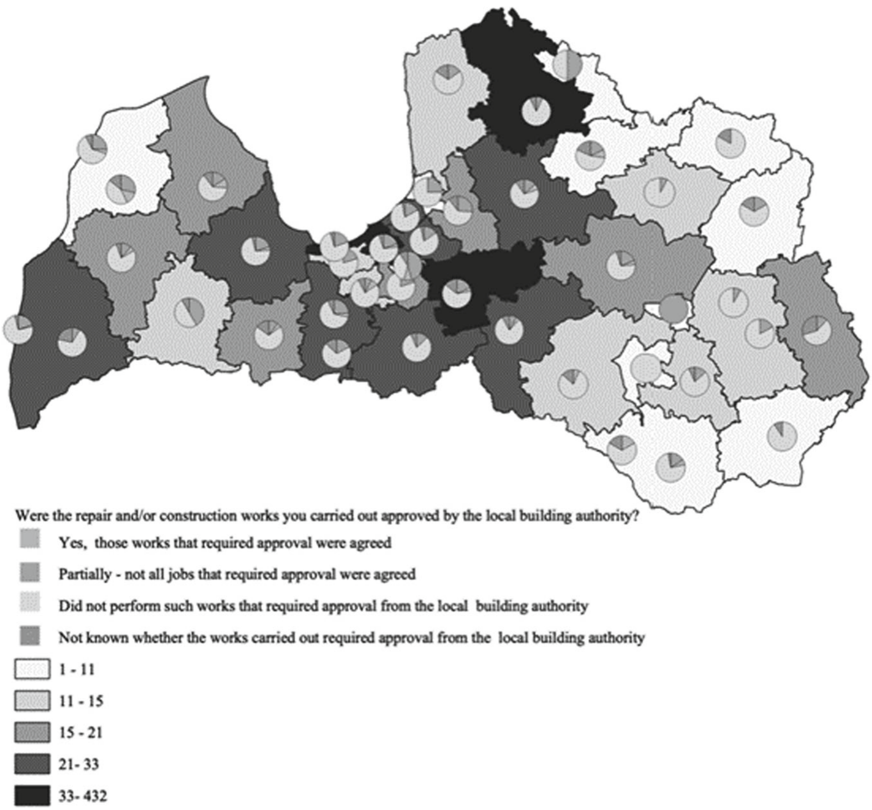


Fig. 22.6 Response distribution for the question, "Were the repair and/or construction works you carried out approved by the local building authority?"

waste when carrying out repair or construction work. More than one cubic meter of waste was generated by 29% of respondents:

- 1–4 m^3—20%;
- More than 4 m^3—9%.

It can be observed that the amount of waste was smaller for those respondents who carried out repairs in the apartment. The next section of the survey also covered the discharge of construction and demolition waste, which is important to assess and reveal tipping points, if any. According to the survey's results, most often, respondents get rid of repair and construction waste by throwing it into the common household waste container (34%) or burning it (29%). These results are undoubtedly revealing a significant gap in access to information in the overall education of the society, for instance, it is forbidden to discharge construction and demolition waste into common household waste containers for unsorted waste, not to mention waste incineration—which is forbidden on the legislative level.

Respondents also tend to get rid of repair and construction waste by taking it to the landfill with a special container for construction waste (19%), taking it to the landfill themselves (16%), contracting a company or private person that they found on the Internet or by other people recommendations to transport the waste to the landfills (16%). It is worth noting that there are also responses that can be biased, i.e., 14% of the respondents got rid of the repair and construction waste by using it for strengthening the road, and 10%—used it for filling low (wet) places. It is quite important to highlight that these activities, if performed on a larger scale and not in the real estate owned by the same person, require specific permits.

Respondents also got rid of repair and construction waste by taking it to the landfill with special construction waste bags (6%), selling (4%), burying it (3%), and throwing it in a forest, quarry, ditch, or similar places (1%). 17% of respondents stated that the waste (or part of it) is still stored with them. This was the central question from the survey, revealing also illegal activities, like burying and throwing in the forest. The authors conclude that these actions are caused by a range of reasons, such as:

- Lack of information on the management of construction and demolition waste;
- High cost of construction and demolition waste management.

It can be concluded that both problems have quite clear and straightforward solutions. Lack of information can be tackled by:

- Revising the information on the municipality web resources;
- Enhancing cooperation between municipalities and waste management companies to provide more educational materials, communication with society, etc.;
- Informing the society on waste sorting activities concerning construction and demolition waste as well (as generally waste sorting is associated with municipal waste solely), to decrease the volume of the waste discharged and thus using the waste sorting points or stations for sorted waste, which is collected free of charge.

Although, according to the survey results, this covers only a small proportion of the respondents, this result cannot be neglected as it directly impacts environmental pollution.

A positive aspect is that a little <2/3 of respondents (63%) have sorted the repair and construction waste for disposal, for example, to reduce costs. However, almost 1/3 of respondents (31%) have not done so in general. Notably, out of this 31, 10% did not sort waste but knew that this way could reduce costs, and 21% out of the respondents stated that they previously did not know that this way could reduce costs.

It can be observed that repair and construction waste was sorted more often by those respondents who carried out repairs in a private house and summer house/ garden house, as well as respondents living outside of Riga:

- The most convenient way for respondents to obtain information about the disposal of repair/construction waste is on their municipality's website or by calling the municipality's hotline (48%). Likewise, respondents would gladly obtain such information by following means:
- Contacting the company that takes care of the respondent's household waste removal (34%); finding the most advantageous offer for them in internet advertisements, for example, private advertisement platform ss.com (27%);
- In printed informational materials (21%);
- From friends or acquaintances (17%).

Another topic that has been addressed within the survey is secondary use of materials. Here, 41% of the respondents believe that there is a generally high possibility that the leftover materials after repair or construction would be offered to others on a special portal (rather high—26%, very high—15%). However, 1/3 of respondents (33%) indicate that the likelihood of offering leftover repair/construction materials to others is generally low or none (rather low—13%, very low—11%, none—9%). It has been assumed that such distribution of the results is explained by the limited availability of information on potential re-use and by the lack of legislative support or explanations i.e., on municipal or waste management company resources, providing information on what are the legal and permitted actions that individual can do with construction and demolition waste to foster re-use.

One positive aspect that the survey has revealed is that almost half of all respondents (48%) generally know places in their neighbourhood where people (individuals) can hand over various repair and construction waste (know where—22%, roughly guess where it could be—26%). However, 45% of the respondents indicated that they do not know if and where people in the neighbourhood can hand over various repair and construction waste. 7% of respondents indicated that they know that there is no such place in their neighbourhood to hand over repair and construction waste. Those living in Riga and those respondents who have not carried out repair or construction work in the last five years, more often stated that they do not know if and where people in the neighbourhood can hand over various repair and construction waste.

Having identified the main outcomes of the survey's results as lacking comprehensive and available information to the public, the authors considered using qualitative research based on text information analysis. They applied their own developed program to scan municipal websites to evaluate the level of available information.

22.6.2 *Case Study—Stakeholder Opinion About CDW Management in Latvia*

This case study was conducted for the purpose of obtaining a deeper understanding of the background and the internal environment within the construction sector in Latvia, as well as the attitudes and the present level of provision of education about construction waste management among the professionals involved in the industry. Owing to the current conditions resulting from the restrictions of interviewing face-to-face, as an alternative, the equally effective mechanism of primary data collection was chosen as a questionnaire-based collection of data.

Firstly, an extensive analysis of the research and publications focused on the background of construction waste management and its current and emerging trends has been done to understand the present situation in the sphere of construction waste management, acquire a comprehension of the legislations on building debris in the EU and the attitude of specialists involved in the managing thereof. Secondly, the questionnaire for target group construction companies was designed after studying the precedent surveys conducted within a similar topic in other countries to evaluate the perception and/or existing situation in the construction waste industry. The questionnaire (adopted from Tambovceva et al. [5]) was then addressed to be internally published to the members of the Latvian Civil Engineers Association (LBS). Where engineers, construction managers, and architects within the selected companies who directly or indirectly related to the management of the waste produced as the result of the construction or demolition work. For reliable data interpretation, questions included in the questionnaire were multiple-choice, some of the answers were set in accordance with the Likert Scale from 1 to 5. The authors also assumed that neither of the answers might be a proper interpretation of the desired response. Therefore, most of the questions included an open answer or "other", which allowed people in the survey to specify their point of view.

There were also a few constraints identified:

- The questionnaire was anonymous. Therefore, the data collected could not be sorted by the type of profession (architects, engineers, managers, etc.) among the respondents. This fact makes this research limited to understanding the construction sphere professionals' perceptions and therefore restrains differentiating the result by occupation;
- The research was limited to a questionnaire-based data collection only, without following face-to-face interviews;

- The geographical limitation is enclosed in targeting professionals involved in the related sphere in Latvia.

Questionnaire's results interpretation and analysis:

To receive reliable data and understanding, there was a need to find out:

- To what extent professionals are aware of the general situation on construction and demolition waste (CDW) and related sustainability concepts?
- To what extent specialists engaged in the construction sphere are satisfied with the opportunities and conditions provided?
- Are professionals motivated and willing to implement sustainable approaches while managing CDW?
- What are the opportunities and obstacles in improving the management of construction-related waste?

Considering the experience and insider knowledge of the respondents, it is also important to notice that respondents were allowed to specify additional answers that authors might not have accounted for when designing the questionnaire. Therefore, the questionnaire can be considered as more or less flexible and able to adapt to the people interviewed and obtain a better and more reliable result.

A total of 94 respondents took part in the survey, which is sufficient to obtain a reliable analysis. The questionnaire had 12 mandatory questions and respondents answered all of them.

The results of the answers of the respondents following:

To obtain answers about their attitude towards CDW recycling from respondents, they were asked to use a 4-point Likert scale from "Not important" to "Very important".

The majority of respondents (see Fig. 22.7) express concerns about the recycling of construction waste and its management in projects. About 39% of respondents, consider recycling important, while 26 and 25% believe recycling construction waste is very and moderately important, respectively. The data indicates a notable concern among professionals in Latvia regarding the recycling of construction and demolition waste (CDW). However, 10% of individuals view CDW recycling in their construction projects as a non-significant issue. Previous research [38] reveals factors influencing the reluctance to take responsibility for proper CW management or a lack of understanding on how to implement it. Despite this, there is an overall positive response, suggesting that specialists recognize the importance of CDW recycling, reflecting a commendable level of awareness and consciousness regarding CDW-related issues.

Information with regard to knowledge of the percentage allocated to construction sector waste is summarized in Fig. 22.8.

This question was designed to provide insight into how aware companies are of their impact on the generation of CW in the EU. Worldwide waste generation amount statistics [39], construction waste in 2018 made up 36% of total waste generated in the EU. The result shows that most (49%) of construction professionals have precise knowledge about the CW generation amounts across European countries. Moreover,

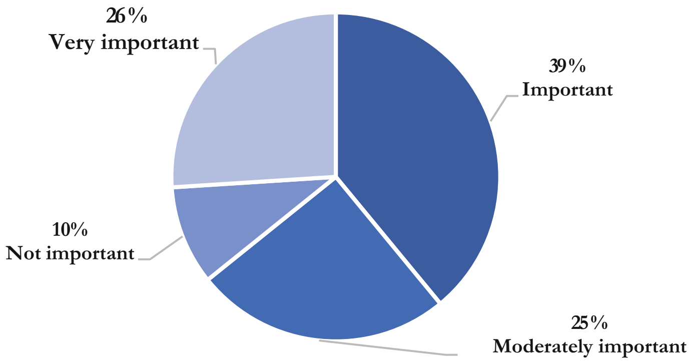
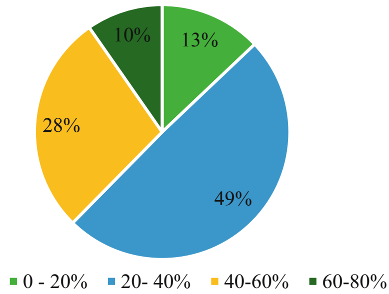


Fig. 22.7 Is it important for you how the waste generated under your construction projects is recycled?

Fig. 22.8 To your mind, what approximate percentage of all waste in the EU is allocated to the construction sector?



the majority were mainly distributed around the answer, which is relatively close to the right 20–40% and 40–60%. The minorities have been equally distributed on both ends of the extremes, which account for the least close to the correct answer of 0–20% and 60–80% CW generation, respectively. It may be, therefore, figured out, that specialists are aware of the trend in waste generation and know their impact in terms of CW production.

Respondents were asked to self-assess and give information about the approximate level of their knowledge about sustainable management practices, if they can apply their expertise in practice, and what is also important to teach others.

The data collected for this question is summarized in Fig. 22.9 the pie chart indicates that about 38 and 33% of the respondents either possess vague knowledge without practical application skills or have limited experience and lack confidence in applying their skills independently. In contrast, 21% (17 + 4%) of the participants can apply their knowledge on their own, and only 4% of all respondents feel confident enough to teach others. This suggests a potential hesitation among individuals regarding their ability to effectively manage waste. Site managers may perceive waste management as a lower priority, possibly conflicting with other business objectives. The constant pressure to achieve goals related to expenses, time, and quality may

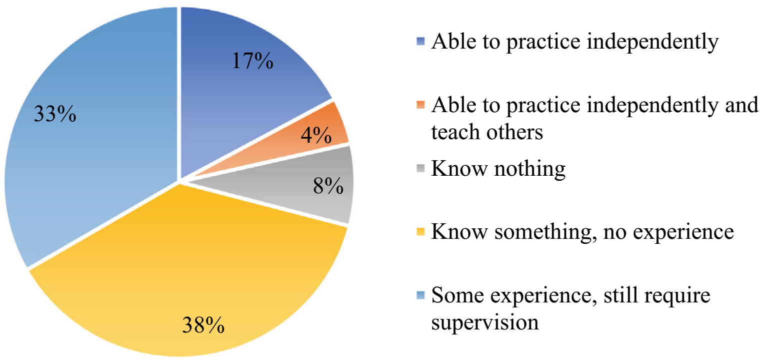


Fig. 22.9 Self-assessment on sustainable construction waste management

contribute to this perception. In such a scenario, their confidence in the return on effort for waste management could be compromised.

Question 4 aims to uncover the motivations behind construction professionals or companies expressing concern about construction waste production. Specifically, it delves into the reasons respondents feel compelled to take responsibility for managing waste stemming from construction and demolition activities. The question also seeks to identify potential drivers and control mechanisms influencing respondents in the implementation of sustainable CW management practices.

According to the pie chart (see Fig. 22.10) more than half of the responses indicate that companies are concerned about the waste issue due to an understanding of its adverse impact on the environment. Approximately a third of the respondents view waste as a source of additional expenses, a valid concern given that CW can constitute up to 30% of project expenses in some countries. Notably, 10% of specialists express the opinion that CW is not their concern, suggesting that it should be addressed by waste management companies.

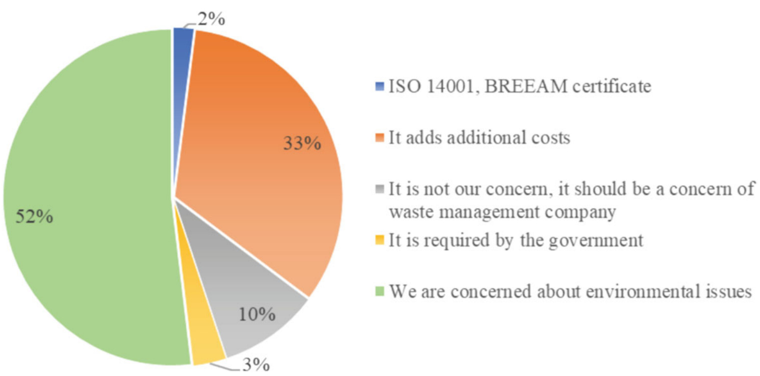


Fig. 22.10 Reasons for taking the responsibility for CW production

In addition, a minority of 3% of respondents cite government obligations as their primary reason for considering waste management, emphasizing the regulatory aspect imposed on them. Another group, comprising 2%, highlights their commitment to responsible practices by referencing the application of BREEAM certification and the ISO 14001 standard. This indicates a conscientious approach, possibly driven by both environmental and financial considerations.

Question 5 focused on eliciting information about the current or potential conditions for implementing waste minimization strategies within the respondents' companies. The responses aimed to reveal whether participants were planning, had already implemented, or had no intention of adopting construction waste minimization strategies, along with the reasons behind their decisions. The question also allowed for an open response if none of the provided options were suitable.

Figure 22.11 presents a summary of the collected data, indicating that approximately one-third of the responses are related to the future implementation of sustainable waste minimization methods. This suggests a significant interest or intention among respondents to adopt strategies for minimizing construction waste in the future.

Approximately 25% of respondents express satisfaction with their current technologies. Interestingly, those content with their technologies also admit to a lack of knowledge about sustainable waste management and an inability to implement such practices. This suggests that despite their satisfaction, the waste management technologies employed by these companies may not meet the criteria for sustainability. A notable correlation emerges from respondents indicating that current governmental requirements compel them to manage waste. The majority of this group expresses environmental concerns, revealing a conflicting relationship between their responses to questions 4 and 5. A more coherent correlation is observed among those who

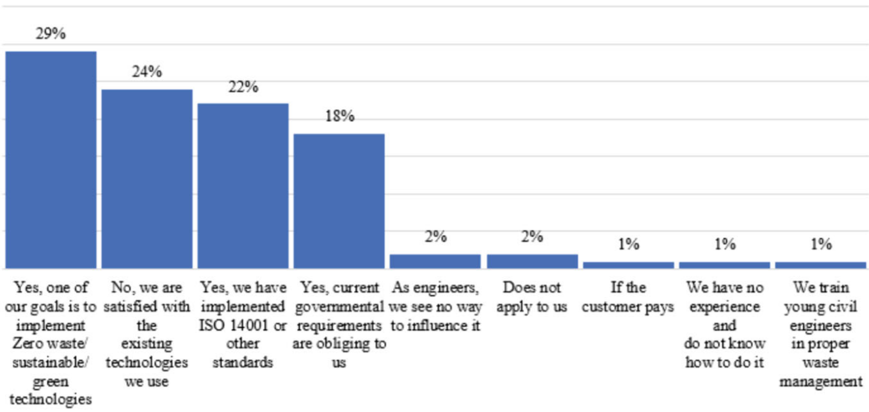


Fig. 22.11 Conditions for applying CDW minimization methods: "Have you been planning to minimize the waste produced during the construction and demolition works?"

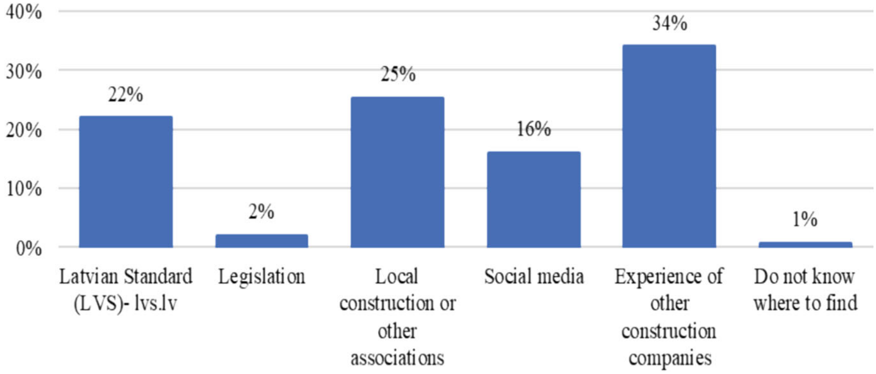


Fig. 22.12 The primary channels through which respondents gather information about waste minimization

express concerns about either environmental or financial issues and have subsequently implemented the ISO 14001 standard (22%). An intriguing contradiction arises when a respondent claims to train young civil engineers on proper construction waste management but concurrently states having "some knowledge, no experience" in question 3. This duality in responses adds a layer of complexity to the understanding of the respondent's expertise in waste management.

The Fig. 22.12 provides an overview of the primary information sources utilized by the respondents in question.

Given the ease of accessing information through online sources, understanding the preferred methods for acquiring knowledge about construction waste minimization in Latvia was crucial. According to the summarized data, the majority of practitioners prefer drawing insights from the experiences of other construction companies. Notably, some respondents specifically highlighted a preference for relying on the experiences of other European Union (EU) countries, with these responses consolidated under the category "Experience of other construction companies" for streamlined data management. The second most utilized source of information is the knowledge available within various Latvian associations, such as Latvijas Būvinženieru Savienība (LBS), Latvijas Arhitektu Savienība (LAS), or any similar associations. Additionally, 22% of respondents opt for the Latvian National Database of Standards (lvs.lv) website to gather relevant information. A portion of the respondents (16%) turns to social media platforms, while a smaller percentage (2%) relies on local legislation to guide them in understanding the concepts of CW minimization.

This question acknowledged the diversity of perspectives and attitudes regarding responsibility by allowing survey participants to select multiple answers. Recognizing that cultural influences, company policies, and the perspectives of various professional groups can shape attitudes, the survey aimed to capture a comprehensive understanding of respondents' views on responsibility.

Certainly, identifying the primary responsible stakeholder(s) remains crucial, as highlighted by Osmani et al. [38]. In the current survey, it was found that the majority, comprising 79.8% (75 out of 94 respondents), do not attribute responsibility for construction waste minimization to architects (Fig. 22.13). Specifically, the prevalent combination of answers points toward Construction and Waste management companies, or the same two entities, with an additional emphasis on the responsibility of suppliers and contractors. In contrast, 22.3% (21 respondents) believe that architects can play a role in influencing waste reduction, particularly during the design stage. This data sets the stage for the subsequent question, aiming to unveil respondents' opinions on the stage at which most construction waste is generated. The findings from this question contribute valuable insights for establishing key assertions regarding the responsibilities of stakeholders in CW minimization efforts.

As it was assumed above, it is logical that most construction waste is produced within the stage of project implementation (see Fig. 22.13), where 87% of the professionals assign construction waste production to construction execution, and only 5 and 8% think that CW may arise during either the design stage or project completion.

Here can be observed similarities with the research made by Osmani [40] revealing that, indeed, the project stage is one of the key components in CW generation. However, very often other stages are not taken into account due to traditional perceptions of waste as a. Inevitable and b. Ignoring other causative factors of CW, which occur in other phases of the project rather than during execution only (Fig. 22.14).

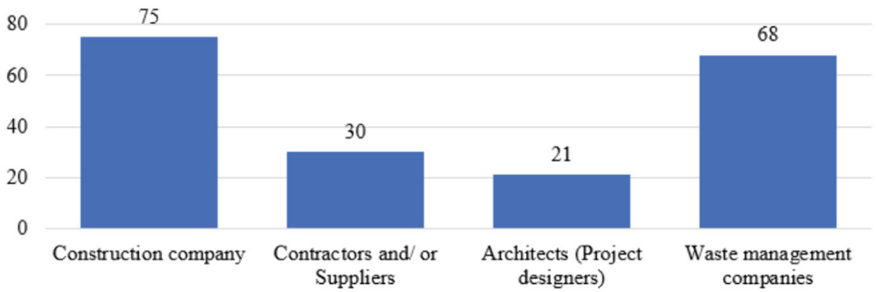
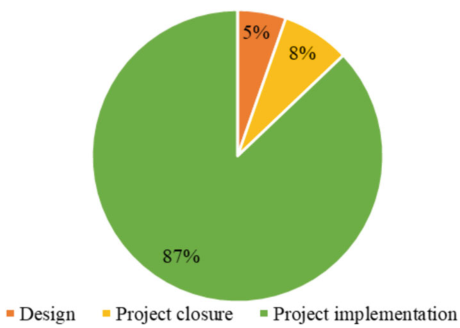


Fig. 22.13 Stakeholder responsible for construction waste minimization

Fig. 22.14 Project stages causing the most CW production



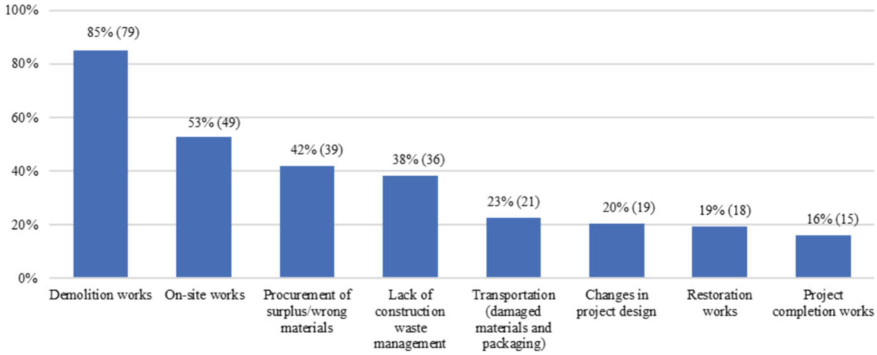


Fig. 22.15 Aspects contributing to material wastage

The research tried to identify the factors leading to waste. Four high contributory factors to material waste at construction sites are revealed in the study presented in Fig. 22.15.

The impact of demolition works ranked highest in material wastage, aligning with the results obtained in Question 8. On-site works secured the second-highest rank, consistent with previous findings. Procurement of surplus/wrong materials emerged as a concern for 42% of respondents, while the lack of construction waste management was identified as a significant contributor to material wastage, according to specialists. Other options, including design changes and material damage, were deemed to have a moderate impact, ranging from 20 to 23%. Interestingly, respondents perceive material wastage to be less prevalent during restoration works and project closure.

This aligns with a study by Oko and Emannuel Itodo [41], which emphasizes the substantial contribution of on-site works, including workmanship, storage facilities, and rework, to materials wastage. The findings underscore the importance of comprehensive training for all on-site participants, from site managers to construction workers, to effectively address material waste on-site. As emphasized by Ekanayake and Ofori [42], the most effective waste management strategy is to prevent waste in the initial stages of construction.

Understanding the importance of implementing methods that can help to cut off the waste generation in construction instead of conventional approaches is essential. The responses are outlined in Fig. 22.16, where interviewees were asked to rate each approach from “never” or “occasionally used” to “use in every project”. As the diagram suggests, almost a third of the respondents use waste sorting on-site, followed workers’ training (28 respondents), use of standard dimensions, and prefabricated elements. Only eight respondents specified the use of recycled elements in every project and other methods like a design for deconstruction, material reuse, and estimation of waste at the design stage applied at an average of 13 respondents. Occasional use of the aforementioned methods, however, is more widespread among professionals. The most popular here is in contrary use of recycled materials, reuse,

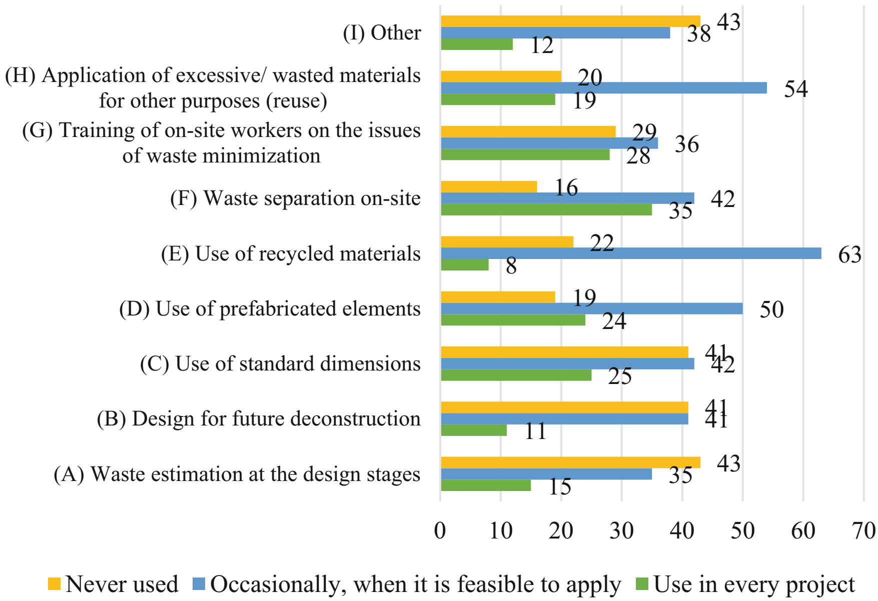


Fig. 22.16 Waste minimization methods ranking

and prefabricated construction. All other methods were also occasionally applied and were chosen by almost a third of respondents.

Nevertheless, it could be noticed, that the mean the approximate total of never used methods were chosen by another half of the interviewees.

Having researched the main barriers in implementing sustainable waste management approaches within the construction sector, it was essential to understand the barriers within the industry that professionals face in Latvia. The respondents were asked to choose the main hindrances in minimizing material wastage. The information obtained is summarized in Fig. 22.16. This question seeks to determine whether the obstacles are internal, like the company's standard approach, attitudes towards waste, or external, such as governmental or stakeholders' encouragement, or insufficient standards.

As it can be seen in Fig. 22.17 the prevailing number of responses stands for external factors to be a primary barrier in implementing waste minimization. The most significant, though, is the indifference of stakeholders to minimize material wastage and the perception of waste to be unavoidable. Another external factor that gains major votes in the absence of a standardized approach and lack of incentives from the government. It is crucial to emphasize that some respondents noted the government to be motivating on paper, but not helping construction companies to make a real step forward in achieving the results in sustainable construction.

In the concluding question, the author investigates whether cost is a significant barrier preventing companies from implementing sustainable technologies to reduce material wastage. According to the summary presented in Fig. 22.18, nearly half

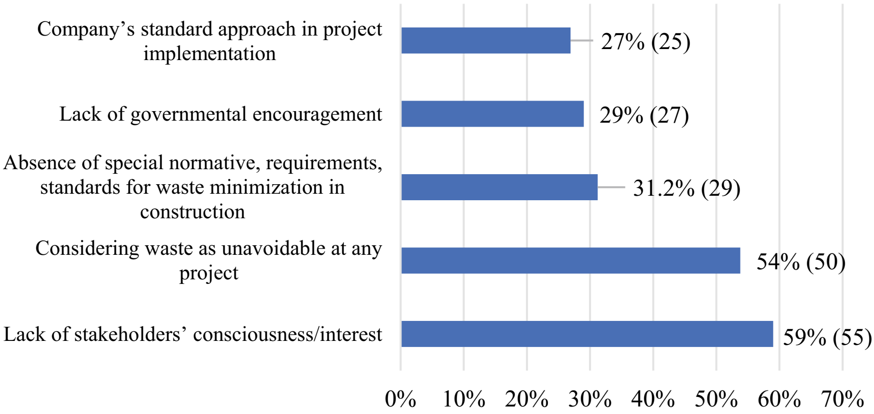


Fig. 22.17 Hindrances for CW minimization methods implementation (respondents' opinion)

of the participants express a willingness to adopt sustainable technologies in their construction practices.

The findings indicate that, despite the potential long-term environmental and economic benefits, nearly half of the respondents are willing to incur additional expenses for the implementation of sustainable technologies. The remaining half of the responses are almost evenly split between those who prefer to maintain their current methods and those who would consider a change only if mandated by the government. This suggests a conscious and adaptable mindset within the construction industry. However, the observed hesitation to change may be attributed to the obstacles identified in question 11, implying a need for a more conducive environment to foster the flourishing of sustainable waste management approaches in the construction sector. The results highlight the importance of addressing existing challenges and creating a supportive framework to encourage the wider adoption of sustainable practices.

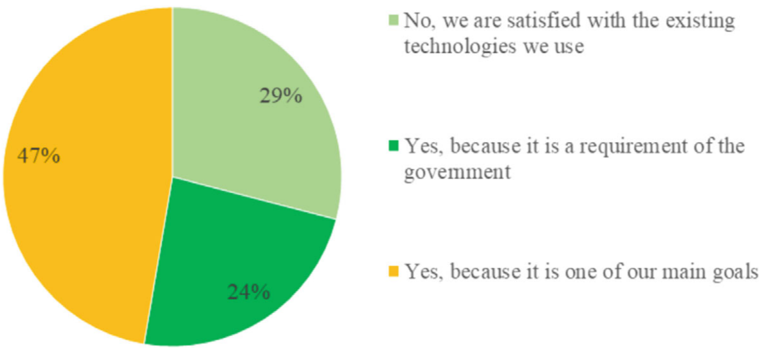


Fig. 22.18 Cost versus implementation of sustainable technologies (respondents' opinion)

22.6.3 Case Study—Stakeholder Opinion About CDW Management in Cyprus

The project, under the name “Build CIRCULAR Up: Circular Transformation of the Construction Industry,” was set to revolutionize the construction sectors in Bulgaria, Cyprus, and Malta. Funded by EIT Climate KICK, the initiative focuses on advancing a Circular Economy (CE). It planned to achieve this through the development of a cutting-edge digital innovation tool tailored for stakeholders, the establishment of a Green Construction Hub, and the facilitation of international knowledge exchange. The project’s core objectives encompass promoting sustainable practices, enhancing resource efficiency, fostering collaboration among industry players, assessing readiness for transformative measures, and laying the groundwork for a systemic shift towards circularity within the construction sector. This sub-study performed for Cyprus by Cyprus University of Technology and authors Dr. Nisiforou Olympia, Dr. Stylianos Yiatros, Dr. Orestes Marangos, and Dr. Costas Andreou. This study delves into user attitudes and practices concerning Circular Economy (CE), exploring opportunities, needs, and concerns associated with CE. The research involved 36 participants, and the questionnaire was structured into distinct sections: (a) demographics, (b) comprehension of and attitude toward CE, (c) CE practices, and (d) Opportunities, needs, and worries linked to CE in the Case Study of Cyprus. The quantitative data collected were subsequently analyzed using Excel.

Demographics

The survey outcomes present a demographic snapshot of Cyprus’ Construction and Demolition Waste (CDW) sector, with participants typically in their early 30 s and a majority (65.7%) being male. Small to Middle-sized companies dominate the sector, and participants, often with a high level of education, showcase substantial experience, with a typical tenure spanning 5–10 years.

Regarding CE awareness, approximately 60% of respondents possess a basic understanding, while 63% demonstrate a somewhat deep or deep comprehension. This positive trend extends to CE practices, with 41% of companies actively engaging in partnerships across the supply chain where CE practices are applied and one-third reporting profits from the sale of recycled materials.

However, the survey reveals notable gaps in awareness within the CDW sector. About 26% of participants are unaware of the legal obligations of CDW producers, emphasizing the need for targeted outreach. Misconceptions exist, with some participants believing that waste from the sector is primarily inert and can be handled casually on-site.

Challenges and opportunities are elucidated through numerical insights. While 66% of participants engage in the separation of CDW, 17% do not separate waste at all. Concerns about cultural attitudes, insufficient training, and the absence of standards for recycled materials are expressed by respondents. Nevertheless, 52.9% of companies engineer their products to minimize waste, highlighting a positive inclination.

In conclusion, the survey provides quantitative insights into the demographic profile, CE awareness, and practices within Cyprus' CDW sector. The detailed document, featuring illustrative graphs and specific numerical data, is accessible in the appendix for a more in-depth exploration.

The provided graphs depict the demographic data obtained from the survey. In the context of the survey, the CDW sector in Cyprus is predominantly represented by individuals in their early 30 s, characterized by a high level of education, with the majority being male participants (65.7%).

In Cyprus, the CDW sector is predominantly composed of Small to Middle-sized companies. The majority of participants are employed in construction companies or engineering consultancies (design bureaus). Additionally, participants exhibit a considerable amount of experience in these sectors, with a typical tenure ranging from 5 to 10 years.

Understanding of and Attitude Towards the CE

The survey results reveal that participants generally possess a basic understanding of the CE, with 60% having basic knowledge and 12% having never heard of it. Approximately 63% of respondents claim to have a somewhat deep or deep understanding of CE. Companies show a growing interest in implementing CE practices, and this trend extends to their supply chain partners. The major key findings showed that regarding familiarity with CE, 60% of participants have a basic knowledge, while 12% have not heard of it.

Depth of Understanding in CE—63% of respondents demonstrate a somewhat deep or deep understanding of CE. Interest in CE within Companies—Companies exhibit interest in CE, with respondents recognising significant interest within their supply chain partners.

74% of participants are aware that CDW producers are required to be part of a collective CDW management system or operate their own licensed CDW management system (Fig. 22.19). There is a prevailing misconception in the CDW industry that waste is predominantly inert, leading to a relaxed handling approach. This emphasises the need for outreach and training. Participants exhibit awareness of legal obligations for waste management, with around half acknowledging the owner's ability to transfer waste management liability to other licensed entities.

Companies are demonstrating a keen interest in the CE concept and actively engaging in the implementation of CE practices. Additionally, they acknowledge that companies within their supply chain also exhibit a notable interest in adopting CE practices.

CE Practices

The survey findings reveal a diverse landscape in adopting CE practices among participating companies. Almost half of the companies lack partnerships throughout the supply chain for CE practices, with reasons ranging from a lack of interest within the company to the absence of interest among their partners. Despite this, one-third of participants report deriving profits from the sale of recycled materials, underscoring

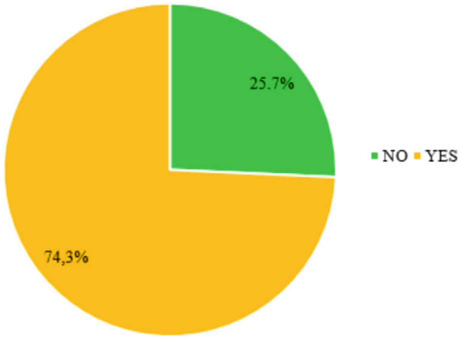


Fig. 22.19 Diagram illustrating the respondents' awareness level in terms of their management system (retrieved from Survey Report—Build Circular Up [43])

a positive economic impact. Approximately 65% of respondents engage in the separation of CDW, while 17% do not separate waste at all. Primary materials used and recycled encompass aggregates, concrete, metals, bricks, tiles, building stone, wood, and plastic. Moreover, 66% of participants are members of a collective CDW management system, and over half of the companies have established proprietary waste management systems. Notably, 52.9% of companies engineer their products to minimise waste during the manufacturing process, showcasing a commitment to sustainability and waste reduction.

Opportunities, Needs, and Worries Related to the CE

For an industry with high uncertainty and low profit margins, cost minimization by adopting CE practices is identified by the participants as a major benefit for the companies. The participants in the study highlight cost minimization as a significant benefit for companies adopting CE practices in an industry characterized by high uncertainty and low profit margins. They identified benefits in implementing CE practices, emphasizing the importance of cost reduction for companies. Additionally, a noteworthy 15.2% of companies lack awareness of the source of their materials, while 18.2% express uncertainty about material origin (Fig. 22.20).

The CDW sector in Cyprus faces obstacles to recycling and reusing materials, with participants citing cultural attitudes, insufficient training on CE, absence of standards for recycled materials, and inadequate infrastructure as barriers. Figures 22.21 and 22.22 illustrate the identified barriers to implementing CE practices.

Transport costs and disposal of CDW emerge as significant concerns (Fig. 22.23), while participants express varying levels of knowledge regarding standards and regulations for CDW (Fig. 22.24).

The overall understanding of CE is foundational, with participants expressing a somewhat deep comprehension, and companies show considerable interest in implementing CE practices across their supply chains. Identified benefits and barriers to using or selling recycled waste are crucial illustrations reflecting the perceived advantages and challenges associated with CE practices in the CDW sector in Cyprus.

Participants highlight cultural attitudes towards Circular Economy (CE) and environmental protection, insufficient training and information on CE, the absence

Fig. 22.20 The participants' knowledge about where the materials their company uses come from [43]

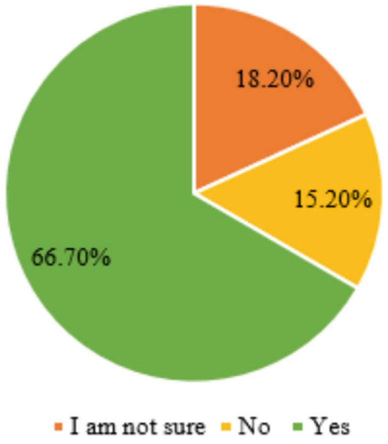


Fig. 22.21 The participants identified barriers in recycling waste [43]

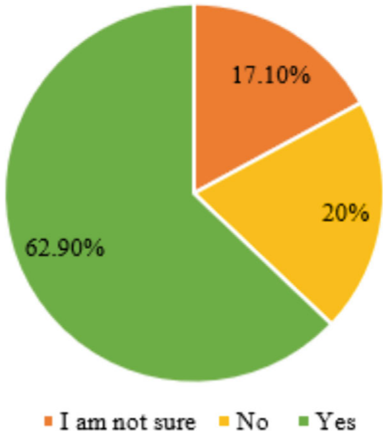
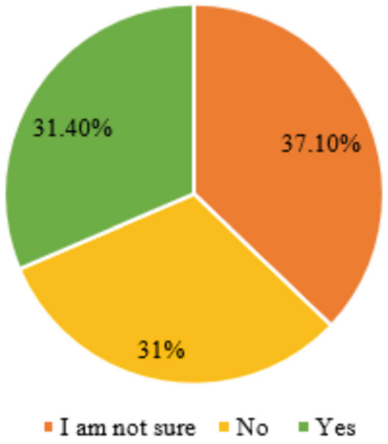


Fig. 22.22 The participants identified barriers in recycling waste [43]



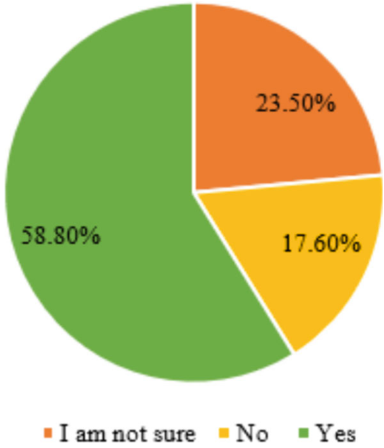


Fig. 22.23 The participants' views on transport costs and disposal of CDW [43]

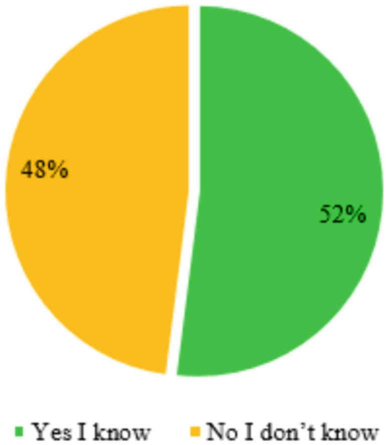


Fig. 22.24 The participants' knowledge level according to standards and regulations for CDW

of standards for recycled materials, and inadequate infrastructure as barriers. The primary challenges reported are the costs associated with transporting and disposing of CDW, leading to on-site waste treatment. Furthermore, the cost and the absence of standards are identified as significant concerns when considering the use of recycled materials. While some participants are aware of the existence of certain standards, they lack familiarity with their specific context.

The escalating global population exerts tremendous pressure on the environment and natural resources. The construction sector in Europe, marked by intense activities, generates substantial amounts of Construction and Demolition Waste (CDW). Our fixation on producing and consuming at minimal costs has fostered a linear economy, where items are briefly utilized and then discarded as waste.

According to the findings of this study, participants generally possess a foundational understanding of Circular Economy (CE), expressing a somewhat deep comprehension. The companies represented by the respondents exhibit a considerable capacity and interest in implementing CE practices, extending to their supply chains.

Furthermore, the survey results reveal that most participants are aware of the existing management system in Cyprus. However, there is a prevalent misconception that waste from this sector is primarily inert and can be handled casually by leaving it on site.

The survey underscores existing barriers in the CDW sector hindering the development of CE practices. Participants find the survey highly useful, with some requesting more information related to CE in the CDW context. It is acknowledged that implementing CE concepts in Cyprus requires time, resources, and synergies [44].

As a result, prioritizing the enhancement of the waste management system to reduce CW and promote CE is crucial. Investment in consultation schemes is deemed valuable, as they have the potential to induce behavioral change, fostering improved waste management and a shift from a linear to a Circular Economy.

22.7 Comparisons of Stakeholders' Influences, Inter-Relationships, and Obstacles in the Implementation of Circular Economy on Existing Building Sectors in Europe

22.7.1 Review of Current Market Barriers to Building Retrofit and Renovation

CE practices for existing, ageing built environments are mainly influenced by specific targets, including (i) prolonged service life of components through enhanced maintenance and retrofit; (ii) minimized energy consumption through deep renovation; (iii) elimination of residual waste by increased recycling and repurposing; (iv) climate change adaptation and reduction of external risks and uncertainties by additional retrofit and reconditioning; and (v) enhancement of structural condition and architectural aesthetics by redevelopment and refurbishment. These CE actions, especially for retrofit and renovation, are often motivated to achieve energy independence or zero energy buildings (ZEB), near-zero energy buildings (NZEB), and even energy-positive buildings (EPB). However, the commercial market for ZEB, NZEB, and EPB concepts is still relatively emerging, particularly in the existing building segment. Existing collaboration structures have yet to enable long-term success beyond exemplary new buildings and some cosmetic renovation projects.

Challenges and obstacles to renovation processes have been identified, including financial constraints and the unwillingness of local councils or local governments to prioritize energy-efficient or circular buildings. Limited awareness and personal engagement of municipal officials, inadequate public policy instruments, and the absence of established CE and energy-efficient standards further obstruct collaboration for the successful implementation of circular practices [45].

An important factor that needs to be addressed is the nature of the renovation market, which is driven by supply than consumer demand. Efforts have also been made to ensure the quality of circular and energy-efficient buildings and the effectiveness of energy performance certificates (EPCs). For example, the REQUEST project highlights the need for support to homeowners more than receiving an EPC, emphasizing the importance of partnerships between supply and demand. Improved communication among stakeholders, building trust, and creating multi-disciplinary partnerships at various levels have proven effective in promoting circularity and energy-efficient buildings [46].

To motivate building owners and influencers to adopt circular and energy-independent design, retrofit, and renovation projects (e.g. beyond NZEBs), it is important to demonstrate the success of such circularity projects in achieving sustainability and high energy performance. However, the sophisticated building process can involve multiple actors with varying levels of influence. These actors can significantly delay the progress of decision-making for circular practices. Therefore, understanding the influences and inter-relationships among actors and stakeholders is the precursor to overcoming obstacles and challenges in CE implementation within the built environment sector.

22.7.2 Concepts of Circular Economy Implementation for the Existing Building Sector

The net-zero economy cannot be achieved without an appropriate transformation of current industry practices. Indeed, McKinsey [47] reported that any action for decarbonization needs to improve the energy mix toward renewable alternatives such as hydrogen, solar power, and wind power. Industrial and agricultural processes need to be revisited to increase energy efficiency and reduce demand for energy; adopt the CE; consume fewer emissions-intensive goods; apply carbon capture, utilization, and storage (CCS) technology; and enhance sinks of long-lived and short-lived greenhouse gases. New studies highlighted that a way to accomplish circularity of new and existing buildings is to promote the development, implementation, and automation of CE strategies by connecting market actors using Industry 4.0 Technologies via digital transformation and by carrying out a series of outreach activities. Adopting digital twins and artificial intelligence can accelerate the pace of and circularity across the scale from materials to components to buildings and the built environment. Strategies to overcome market barriers include simplifying the design process, manufacturing, retrofit and renovation to incorporate CE strategies, life cycle costing, and carbon-free co-benefits.

CE for existing building stocks generally implies an industrial intervention that can be restorative by design; aims to rely on alternative renewable energy; reduces, monitors, and eliminates the use of energy, water, carbon, and toxic chemicals; and eliminates waste through careful re-design, renovation, rehabilitation, and planning. The CE implementation for existing building stocks will generally target less resources and energy consumption while simultaneously being more carbon efficient and maximizing waste reduction and management. The traditional stages to implement CE concepts are the planning stage, execution stage, and commission stage.

Planning Stage

Firstly, it is important to determine best practices of CE, requirements, and specifications for circular re-design, retrofit, and renovation suitable to the existing buildings (i.e., residential or non-residential buildings). In this stage, assessing available technologies, innovation and processes for circular buildings is crucial. Market conditions, technical stakeholders, and required expertise for circular design, retrofit, and renovation should be listed, including other stakeholders that are often neglected in the retrofit and renovation process for existing buildings, such as architects, planners, insurers, energy, and financial advisors. They are key actors who will have a significant role in CE concepts. Accordingly, the original purpose of the project can be maintained despite any difficulties that may be encountered. The actors could also encourage smooth information exchanges and collaboration between professionals and contractors.

A number of non-technical stakeholders can influence any decision-making in circular building design, retrofit, and renovation. They could be public authorities (at national, regional, municipal, or local levels) in various roles as building owners, enablers/ facilitators, policymakers, or financers. Stakeholders include building owners, industry players (suppliers, contractors, energy service companies), professionals (architects, engineers, building managers, surveyors), insurance and financing entities (public or private), occupiers, and end-users.

In order to motivate more asset owners and managers to implement CE concepts, circular design and renovation projects, it is essential that the project developments can share the vision and demonstrate the potential success of their projects towards net zero (e.g. for circular materials; for zero waste; or high energy performance beyond NZEB, ZEB and/or EPB). In addition, the involvement of local municipalities can overcome the barrier to implementing CE practices. Regarding technical solutions, different re-design, retrofit, and renovation approaches based on CE principles can be determined based on the type of buildings, state of the building, location, and purpose of renovation, etc.

In practice, the capability to access and share clean energy grids for a building can improve the circularity of existing building service systems. The capability will reduce the demanding activities required to deeply renovate the building stocks. The advanced sensing for energy performance and structural health in built environments and the potential of sharing renewable energy systems (RES) between buildings can also be explored in this stage. The automation for RES can be analyzed to support the decision-making process for circularity. Key issues with RES installations often found are 'cross-ownership', or the superposition of rights on land and infrastructure. Various stakeholders at the various political levels (local, regional, national, EU) could hamper the integration and implementation of cross-sectorial solutions. However, life cycle costing (LCC) and carbon footprint can be conducted to support the decision-making. Building and homeowners often do not have access to a structured approach to obtain all essential information to make a decision. Therefore, financial and benefits incentives are necessary.

Homeowners and building professionals will need to easily assess and compare different re-design, retrofit, and renovation strategies for a given building, combining energy and cost calculations with flexibility and a depth that makes it unique and vividly visual. Note that there are differences in national calculation procedures for determining circular materials, water consumption, and energy needs in buildings and assessing energy performance in buildings despite the common norms and regulations. These differences must be considered at the planning stage.

Execution Stage

Once the decision for any circular action has been reached, pre-simulations of the actions can be performed for the existing buildings. The best scenarios for circularity can be determined and applied to the building stock. The circular building data should be simultaneously collected to update the building information systems and to improve automation towards circular practices (e.g., materials, water, wastes, and energy usage control in each part of the building). Notably, the data and building information system can overcome current market barriers to CE implementation by increasing stakeholders' awareness of the circular practices. Collaboration and partnerships among academia, industry, municipalities, and SMEs are instrumental in implementing successfully CE concepts. The technical and quality assurances of the circular design, retrofit, and renovation measures should be warranted, and CE checklists should be prepared to assess this process. All activities and actions need to be well planned, scheduled, and recorded to execute the successful delivery of CE implementation.

Commission Stage

It is crucial to ensure the monitoring platform is established for compliance purposes to validate the results with CE goals, targets or indicators. Also, there will be a need for a correct assessment of the reliability and repeatability of the results. An iterative process should be carried out in order to verify the outcomes of the CE concept application. Monitoring action can be implemented using sensors, routine inspections, and smart meters to monitor different parameters affecting materials, water and energy consumption, waste and toxic management, and/or internal comfort. These data are crucial for smart building and smart city concepts that will transition to net zero. Assessing user experience through interactive engagement, mutual activities, and surveys is inevitable. The insights can help to further improve the implementation of CE practices.

Recent reports [48, 49] showed new evidence that energy renovation of existing buildings offers many valuable outcomes to existing buildings' owners and stakeholders beyond cost savings from energy expenditure. Note that it should not only measure energy performance (kWh/m^2) but also waste reduction, recyclability of materials and components, service life and durability of assets, indoor environmental quality (e.g. temperature, air quality, and visual comfort), airtightness, the rebound effect, the weather conditions, occupancy (internal gains, building use), maintenance activities, and user experiences. These measurements will help to accurately establish a better guideline and harmonized standard for a circular design upgrade, retrofit, and renovation measures for existing building stocks. Business case and advertisement experts should be invited to join the implementation process from the beginning and develop clear and interactive campaigns to promote CE concepts. This will increase awareness and influence to overcome any obstacle to implementing CE practices for existing building stocks at all levels.

There have been many projects to implement CE concepts and applications to existing building stocks. However, the adoption rate of those measures is far from enough to achieve the net zero target by 2050. This is because over 90% of buildings globally are ageing or existing building stocks. With an adoption rate of CE between 0.5 and 1% annually, it would take over 100 years to reach net zero for existing building stocks [50]. Built environments with special attention to ageing and existing building sectors thus face significant challenges in successfully implementing CE towards the transition to net zero. These challenges stem from (i) the lack of incentives and financial support; (ii) technical solutions and bottom-up technologies suitable to the diverse ranges of existing building stocks; (iii) non-inclusive, undiversified policies, target directives, indicators, and regulations; (iv) inadequate cooperation among fragmented stakeholders and circular value chains; and (v) poor inter-relationships and influence among stakeholders. CE transition towards net zero is a global challenge, and we must strike to resolve the climate issue altogether through both domestic and international cooperation [50]. Therefore, we all need to work together to harmonize actions with tactical and pragmatic strategies to overcome technical challenges and barriers to CE implementation.

22.8 An Assessment of European Stakeholders' Opinions on the Costs and Benefits of Circular Economy Implementation in the Construction Value Chain

CE aims to create a closed-loop system, minimising waste and maximising resource use in response to the current linear economic model [51]. The construction sector, being one of the top-polluting industries, is driven by financial outcomes and, therefore, faces challenges in embracing innovations due to uncertainties about costs and benefits [52]. Defining the costs and benefits of circular business models in construction and engaging stakeholders is essential for its adoption [53].

The transition to CE requires significant upfront investments [54]. The costs and benefits may vary across different countries and cities where construction takes place, depending on the availability of resources, technology equipment, human resources, various factors that can contribute to costs, such as opting to use recycled materials that may be pricier, consuming more water and energy for recycling processes, investing in innovative equipment and software, as well as training and certifying human resources.

Nevertheless, the construction sector can also derive advantages from adopting CE principles, especially when focusing on materials. These benefits encompass the reduction of waste generation, decreased reliance on new resources, and a decline in the environmental impact associated with producing new materials, including energy consumption and greenhouse gas emissions from transportation [55]. Resource reuse might be more advantageous than purchasing new materials, while refurbishment presents a cost-effective alternative to constructing new buildings [55]. Implementing CE can develop resale markets, improve local resource use, tax benefits, and create new workplaces [56].

In general, in the European region, CE support is reinforced by the national strategies implemented in these countries, which endorse the adoption of CE practices and allocate significant funds towards their implementation. The Circular Economy Package encompasses an EU Action Plan for the Circular Economy, which outlines a specific and ambitious course of action. It includes initiatives that address every cycle phase, from production and consumption to waste management and the secondary raw materials market.

Nevertheless, there is a research gap regarding the costs and benefits of applying CE methods in the construction sector, specifically related to construction materials. Despite growing awareness of the advantages, such as waste and emission reduction, there is limited understanding of how to implement circular practices in construction while considering various stakeholders. This highlights the need for a comprehensive analysis of the costs and benefits of adopting CE practices in construction and incorporating perspectives from different stakeholders. Further investigation is necessary to promote sustainable growth and meet the needs of all stakeholders in the construction sector.

Therefore, this study has been conducted, which is a qualitative analysis of stakeholders' perspectives towards CE costs and benefits in the European region to gather relevant ideas and an overview of the specific challenges and opportunities. The survey results can help develop tailored strategies and policies that could aid in promoting the successful adoption of circular practices in construction while considering the diverse needs and perspectives of stakeholders.

The research questionnaire includes inquiries regarding the respondents' country of origin and stakeholder affiliation. Subsequently, a series of questions employing the Likert scale is employed to gauge stakeholders' perceptions of the impact of CE implementation on costs and benefits. Prior ethical clearance for conducting this survey has been obtained from the Institutional Review Ethics Committee (IREC). The survey employed a combination of random sampling and snowballing techniques. Utilizing the Qualtrics online platform, the survey was administered from

June to July. Access to the survey can be found at the following link: https://nukz.qualtrics.com/jfe/form/SV_3mZiu5qJbjxLfU2. Simple descriptive statistics were utilized to analyze the data. It is important to acknowledge the inherent limitation of self-reporting bias. After filtering out incomplete responses and those with over 60% unanswered questions, a total of 265 valid responses were obtained from participants residing in the European region.

The data presented in Table 22.7 shows that the survey was conducted in 28 countries. Norway had the highest number of participants, with 114, followed by Spain (34), Latvia (30), Portugal (11), and Albania (9). Figure 22.25 displays the number of responses categorised by stakeholder type. The majority of respondents were from academia (63), project management (52), engineering (36), and contractor stakeholders and manufacturing (22 and 21 respectively). Figure 22.26. depicts the number of respondents who stated they had experience with circular, sustainable, or green building practices. Norway had the highest number of such respondents (50), followed by Spain (23), Latvia (13), and Portugal (8).

In Figs. 22.27, 22.8, 22.9 and 22.30, the perception of stakeholders toward implementing CE practices in companies is shown in terms of its impact on costs and benefits. The Likert scale was used to measure responses on a scale of 1–5. Responses were categorised as 0% for "very low", 25% for "low", 50% for "moderate", 75% for "high", and 100% for "very high." The percentages shown in Figs. 22.27, 22.28, 22.29 and 22.30 were calculated by adding up the responses for each country. The cut-off value for country responses was more than six values for these specific questions, which has resulted in an analysis of Norway, Spain, Portugal, Latvia, and Albania.

Figures 22.27 and 22.28 highlight the experts' perception of the importance of the advantages gained and costs required from the implementation of CE practices. Notably, all the countries' respondents have a relatively high appreciation for these practices, both benefits and costs (more than 50%). In Fig. 22.27, the highest value was observed from respondents from Spain (75%), while the lowest was from Portugal (50%). Figure 22.28 displays the perception of CE implementation costs importance. For Albania, that is the most significant (75%). While for Portugal—the smallest (58%). It is interesting to note that for both costs and benefits, the ranks identified by respondents from the countries are similar—Spain and Albania lead (although changing each other in first and second places), Latvia is in the middle, while Norway and Portugal are closing in both charts. Nevertheless, Spain is the only country, among others, for which the benefits were observed to be more important than costs (75% contrasting to 65%, respectively). For Albania, the perception of cost importance was almost 30% higher compared to the perception of benefits importance, and it was the highest difference among other countries. For Latvia, Norway, and Portugal, the assessment of the significance of expenditures and advantages was relatively similar, with differences of around 10–15%.

Spain is one of the leading countries in terms of CE development, either in practice implementation or in research [57]. Construction is one of the main priorities in the Spanish Circular Economy Strategy (España Circular 2030) [58]. Spanish City Councils aid in financing circular projects promoting CE businesses. Access to

Table 22.7 The number of responses versus the country name (European region)

Country	Number of responses
Norway	114
Spain	34
Latvia	30
Portugal	11
Albania	9
Austria	6
United Kingdom of Great Britain and Northern Ireland	6
Ireland	4
Italy	4
Netherlands	4
Serbia	4
Bulgaria	3
Croatia	3
Greece	3
Slovakia	3
Belgium	2
Germany	2
Poland	2
Sweden	2
Switzerland	2
Bosnia and Herzegovina	1
Czech Republic	1
Estonia	1
France	1
Luxembourg	1
Montenegro	1
Republic of Moldova	1
The former Yugoslav Republic of Macedonia	1

funding is noted as one of the priority barriers, yet it is not listed as the top (21st rank from 24 identified barriers). These facts fairly support the observed results of Spain finding CE implementation advantages to be more significant than costs.

In Albania, CE in the construction sector, as well as associated organizational costs importance is supported by the available literature. As GIZ [59] has argued, the construction sector is one of the main priorities for circularity development. The implementation strategies are suggested to be the improvement of procurement regulations and financial funding of waste management facilities (through low-cost debts and financial coverage of waste treatment and collection). Companies view the

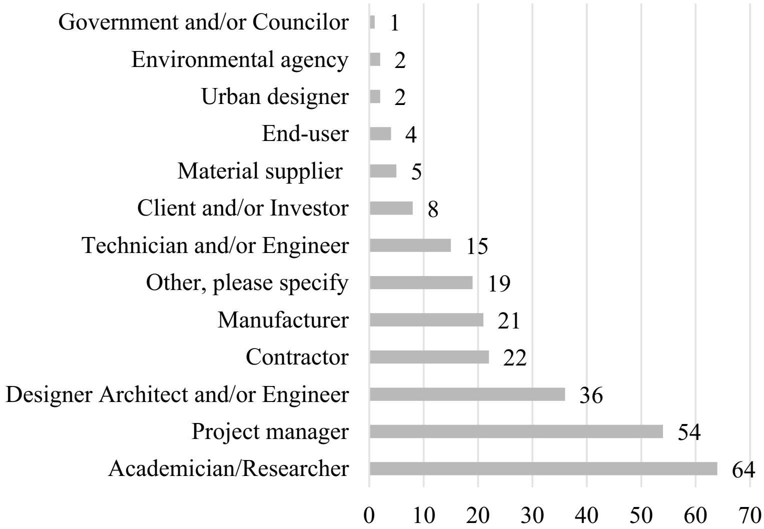


Fig. 22.25 The number of responses versus the stakeholder type (European region)

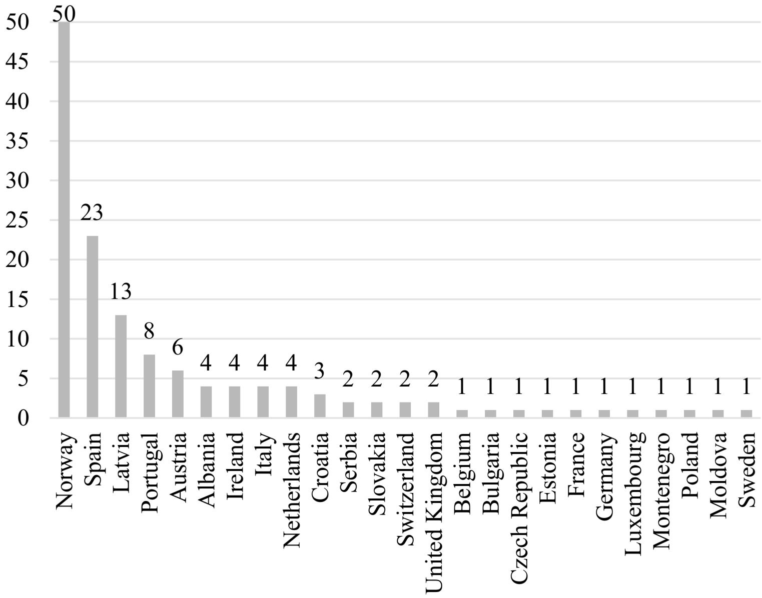


Fig. 22.26 Number of respondents who have been involved in circular building practices

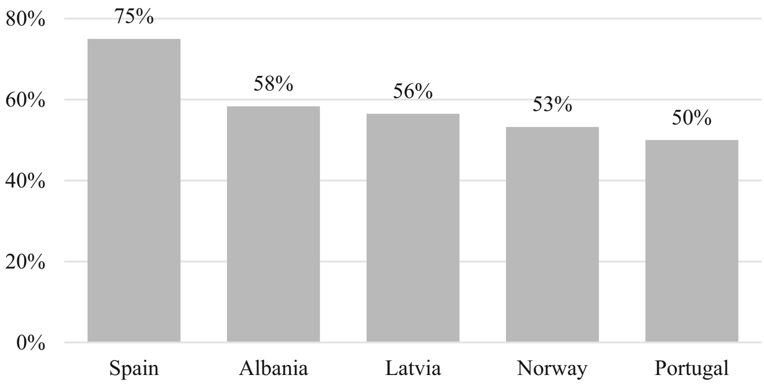


Fig. 22.27 Percentage of the perception of benefits importance provided by the CE implementation

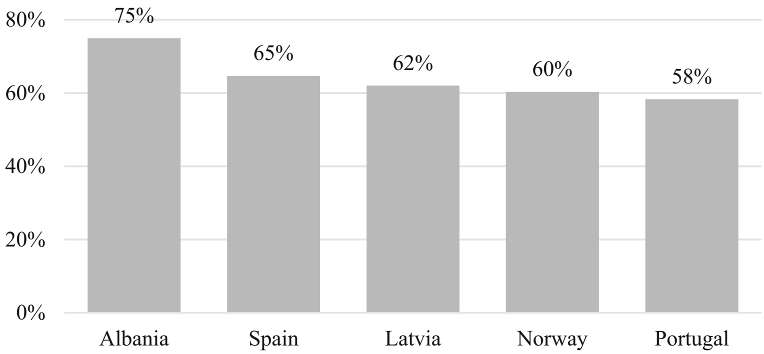


Fig. 22.28 Percentage of the perception of costs importance provided by the CE implementation

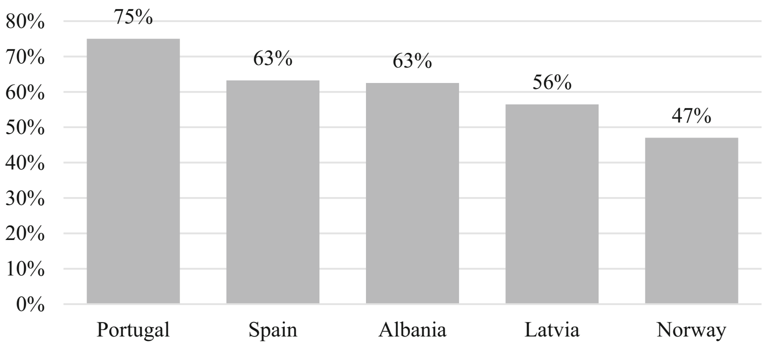


Fig. 22.29 Percentage of the perception of CE implementation effect on organizational financial performance

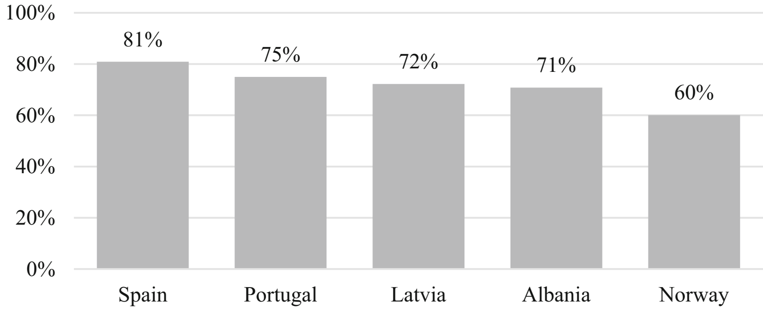


Fig. 22.30 Percentage of the perception of CE implementation effect on organizational reputation and brand

significant expense associated with adaptation choices as the primary deterrent to the execution of risk management measures [60]. In addition, more than a quarter of Albanian citizens believe that business costs impede CE development [61].

For Portugal, costs associated with CE regulatory procedures are considered as one of the main barriers to its implementation [62]. Nevertheless, it is emphasized that reducing associated costs for waste management for businesses is successful. In addition, Henriques et al. [63] suggest that Portugal needs more relevant specific incentives for better CE adoption in terms of economic benefit, which supporting the results obtained in this study.

Prevailing economic reliance of Latvia on linear economy models, thereby influences their limited acceptance and uptake of CE practices [64]. Recent material cost increases resulted in rising rigidity towards expensive innovative decisions in the building sector, which results in a minuscule desire for investment into circularity options [65]. Nevertheless, the opportunities for CE development are argued to be promising, as businesses are interested in benefitting circular solutions.

In general, Norway's government has developed certain Circular Strategies as a response to the EU Circular Economy Action Plan [66]. Nevertheless, costs remain a hot topic for businesses. As it is argued in several studies, Norwegian stakeholders need a quantitative assessment of the costs and benefits of CE implementation as well as fair allocation of expenditures, advantages, and hazards in reclamation and recycling procedures within the construction sector [67, 68]. CE investments are also identified as a prime barrier to CE development in the construction sector. Thus, the literature supports the findings of the current study about the importance of costs and benefits for Norwegian stakeholders.

All in all, the analysis of stakeholders' assessment of perceived costs and benefits received from CE implementation in the construction sector was conducted. Although the survey included different countries from the whole European region, certain countries revealed higher response rates, which caused them to be analyzed more deeply in this study. Thus, the discussion provided is based on Spanish, Portuguese, Latvia, Albanian, and Norwegian representatives. These countries are located in various regions of the European continent, with Norway in Northern Europe, Latvia in Northern Europe, Spain in Southern Europe, Albania in South-eastern Europe, and Portugal in Southern Europe.

This study revealed that respondents generally perceive both the advantages and costs of implementing CE practices as important, with Spain and Albania having the highest appreciation. Interestingly, Spain is the only country where benefits were considered more important than costs, while Albania had the largest difference between the perception of cost and benefit importance. The other countries showed relatively similar assessments of the significance of both expenditures and advantages.

This study also investigated the perceived impact of CE on financial performance, professional reputation, and brand. Norway had the lowest perception in both areas, while Portugal, Spain, Albania, and Latvia showed significant agreement that CE has a positive effect, especially on professional reputation and brand image, indicating strong expert support for the assessment.

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Chapter 23
CE Management

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Abstract This chapter presents a deep discussion of the recent case studies on implementation of best practices and strategies for the circular economy, and an integrated approach to CE management in the built environment. The case studies were evaluated by the following aspects: Design for Circular Economy; Resource Optimization; Collaborative Approaches; Digital Technologies; Policy and Regulatory Frameworks; Consumer Engagement; Life Cycle Assessment; Circular Business Models; Smart Monitoring and Evaluation; Stakeholder Collaboration. These studies indicated the diversity of best practices in CE management in different fields. On the other hand, a strategic planning and collaborative development of circular

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practices with relevant stakeholders are crucial for the effective development and implementation of circular capabilities and initiatives in the built environment.

Keywords Circular economy · CE management · Built environment · Implementation · Circular materials · Stakeholder

23.1 Case Studies—Best Practices in Management

Circular economy (CE) management refers to the implementation of best practices and strategies aimed at achieving CE within organizations, industries, and societies. It involves adopting a holistic approach to resource management, focusing on reducing waste, maximizing resource efficiency, and promoting sustainable production and consumption patterns.

Best practices in CE management encompass various aspects, including:

- Design for Circular Economy;
- Resource Optimization;
- Collaborative Approaches;
- Digital Technologies;
- Policy and Regulatory Frameworks;
- Consumer Engagement;
- Life Cycle Assessment;
- Circular Business Models;
- Smart Monitoring and Evaluation;
- Stakeholder Collaboration.

23.1.1 Design for Circular Economy

Incorporating principles of circularity at the product and process design stage, considering factors such as material selection, durability, recyclability, and reparability.

Case Study I Design for Circular Economy: The Circle House

The Circle House project, commissioned by Lejerbo, is pioneering the construction of the first social housing units based on circular principles. This ground-breaking approach ensures a higher level of flexibility throughout the building's lifespan, with 90% of its materials designed to be disassembled and reused at a significant value.

The Circle House project consists of 60 social housing units in Lisbjerg (Aarhus, Denmark) and represents three typologies: a mix of two- and three-story terraced houses and 5-storey tower blocks with an overall 100 m^2 of communal facilities. The building density on site is 65–80%.

Lisbjerg is a development zone focusing on sustainability. Thus, the Circle House is designed and built according to the principles of the Circular Economy. Therefore, it becomes a scalable lighthouse project that will bring new know-how about circularity in architecture and construction to the building industry. The objective is that 90% of the building materials can be reused without appreciable loss of value. To enhance the re-usability, the structural system is limited to a few different elements: two sizes of wall elements and two lengths of beams and deck elements. The approach is rooted in the 15 principles within the categories Design for Disassembly, Material ID and Circular Economy, which have been developed as guidelines and strategies for implementing reuse and circular economy in the building industry. Accordingly, the Circle House consists of a range of building systems that can be disassembled, reused or reassembled into outer buildings while the value is preserved. Thereby, great architectural freedom and creativity are achieved in terms of material selection and circular construction.

A project like Circle House makes cross-industry collaboration necessary in order to enable a circular building practice. Accordingly, the entire value chain of the building industry needs to be engaged. The project Circle House involves more than 60 Danish companies from the construction sector. It was made possible by the funding's from the Danish Environmental Protection Authority and the Realdania philanthropic association.

23.1.2 Resource Optimization

Maximizing the use of resources through strategies like recycling, remanufacturing, and refurbishment. This involves minimizing waste generation and extending the lifespan of products and materials.

Case Study II Resource Optimization

The case study centers on the construction of a three-story building, where the basement is designated for parking, and the remaining two stories consist of residential flats. The project involves a variety of interconnected activities with different dependencies, highlighting the significance of resource management for successful project execution [1].

Organizing and training the project team: Human resource management plays a vital role in ensuring exceptional project achievements. Proper organization and training are crucial for team efficiency and performance

Equipment resource management: Careful selection of equipment is essential for cost control and timely completion. Factors such as availability, mobility, versatility, suitability, and equipment capability must be considered.

Material resource management: Timely provision of materials in the right quantities and locations is crucial for achieving scheduled production levels at minimum cost. Monitoring material information and flow is key to effective material resource management.

Resource levelling technique: Resource levelling ensures a balanced distribution of resources to avoid exceeding availability. It aims to maintain uniform resource levels during peak and off-peak periods. Labor and equipment resource management are fundamental parameters in resource levelling.

Techniques for resource levelling: Fast-tracking, crashing, delay-critical path tasks, extend-critical path tasks, non-sequential task divisions, authorized overtime, and MS Project are used to optimize resource allocation and meet project goals.

Resource Levelling with MS Project: MS Project offers a comprehensive resource levelling feature for efficient project management. By inputting resource schemes, activity types, and dependencies, MS Project enables automatic or manual resource levelling. It provides flexibility to resolve resource conflicts through activity delays, additions or removals, resource reassignments, and dependency adjustments. Manual resource levelling is recommended for better alignment with real-world conditions.

The case study concludes that manual resource levelling using MS Project is the preferred option due to its flexibility and ability to consider on-site conditions. Extending activity durations to address resource overallocation is acceptable. However, MS Project does not allow a single resource to be allocated to parallel activities. The study emphasizes the productivity and efficiency of MS Project, particularly for small construction projects with limited resources.

Recommendations: Based on the findings of this case study, it is recommended that project managers utilize MS Project for resource levelling and enhance productivity in construction projects. Regular checks and revisions of the project schedule are necessary to align with real-world conditions. MS Project's features enable optimal resource allocation, ensuring timely completion and cost control.

23.1.3 Collaborative Approaches

Encouraging collaboration and partnerships across value chains to promote resource sharing, product-service systems, and closed-loop systems. This includes establishing networks for material exchanges and fostering collaborations among different stakeholders.

Case Study III Collaborative Approaches

One of the newest examples of industrial symbiosis is the Port of Rotterdam in the Netherlands [2]. The port has developed an innovative circular economy program called "Rotterdam Circularity Program" that aims to transform the port into a sustainable and circular hub.

Under this program, various initiatives have been implemented to foster industrial symbiosis and resource efficiency. For example, waste heat from the refining and chemical industries is captured and used to provide heating for nearby buildings and greenhouses. The excess CO_2 emissions from industrial processes are captured and transported to greenhouses for enhanced plant growth. Additionally, residual heat from data centers is utilized to warm water for local households.

Through these collaborative efforts, the Port of Rotterdam is creating a circular ecosystem where waste streams are turned into valuable resources, reducing environmental impact and promoting a more sustainable economy.

23.1.4 Digital Technologies

Utilizing digital innovations, such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain, to enhance resource tracking, supply chain transparency, and product traceability, enabling better management and optimization of resources.

Case Study IV Digital Technologies

Blockchain technology is mentioned as a potential enabler for circular economy practices. It can provide transparency and traceability in supply chains, facilitate material and product tracking, and enable secure transactions in circular business models [3].

One example of utilizing blockchain technology for circular economy practices is the Plastic Bank initiative. Founded in 2013, the Plastic Bank aims to reduce plastic waste in the oceans while creating socio-economic opportunities for communities in developing countries.

The initiative utilizes blockchain technology to create a transparent and traceable system for recycling plastic waste. Local communities can collect plastic waste and exchange it for digital tokens, which can then be used to purchase goods and services. The entire transaction process is recorded on the blockchain, ensuring transparency and accountability.

By using blockchain technology, the Plastic Bank provides a secure and reliable platform for plastic waste collection, recycling, and monetization. It enables individuals to become active participants in the circular economy by incentivizing the proper disposal of plastic waste and promoting its recycling and reuse.

23.1.5 Policy and Regulatory Frameworks

Implementing supportive policies and regulations that incentivize circular practices, such as extended producer responsibility (EPR) schemes, tax incentives, and waste management regulations.

Case Study V Policy and Regulatory Frameworks

The European Union's Waste Framework Directive, which sets out waste management principles, including waste prevention and recycling targets, is considered a best practice in circular economy policy.

One of the newest examples of policy and regulatory frameworks promoting the circular economy is the European Union's Circular Economy Action Plan, adopted in March 2020 [4]. This plan builds upon the Waste Framework Directive and sets ambitious targets and measures to transition Europe to a more sustainable and circular economy.

The Circular Economy Action Plan includes a wide range of initiatives and policies to promote waste prevention, improve resource efficiency, and foster the transition to CE. It sets targets for recycling and reducing waste, encourages eco-design and product durability, promotes the use of secondary raw materials, and aims to tackle key sectors such as plastics, textiles, and electronics.

The plan also emphasizes the importance of sustainable production and consumption patterns, innovation, and investment in circular economy projects. It aims to create a supportive regulatory framework that encourages businesses, consumers, and governments to embrace circular practices.

By implementing this comprehensive policy and regulatory framework, the European Union seeks to accelerate the transition to CE, reduce environmental impacts, create new business opportunities, and promote sustainable growth.

23.1.6 Consumer Engagement

Educating and engaging consumers in circular behaviors, such as reuse, repair, and recycling, and promoting sustainable consumption patterns. This can be done through awareness campaigns, product labelling, and consumer incentives.

Case Study VI Consumer Engagement—Whole House Reuse

One of the newest examples of consumer engagement in the building industry is the "Whole House Reuse" campaign launched by the Building Materials Reuse Association (BMRA) in New Zealand [5]. The campaign aims to raise awareness among homeowners and builders about the environmental and economic benefits of reusing building materials.

The "Whole House Reuse" campaign promotes the concept of deconstruction, which involves carefully dismantling a building to salvage reusable materials instead of demolishing it. By emphasizing the value of reclaimed materials and the importance of diverting construction waste from landfills, the campaign encourages homeowners and builders to consider reuse as a sustainable and cost-effective option.

Through educational resources, case studies, and partnerships with industry stakeholders, the campaign provides information and support to those interested in incorporating reuse practices into their building projects. It highlights the environmental benefits of reusing materials, such as reducing carbon emissions and preserving natural resources, while showcasing the potential cost savings and unique design opportunities that arise from using reclaimed materials.

By engaging consumers and promoting the reuse of building materials, the "Whole House Reuse" campaign contributes to the circular economy by extending the lifespan of materials, reducing waste, and fostering a more sustainable approach to construction and renovation.

Case Study VII Consumer Engagement—Reducing Waste in Fit-Out Processes through AI-Enabled Reuse [6]

The construction sector faces a critical challenge in reducing waste generated during fit-out processes to achieve net zero carbon targets and minimize environmental impact. Time pressures often hinder the reuse or recycling of materials, resulting in a significant increase in carbon footprint. To address this issue, the 'LINK' project, funded by Innovate UK, aims to revolutionize waste reduction in fit-outs using artificial intelligence (AI) and machine learning. By rapidly identifying reusable materials and connecting those who wish to dispose of materials with those in need, the project aims to facilitate the CE approach and decrease waste in the construction sector.

The primary objective of the 'LINK' project is to develop a mobile app that enables the rapid listing of reusable materials. The project aims to engage all stakeholders in the fit-out and interior design sector to transform the reuse process and establish it as the norm in construction. By harnessing digital technology, the project seeks to revolutionize the way materials are reused, promoting sustainability and reducing waste throughout the industry.

Industry Workshop: The project partners hosted an industry workshop to gather insights on challenges and opportunities in March 2023. The workshop was held online. It invited stakeholders from the fit-out and interior design sector, including designers, clients, manufacturers, contractors, and individuals passionate about promoting reuse. The workshop aimed to explore the potential of digital technology and identify key drivers and success factors in making reuse a common practice.

Workshop Program: The workshop featured presentations covering various aspects of sustainability, reuse, and the role of AI in revolutionising the industry. The presentations include.

Sustainability for Finishes and Interiors: Iain Mcilwee, CEO, and Flavie Lowres, Sustainability Champion, Finishes and Interiors Sector (FIS).

The workshop also included interactive discussion groups focusing on information needed for facilitating reuse and exploring the roles of different stakeholders in achieving higher levels of reuse.

Workshop Registration and Contact: Interested participants can register for the workshop, and attendance is free of charge. The project team welcome individuals who are passionate about promoting reuse or seeking more information about the project.

23.1.7 Life Cycle Assessment (LCA)

Conducting comprehensive assessments of the environmental impacts of products and processes throughout their life cycles to identify areas for improvement and inform decision-making.

Case Study VIII Life Cycle Assessment [7]

This case study focuses on the development of comprehensive circular economy (CE) indicators for port clusters, aiming to support port managing bodies (PMBs) and stakeholders in monitoring the transition towards CE [2].

The study utilizes a multimethod qualitative research approach, including content analysis, focus groups, a gap analysis, and a qualitative survey, to establish a set of 12 actionable CE indicators for ports. The feasibility and relevance of these indicators are evaluated, highlighting seven highly feasible and five moderately feasible indicators. Additionally, the study discusses the limited CE ambition levels of PMBs and variations in indicator values across different port typologies. The findings of this study provide practitioners with an actionable set of key performance indicators (KPIs) to support their efforts and communication related to the circular economy transition in port clusters.

The transition towards CE in port clusters is gaining importance in facilitating regional and global transport within circular production chains. However, there is a lack of in-depth research on the development of circular economy indicators specifically for port areas. This case study aims to address this gap by developing a comprehensive set of relevant and feasible CE indicators to monitor the circular economy transition in ports.

Methodology: The case study employs a multimethod qualitative research approach. Content analysis, focus groups, a gap analysis, and a qualitative survey are conducted to gather data and insights. These methods allow identifying relevant CE indicators and assessing their feasibility and stakeholder relevance.

Development of CE Indicators for Ports: Through the research methods employed, a list of 12 actionable CE indicators for ports is developed. These indicators cover various aspects of the circular economy, including resource efficiency, waste management, reuse, and stakeholder engagement. The indicators are categorized based on their feasibility, with seven identified as highly feasible and five as moderately feasible.

Findings: The study highlights two key findings. Firstly, it reveals the overall limited CE ambition levels among PMBs, indicating a potential area for improvement in promoting circular economy practices. Secondly, variations in indicator values are observed across different port typologies, suggesting the need for tailored approaches to circular economy implementation in diverse port settings.

Value for Practitioners: This case study provides practitioners with an actionable set of CE indicators that can support their efforts and communication regarding the transition to CE in port clusters. The identified indicators enable PMBs and port stakeholders to monitor progress, identify areas for improvement, and effectively communicate their circular economy initiatives.

Developing comprehensive CE indicators for port clusters enhances the monitoring and evaluation of the circular economy transition. By offering a set of relevant and feasible indicators, this case study empowers practitioners to drive the implementation of circular economy practices in ports. The findings highlight the importance of strengthening CE ambition levels and tailoring approaches based on port typologies. The study underscores the continual contribution of life cycle assessment in advancing the circular economy in the built environment and presents a proposal for a circular and sustainable future in the sector.

23.1.8 Circular Business Models

Adopting innovative business models, such as product-as-a-service, sharing economy platforms, and leasing arrangements, which prioritise access over ownership and promote resource efficiency.

Case Study IX Circular Business Model—The Circular Retrofit Lab in Brussels, Belgium

The Circular Retrofit Lab is an innovative project based in Brussels, Belgium, that focuses on applying circular economy principles to retrofit existing buildings. It is a collaborative initiative between various organizations, including research institutes, industry partners, and government agencies.

The pilot project tested and implemented different scenarios for reusing and refurbishing the VUB Campus' prefabricated student housing, without generating a large amount of waste. Strategies have been explored for internal transformations, external transformations, and the module's multiple functional reconfigurations.

Depending on their expected rate of change in the floor plan, three different types of walls were defined, analyzed, constructed and transformed: walls with (1) a high rate of change, (2) a high degree of flexibility for the integration of technical infrastructure and (3) a low rate of change.

The project aims to transform traditional linear renovation processes into circular ones by adopting strategies such as:

- *Material Recovery and Reuse:* The Circular Retrofit Lab explores ways to recover and reuse building materials from demolition sites or renovation projects. Materials such as bricks, concrete, and wood are carefully deconstructed, sorted, and prepared for reuse in future building projects.
- *Value Chain Collaboration:* The project encourages collaboration among different stakeholders in the construction value chain, including architects, contractors, material suppliers, and waste management companies. This collaboration enables the identification of opportunities for material recovery and facilitates the development of innovative circular business models.
- *Design for Disassembly:* The project promotes Design for Disassembly (DfD) the concept, which involves designing buildings and components

with easy disassembly in mind. This enables the separation and reuse of materials at the end of a building's lifecycle, reducing waste and maximising resource efficiency.

- *Circular Procurement:* The Circular Retrofit Lab incorporates circular procurement practices by sourcing materials with high recycled content and low environmental impact. This encourages the use of sustainable materials and supports the market for circular products.
- *Knowledge Sharing and Capacity Building:* The project organises workshops, seminars, and training programs to share knowledge and build capacity among professionals in the construction sector. This helps disseminate best practices and encourage the adoption of circular approaches in building retrofit projects.
- The Circular Retrofit Lab serves as a demonstration and research platform for circular retrofitting, showcasing innovative techniques and technologies that can be replicated in other building projects. By integrating material recovery, collaboration, DfD principles, circular procurement, and knowledge sharing, the project contributes to the advancement of circular economy practices in the building industry

Case Study X Circular Business Model—The BLOXHUB Circular Building in Copenhagen, Denmark [8]

The BLOXHUB Circular Building is an innovative construction project located in Copenhagen, Denmark. It is a collaborative initiative between BLOXHUB, a Nordic hub for sustainable urban development, and a group of industry partners.

The circular business model employed in the project focuses on the concept of "demountable construction," aiming to maximize material reuse and minimize waste generation. Some key features and practices include:

- *Modular Design:* The building is designed with modular elements that can be easily disassembled, allowing for the reuse of materials in future construction projects. The modules are carefully documented and labelled to ensure efficient disassembly and reassembly.
- *Material Passport:* Each component used in the building is assigned a unique identification code, which is recorded in a digital material passport. This passport contains detailed information about the origin, composition, and quality of the materials, facilitating their future reuse and recycling.
- *Material Reuse and Recycling:* The project prioritises the use of recycled and reused materials, including timber, bricks, and insulation. These materials are sourced from existing buildings, construction waste, and local recycling facilities.

- *Circular Collaboration:* The BLOXHUB Circular Building serves as a collaborative space for various stakeholders in the building industry, including architects, engineers, contractors, and researchers. This fosters knowledge sharing and innovation in circular construction practices.
- *Life Cycle Assessment:* The project utilises life cycle assessment methodologies to evaluate the environmental impacts of different design choices and construction techniques. This allows for informed decision-making and optimisation of resource use.

The BLOXHUB Circular Building showcases how circular business models can be applied in the building industry to promote resource efficiency, reduce waste, and enable material reuse. The project exemplifies the transition towards a more circular and sustainable built environment by integrating modular design, material passports, collaboration, and life cycle assessment

Case Study XI Circular Business Model: Resource Optimisation [2]

The Ellen MacArthur Foundation's report on the circular economy in cities highlights the case of Amsterdam's circular economy program [9] which includes initiatives like recycling construction and demolition waste, promoting circular procurement, and implementing material passports for buildings to enable future reuse.

This program encompasses various initiatives aimed at promoting circularity in the city. Some key initiatives mentioned in the report include:

- *Recycling Construction and Demolition Waste:* Amsterdam has implemented strategies to promote the recycling of construction and demolition waste. By diverting waste from landfills and reintroducing materials back into the economy, the city aims to reduce resource consumption and minimise waste generation.
- *Circular Procurement:* The city of Amsterdam has embraced circular procurement practices, which involve sourcing products and services that have a lower environmental impact and can be easily reused or recycled. Circular procurement supports the development of CE by stimulating demand for circular products and services.
- *Material Passports for Buildings:* Amsterdam has introduced the concept of material passports for buildings. Material passports provide detailed information about the composition and characteristics of building materials, enabling efficient and safe dismantling and future reuse. This approach facilitates the circularity of building materials and promotes the transition towards a more sustainable built environment.

The case of Amsterdam's circular economy program serves as an example of how cities can implement a range of strategies and initiatives to foster circularity. By adopting measures such as recycling construction waste, promoting circular procurement, and implementing material passports, Amsterdam is striving to create a more sustainable and resource-efficient city

23.1.9 Monitoring and Evaluation

Implementing monitoring and evaluation systems to track progress, measure the effectiveness of circular initiatives, and identify areas for continuous improvement.

Case Study XII Smart Monitoring and Evaluation for CE Implementation at University of Birmingham Campus Building

The University of Birmingham (UK), in partnership with Siemens, is combining digital sensor and analytics technologies, artificial intelligence, decentralized energy generation and storage, renewable energy and concepts that help change users' behavior to transform the University's Edgbaston and Dubai campuses into the world's smartest global campus, creating a 'Living Lab' where research, teaching and learning all benefit from access to new data and connectivity for circular economy and sustainability. The 'Living Lab' will capture data from the University's building technologies, estate infrastructure and energy plants and use it for innovation, R&D activities, as well as teaching. Scrutinizing energy demand and production with live data from across the sites (for both new and existing building stocks) provides students with a unique opportunity for applied learning and creates a platform for cutting-edge research. Siemens sponsors a team of PhD studentships at the University based in the UK and Dubai. Their research projects are co-designed by Siemens and the University to address important challenges in data, technology, urban systems and the NetZero goal.

In 2023, the University of Birmingham became the first university in the world to roll out Internet of Things (IoT) technology at scale. Starting in Autumn 2021, the first phase of this major energy efficiency project included the rollout of 23,000 Enlighted IoT sensors across the University estate. As one of the largest universities in the UK—with a global community of more than 38,000 students—the university is already an energy prosumer, and these technologies are further optimized in the system we are now working on together. Partnerships like this are extremely important for gathering new insights, testing and developing new technologies and creating efficient and sustainable energy infrastructure. The university's campus in Dubai is a global example of sustainability at the rescheduled Dubai Expo 2020.

CEO Siemens, GB & Ireland stated that, "We are excited to be working with the University of Birmingham on this project and confident that together we can develop a clear pathway to the University becoming a smart campus and net zero. Our goal is to apply the University's strategic vision to their campus. We will uncover where carbon savings are possible by managing resources more efficiently in a system that is adaptable to changing demand. All of this can be achieved with a combination of connected digital technologies, artificial intelligence, decentralized energy generation and storage, renewable energy and ideas that help change users' behavior." In addition, Siemens will deliver a 10-year bureau for Energy and IoT services to ensure that the University reaps the full potential of both the technology and industry expertise. The University has already made significant progress in making its operations more sustainable, including achieving its 2020 target of reducing carbon emissions by 20% and is constantly looking to improve the environmental performance of its buildings, including a reduction of 2,856 tCO_2 annually, equivalent to 5% of the University's current emissions. Earlier this year, the University of Birmingham signed up to the United Nations Global Compact—the world's largest corporate responsibility initiative—as part of its commitment to reducing its environmental footprint and maximizing the impact of its research. The University of Birmingham is also a participant in the COP26 Universities Network and will have a presence at the COP26 conference in Glasgow in November.

This case study at the University of Birmingham highlights the implementation of the circular economy program and its real-time monitoring and performance management using advanced sensors and IoT. It serves as an example of how a cluster of integrated new and existing building stocks can implement a range of strategies and initiatives to foster circularity towards net zero.

23.1.10 Stakeholder Collaboration

Engaging a diverse range of stakeholders, including businesses, government entities, academia, non-profit organisations, and local communities, to collectively work towards circularity goals and address systemic barriers.

By implementing these best practices, organizations and societies can move towards CE, where resources are utilized more efficiently, waste is minimized, and environmental impacts are reduced, leading to a more sustainable and resilient future.

Above are a few examples of best practices in circular economy management mentioned in the literature.

These examples demonstrated the range of best practices in circular economy management across different domains, including design, resource optimization, collaboration, technology, policy, consumer engagement, and business models. Implementing these practices can contribute to the transition towards a more circular and sustainable economy.

23.2 An Integrated Approach to CE Management in the Built Environment

Following from the section above, it is clear that the extant literature suggests that both strategic planning and collaborative development of circular practices with relevant stakeholders are necessary for the effective development and implementation of circular capabilities and initiatives in the built environment. From a strategic planning perspective, first, there is a growing body of literature exploring the issues around material resource planning and management. Viewing buildings as material depots changes how resources need to be managed within the construction sector and the built environment. Such a view requires documentation and communication of which materials in what quantities and qualities become available for reuse or recycling where and when [10]. To facilitate this documentation and communication, several material cadaster projects have been developed [10–13]. Second, and in connection with the first point, there has been a growing number of publications on material flow analysis because it is only through a good understanding of the flows that effective material resource planning and allocation can be achieved. While some of these material flow analyses focus on individual material types, such as timber in residential buildings [14], some others focus on individual sectors, such as road transport [15], and others focus on specific territories [16].

Several publications implicitly or explicitly stated that issues around material resource planning and management cannot be thought of independently from wider socio-economic and technological barriers/enablers of circular economy [17]. Therefore, it is important to develop enabling legislation and policy [18, 19], develop and capture viable business models [20], circular building materials [21], and end-of-life strategies (e.g., construction and demolition waste strategies) [22]. Furthermore, considering the wide range of material types and cases, as well as stakeholders, involved in the built environment, there is a strong emphasis on the use of digital tools and capabilities as an enabler for strategic planning and management of circularity in the built environment [23].

At the same time, there has also been interest in empirical exploration of circular initiatives on the ground, which provided insights on operational development and management of circular capabilities and initiatives in the built environment. For example, [24] present a case where a team of experts from the UK and Nigeria worked with local Nigerian entrepreneurs to build a prototype home from upcycled materials, such as plastic bottles and agricultural waste in construction. They conclude that adopting a user-centered, co-creation methodology and working with local skills, allowed for a solution (a prototype home), with improved functionality and sustainability. Giorgi et al. [25] conducted interviews with construction stakeholders in multiple European Union countries to explore the gap between the EU construction circular economy policy and practice. They found that certain strands of circular initiatives tend to be driven by certain stakeholder groups on the ground. For example, while the legislative framework promotes waste management strategies focusing on recycling, the design strategies for reversible buildings are generally private initiatives driven by market competition. Arora et al. [26] study two cases of component-focused urban-mining and highlight that what is required is the engagement of local stakeholders (i.e., potential consumers and real estate developers) with the demolition contractors to salvage the required building components. In a similar line of thought, Joensuu et al. [27] emphasize that a successful plan with the main objectives of a circular economy in the built environment could only be "achieved with inclusive and location-sensitive politics functioning from both bottom-up and top-down perspectives". This implies that there is a need for simple, innovation-positive rules which leave room for stakeholder inventions. However, so far, there has not been a universally accepted, or used, comprehensive management framework that integrated both perspectives.

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