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

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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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L. Bragança et al. (eds.), *Circular Economy Design and Management in the Built Environment*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-3-031-73490-8_6

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.

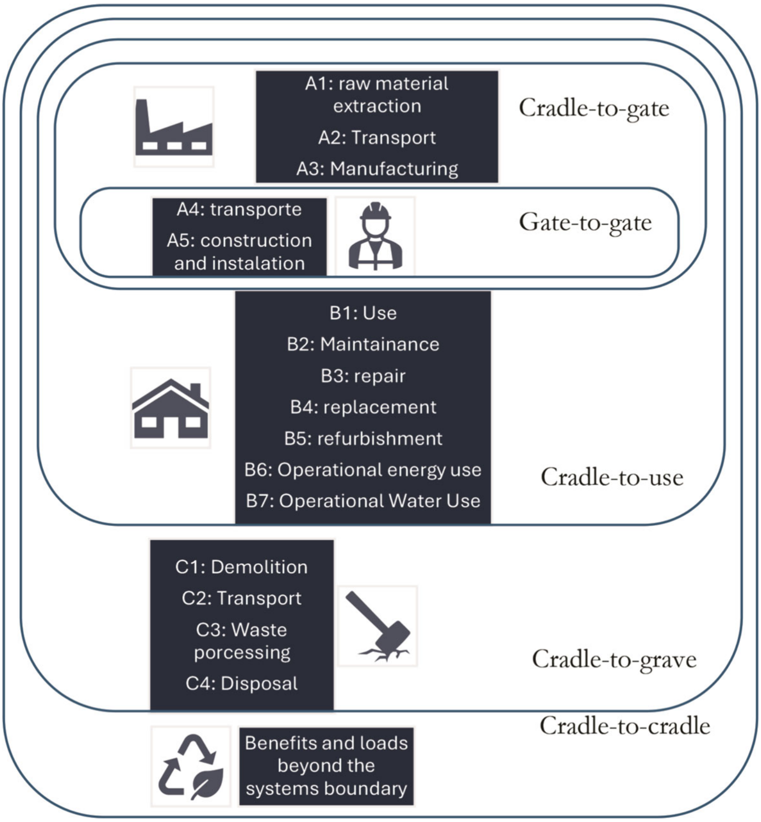

Fig. 6.1 Life cycle stages according to ISO

- 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^{2}eq/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 Reducing waste/wastage rates/ waste generation from construction activities	Demolition waste generated from the deconstruction/ demolition (measured in tons)
	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 Increasing direct reuse of products and material	Demolition Waste reused, recycled, recovered, landfilled resulting from the deconstruction/demolition (measured in % by mass)
Organization or process level	In-use, refurbishment stages	Lifetime extension e.g. through retaining and refurbishing Designing for flexibility and adaptability	Refurbishment/ Transformation rate of buildings/assets portfolio (% of buildings/infrastructure refurbished/year)
	Design, in-use stages	Improving durability, lifespan, repairability of construction works Lifetime extension e.g. through retaining and refurbishing	Predicted service life of buildings/assets (measured in years)
	Manufacture, design, construction stages	Increasing recycled and secondary content of construction products and materials Increasing direct reuse of products and materials Increasing reuse/recycling of waste from construction works	Average proportion of a reused and recycled content in new assets/infrastructure (measured as % by mass)
	Manufacture stage	Increasing recycled and secondary content of construction products and materials Increasing direct reuse of products and materials Increasing reuse/recycling of waste from construction works Increasing reuse/recycling of waste from demolition works	Reused, recycled and secondary content input (% by mass)
	Construction, refurbishment, demolition stages	Reducing waste/wastage rates/ waste generation from construction activities Lifetime extension e.g. through retaining and refurbishing	Non-hazardous waste arisings generated by construction, refurbishment and demolition (measured in tons /100 K Euros (overall project value)
	Construction, refurbishment, demolition stages	Reducing waste/wastage rates/ waste generation from construction activities Increasing reuse/recycling of waste from demolition works Increasing reuse/recycling of waste from construction works	Amount of hazardous waste generated by construction, refurbishment, and demolition (Tons /100 K Euros (overall project value)

(continued)

Table 6.14 (continued)

Level	Stage	Strategy	Indicators (unit)
	Construction, refurbishment, demolition stages	Increasing direct reuse of products and materials Increasing reuse/recycling of waste from construction works Increasing reuse/recycling of waste from demolition works	Waste management routes generated from construction; refurbishment; and demolition (measured in % by mass/year for reuse, recycling, recovery or disposal)
	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 Increasing reuse/recycling of waste from demolition works	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)
Urban level (city/region/ national)	Construction, demolition; concept/ planning stages	Reducing waste/wastage rates/ waste generation from construction activities Lifetime extension e.g. through retaining and refurbishing	Construction and demolition waste generated from construction, demolition, and refurbishment in a defined urban area (measured in tons/ capita)
	Construction, demolition; concept/ planning stages	Increasing reuse/recycling of waste from construction works Increasing reuse/recycling of waste from demolition works	Recycling/recovery rate of construction and demolition waste: proportion of construction, refurbishment and demolition waste being recycled (or recovered) (measured in % by mass)
	Concept/ planning stage	Lifetime extension e.g. through retaining and refurbishing Designing for flexibility and adaptability	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)
	Demolition; concept/ planning stages	Lifetime time extension e.g. through retaining and refurbishing Reducing waste/wastage rates/ waste generation from construction activities	Demolition rate: number of buildings demolished over a given timeframe (measured as tons/capita)
	Demolition; concept/ planning stages	Lifetime extension e.g. through retaining and refurbishing Reducing waste/wastage rates/ waste generation from construction activities	Average age at demolition (years)

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

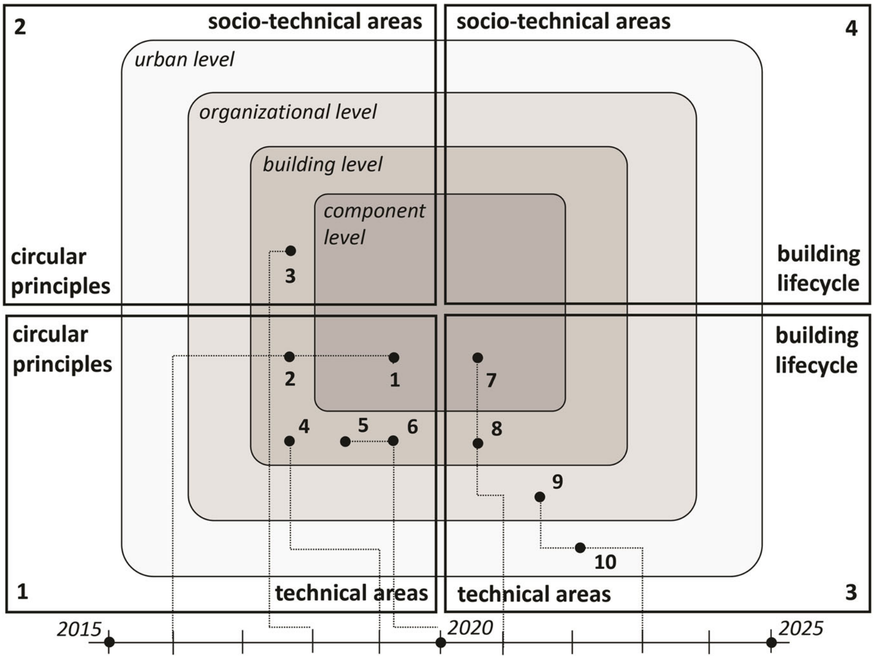

Fig. 6.2 Design framework map for circular building design

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

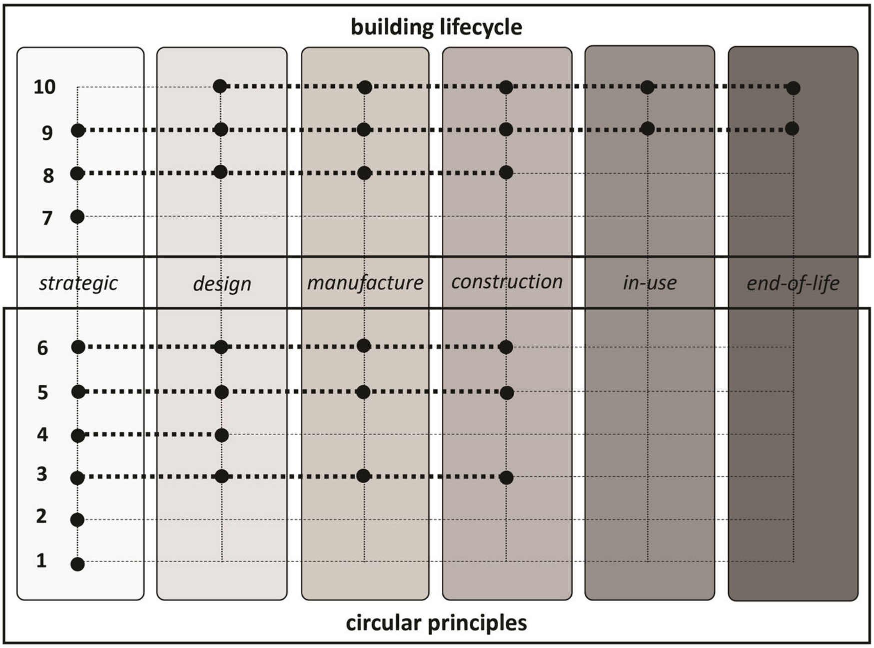

Fig. 6.3 Design frameworks for circular buildings and supported stages

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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