

## Ten questions concerning circularity in the built environment

N. Cihan Kayaçetin <sup>a</sup>, Rengin Aslanoğlu <sup>b</sup>, Chiara Piccardo <sup>c</sup>, Yasemin Afacan <sup>a,d</sup>,  
 Gabriele Masera <sup>e</sup>, Qiuxian Li <sup>c</sup>, Carlo Andrea Biraghi <sup>e</sup>, Francesco Pittau <sup>e</sup>,  
 Dirk Saelens <sup>f,g</sup>, Veronica Soebarto <sup>h</sup>, Jian Zuo <sup>i</sup>, Ruidong Chang <sup>i</sup>, Hanne Vrebos <sup>j</sup>,  
 Karel Van Acker <sup>j,k</sup>, Rizal Sebastian <sup>l,m</sup>, Jeroen Dikken <sup>n</sup>, Loredana Ivan <sup>o</sup>, Luc Alaerts <sup>j</sup>,  
 Duygu Aral <sup>p</sup>, Liliya Terzieva <sup>l</sup>, Joost van Hoof <sup>b,n,\*</sup>

<sup>a</sup> Department of Interior Architecture and Environmental Design, Bilkent University, Ankara 06800, Türkiye

<sup>b</sup> Department of Systems Research, Faculty of Spatial Management and Landscape Architecture, Wrocław University of Environmental and Life Sciences, ul. Grunwaldzka 55, Wrocław 50-357, Poland

<sup>c</sup> KU Leuven, Department of Civil Engineering, Building Physics and Sustainable Design, Gebroeders De Smetstraat 1, Ghent 9000, Belgium

<sup>d</sup> Department of Neuroscience, Bilkent University, Ankara 06800, Türkiye

<sup>e</sup> Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, Milan 20133, Italy

<sup>f</sup> KU Leuven, Department of Civil Engineering, Building Physics and Sustainable Design, Kasteelpark Arenberg 40, Heverlee 3001, Belgium

<sup>g</sup> EnergyVille, Thor Park 8310, Genk 3600, Belgium

<sup>h</sup> School of Architecture and Built Environment, Adelaide University, North Terrace, Adelaide, SA 5005, Australia

<sup>i</sup> School of Civil Engineering and Construction Management, Adelaide University, North Terrace, Adelaide, SA 5005, Australia

<sup>j</sup> KU Leuven, Department of Material Engineering, Sustainability Assessments of Materials and Circular Economy (SAM), Kasteelpark Arenberg 44, Heverlee 3001, Belgium

<sup>k</sup> KU Leuven, Center for economics and corporate sustainability (Cedon), Naamsestraat 69, Leuven 3000, Belgium

<sup>l</sup> Centre of Expertise Mission Zero, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, EN Den Haag 2521, the Netherlands

<sup>m</sup> Digital x Data Research Centre, College of Technology and Environment, London South Bank University, 103 Borough Road, London SE1 0AA, United Kingdom

<sup>n</sup> Centre of Expertise Governance of Urban Transitions, The Hague University of Applied Sciences, Johanna Westerdijkplein 75, EN Den Haag 2521, the Netherlands

<sup>o</sup> Communication Department, National University of Political Studies and Public Administration, Bulevardul Expoziției 30A, Bucharest 012102, Romania

<sup>p</sup> Department of Architecture, Faculty of Architecture, Izmir Institute of Technology, Urla, Izmir 35430, Türkiye

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### ABSTRACT

The rapid urbanisation of our societies calls for an urban renewal movement, including developing new areas to accommodate housing facilities and services and regenerating existing urban areas. Yet, urban renewal projects pose trade-offs impacting both environmental and socio-economic aspects. The renovation and new construction of buildings can escalate the use of energy and material resources as well as increasing greenhouse gas emissions. The European Union plays a leading role in promoting the transition towards sustainable and inclusive cities, whereas other regions such as North America, Australia and Asia follow suit via Circular Economy Action Plans or Frameworks, highlighting the need to enhance resource efficiency in buildings through the use of durable and circular materials. Current research on resource efficiency in buildings follows the Circular Economy concept, which aims to reduce the use of raw materials and the waste of existing materials while retaining their value for as long as possible. However, the role of the circular economy in sustainable transition and the adoption of its principles in urban contexts remain unclear while its practical implementation still faces significant challenges, including the lack of analytical instruments and assessment methods as well as co-creative approaches. This 'Ten Questions contribution' provides an overview of the pressing issues concerning circularity in the built environment, the state-of-the-art and best practices, challenges and benefits, policies and regulations, as well as numerous strategies applied on the building and neighbourhood level, assessment methodologies and future trends.

\* Corresponding author.

E-mail address: [j.vanhoof@hhs.nl](mailto:j.vanhoof@hhs.nl) (J. van Hoof).

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## Nomenclature

Additive & Digital Manufacturing (AM/DM)	Identification/Identity (ID)
Artificial Intelligence (AI)	Issued for Construction (IFC)
Augmented & Virtual Reality (AR/VR)	International Organization for Standardization (ISO)
Big Data & Analytics (BDA)	Light Detection and Ranging (LiDAR)
Blockchain Technology (BCT)	Life Cycle Assessment (LCA)
Building Research Establishment Environmental Assessment Method (BREEAM)	Internet of Things (IoT)
Building Information Modelling (BIM)	Leadership in Energy and Environmental Design (LEED)
Criteri Ambientali Minimi (CAM)	Life Cycle Costing (LCC)
Circular Economy (CE)	Machine Learning (ML)
Circular Economy Action Plan (CEAP)	Material Circularity Indicator (MCI)
Circular Economy Service Companies (CESCO)	Material Flow Analysis (MFA)
Construction and Demolition Waste (CDW)	Material Passports (MPs)
Design for Disassembly (DfD)	Operations and Maintenance (O&M)
Digital Twins (DT)	Per- and Polyfluoroalkyl Substances (PFAS)
Environmental Product Declarations (EPDs)	Product as a Service (PaaS)
European Union (EU)	Recycled Concrete Aggregates (RCA)
German Sustainable Building Council (DGNB)	Radio Frequency Identification (RFID)
Global Alliance on Circular Economy and Resource Efficiency (GACERE)	Social Circular Economy (SCE)
Geographic Information System (GIS)	Sustainable Development Goals (SDGs)
Green Infrastructures (GIs)	Simultaneous Localisation and Mapping (SLAM)
Green Public Procurement (GPP)	Terrestrial Laser Scanning (TLS)
	United Nations Climate Change Conference (COP)
	Unmanned Aerial Vehicles (UAV)
	Urban Living Lab (ULL)

## 1. Introduction

Cities are facing rapid socio-environmental transformations driven by demographic changes, population ageing, evolving housing patterns, as well as increased risks due to climate change and environmental degradation. The global urbanisation trends call for an urban renewal movement, including the development of new urban areas to accommodate housing facilities and services and the regeneration of existing urban areas. Yet, urban renewal projects pose trade-offs, which impact both environmental and socio-economic aspects [1]. The renovation and new construction of buildings can escalate the use of energy and material resources. Renewed urban areas may increase the cost of living and limit the access to housing and services for lower-income individuals, contributing to displacement and social inequality [2]. The built environment is one of the most carbon and resource-intensive sectors. Building and demolition results in over 30 % of the world's resource extraction and 25 % of solid waste generation [3]. This linear "take-make-dispose" industry accelerates the depletion of raw materials, carbon emissions, and environmental degradation, which highlights the importance of adopting circularity in the built environment.

The European Union (EU) plays a leading role in the global arena in promoting the transition towards sustainable and inclusive cities, notably through the EU Green Deal [4] and the New European Bauhaus [5] initiatives. The Renovation Wave [6] emphasizes the need to improve the energy efficiency of over 65 % of residential buildings built before 1970 to meet the EU goal of carbon neutrality by 2050. This necessitates significant changes for large urban areas and entire neighbourhoods. Furthermore, the Circular Economy Action Plan [7] highlights the need to enhance resource efficiency in buildings through the use of durable and circular materials. In the United States, the concept is regulated by the national circular economy framework (U.S. Environmental Protection Agency). China issued the Circular Economy Promotion Law of the People's Republic of China in 2008 and revised it in 2018, while in Australia, the National Circular Economy Framework, the National Waste Policy Action Plan, and Recycling and Waste Reduction Act [8,9] govern the national approach in adopting circularity. At the state level, Victoria also introduces a landfill ban for electronic waste

while the state of New South Wales implements the Product Lifecycle Responsibility Act 2025 providing a legislative basis for product stewardship for several product categories. In the recently announced Circular Economy Strategy 2025–2030, the state of South Australia will pay more attention to problematic waste streams such as per- and polyfluoroalkyl substances (PFAS) and lithium-ion batteries [10].

Current research on resource efficiency in buildings follows the Circular Economy (CE) concept, which aims to reduce the use of raw materials and the waste of existing materials, while retaining their value for as long as possible [11]. However, both the adoption of CE in urban contexts and its role in sustainable transitions remain unclear [12]. The practical implementation of CE at the neighbourhood scale still faces significant challenges but can be improved by providing (1) case studies and best practices; (2) comprehensive analytical instruments; (3) harmonised assessment methods; (4) inclusive co-creative approaches.

Circularity addresses environmental challenges by linking them to significant economic advantages as well as social benefits. Circularity functions as an evolving system, which combines innovation with policy frameworks and collaborative tools to establish a path towards sustainable and resilient urban areas that use resources efficiently. Discussions on circularity are often diverse, with concepts, methods and practices fragmented across disciplines such as engineering, architecture, urban planning, economics and policy studies [13]. Such fragmentation causes difficulties in knowledge transfer, comparability of the results and development of holistic frameworks to guide research and application in circularity [14]. Circularity requires systems thinking that integrates environmental, social, technological and economical aspects which leads to clearer knowledge transfer, improved comparability, more effective implementation and dissemination of circular solutions in the built environment, and improved scalability [15].

Thus, the aim of this paper is to provide a comprehensive overview to the concept of circularity in the built environment with the aim of introducing a common understanding on a wide range of concepts and resolving the fragmented state-of-the-art and research. The existing literature focuses on circularity of buildings, leaving a significant research gap in circularity at larger scales such as neighbourhoods and cities. This study extends the field to urban scales while drawing

inspiration from the building level.

The systematic thinking approach of this Ten Questions contribution is represented in Fig. 1. The concepts are evaluated within three clusters: (i) foundational framework, (ii) strategies in practice and (iii) evaluation and outlook. The first cluster supports the general understanding and language of CE with an aim to demonstrate existing best practices of circular strategies, evaluated in the second cluster. The third cluster considers measurement, assessments and future trends. They ultimately aim to describe the interdependent circular strategies and formulate a system approach.

The paper provides a comprehensive overview of the concepts and methods for analysing circularity of the built environment. Therefore, it can be used for integrating concepts and methods into practices, policies, and global case studies. The paper concludes by identifying key challenges necessitating further investigation. Specifically, the paper begins by defining circularity, circular economy, circular design and building (Question 1) followed by the current state of the art and the best practices in the built environment (Question 2). The challenges and the potential benefits associated with implementing circularity (Question 3) together with the discussion on the policy plans and regulatory

frameworks for guiding circularity in the built environment (Question 4) further enriches the paper. Explanations on the economic (Question 5), social (Question 6), environmental (Question 7), and technological (Question 8) strategies applied on various scales broaden the paper's contribution to the field. The methods for measuring and assessing circularity in the built environment expand paper's relevance (Question 9), which leads to the final question (Question 10) highlighting future trends for realising a transition towards a more circular built environment.

## 2. Overview of questions and preliminary answers

### 2.1. Question 1: what are the common definitions of circularity, circular economy, circular design, and the circular built environment?

Circularity is an emerging concept that can provide solutions for several environmental bottlenecks. It is considered an essential principle of sustainable development, which promotes resource regeneration and waste reduction through continual material usage. The CE is an economic system that maintains a circular flow of resources by recovering,

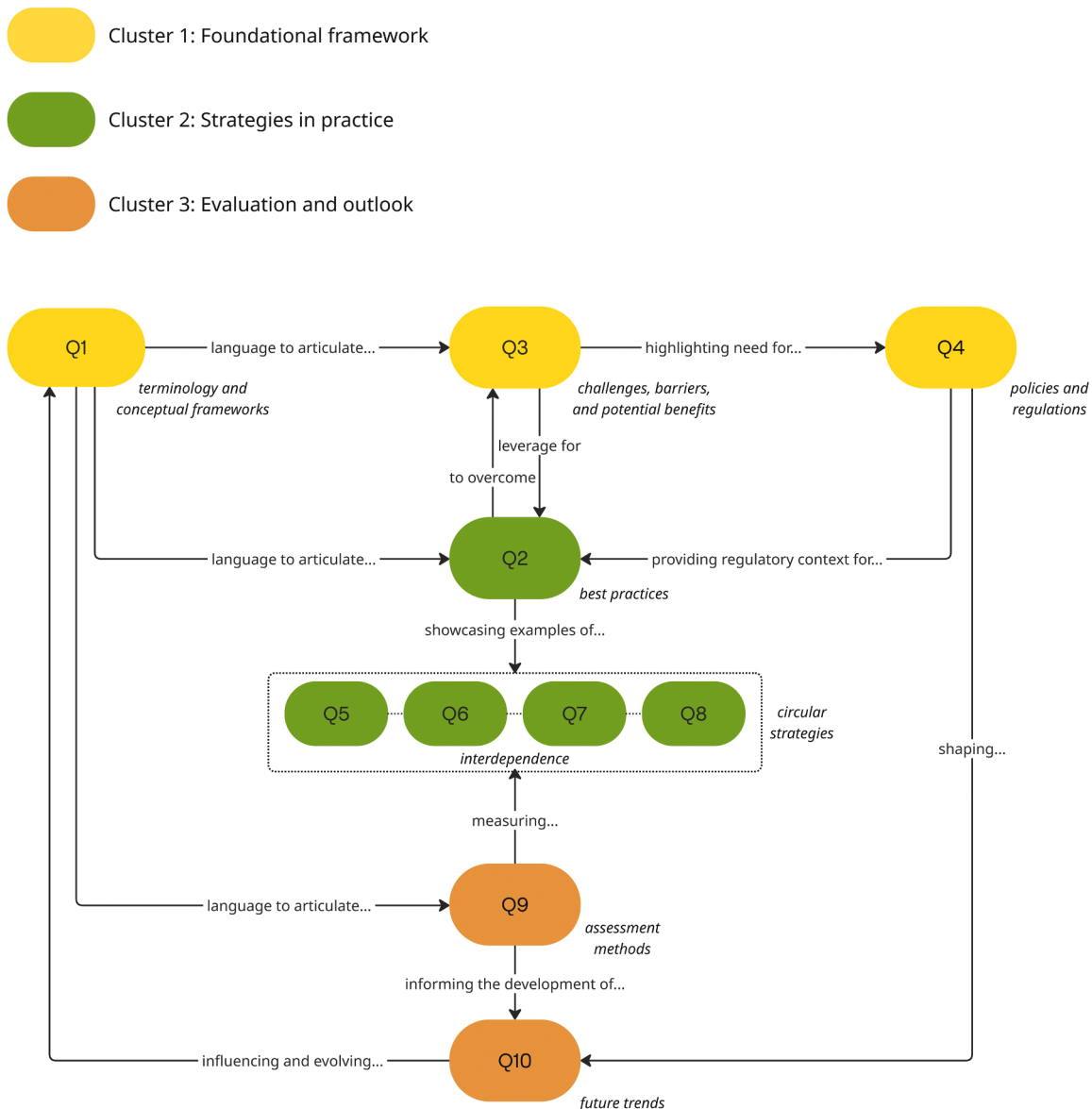


Fig. 1. Framework of the Ten Questions concerning circularity in the built environment.

retaining, or adding value, while contributing to sustainable development (ISO 59,004: 2024 [16]). This system represents a change from the conventional linear economy, which is predicated on the extraction, production, use, and disposal of resources, to a restorative model that emphasizes system resilience and long-term resource efficiency [17]. By encouraging circular processes in which goods and materials are recycled, mended, refurbished, or reused, the CE operationalizes circularity, limiting environmental impact and reliance on finite resources [18].

As the concept of circularity is emerging, many different assessment and implementation frameworks have been developed (also see Question 9). The current state-of-the-art is dispersed, localised, and unharmonised [19]. The frameworks tend to focus on a specific perspective (such as environmental or technical aspects), whereas more comprehensive approaches are necessary for the additional inclusion of social and economic aspects of circularity. An interdisciplinary approach is required to include geographical, cultural and societal differences, specifically in climatic conditions, behaviour towards circularity, governance and participation approaches and so on. Although the focus of this Ten Questions article is on the built environment, there is a lack of studies considering issues related to multi-scales, i.e., component, building, neighbourhood, and so on [20].

Circular design is a front-end approach that prioritizes material selection, modularity, durability, reparability, and pathways for reuse, remanufacturing, and recycling in order to make goods, assets, or systems naturally regenerative [21]. This way, resources 'loop rather than leak'. Planning, on the other hand, establishes scope, stakeholders, budgets, risks, and timelines. Execution (delivery/construction) turns plans into a realised asset with an emphasis on schedule, cost, quality, and safety. Operations and maintenance (O&M) focus on uptime, performance, compliance, and incremental life extension. Planning is frequently technology- and vendor-agnostic. Circular design decides what is made and how it will circulate over multiple lifecycles, defining interfaces (for instance, standardised fasteners), documentation (for instance, material passports), and reverse-logistics enablers that those later phases can implement [22]. Planning, execution, and O&M can incorporate circular design strategies such as design for longevity, flexibility and adaptability, or strategies regarding material selection or procurement [23] so that the products can maintain their value throughout several life cycles because of their emphasis on material selection, modularity, reparability, and end-of-life methods [24]. The details of the benefits of CE strategies are elaborated in Question 3.

CE strategies primarily focus on preventing and reducing the use of raw materials, as well as recirculating materials already in use. According to the definitions provided by the international standard ISO 59,004 [16], circular strategies aim to combine the greatest possible value relative to resource use, minimising waste, losses and emissions generated by all processes during the entire life cycle. These strategies are often categorised based on the waste hierarchy concept, later formalised in documents such as the European Waste Framework Directive [25] and further expanded on the so-called R-ladder framework (see Question 2). The EU Circular Economy Action Plan aims to enhance resource efficiency in all sectors [7]. In this respect, the EU Taxonomy provides definitions and tools, such as the EU Level(s) aim to harmonise environmental assessments [26] (see Question 4 for details).

Circular building is the application of these ideas to architectural design and construction in the built environment [27]. In order to help save resources and decrease construction waste, it focuses on developing structures that are flexible, can be disassembled, and composed of materials that can be recovered and reused [13]. Circular buildings are in the focus of CE studies in the built environment and there are several pioneering studies in this scale. For example, the prominent framework that systematically describes the circularity in building (layers) was proposed by Brand [28]. This shearing layers framework allows the categorisation of components (structure, skin, space plan, and so on) according to their function and lifetime. Later, the framework was adapted to transformable building structures design-for-disassembly

(DfD) [29,30] and quantitative evaluation tools such as demountability index [31]. Such concepts evolved into the development of modular building components that can be used in more than one building in multiple lifetimes [32]. To ensure the recovery of such components by nature itself, bio-based construction is currently being explored as an integrated part of circular buildings [33].

When the definition of CE is extended to urban scales, such as neighbourhoods and cities, it begins to include resources beyond materials, such as human resources; citizens' skills, time and engagement or locally produced solar energy, and urban greens, as well as digital resources and social aspects [34]. There are several definitions in the literature regarding the circular urban built environment. According to Vanhuysse et al. [35], the circular cities are commonly defined as regenerative, collaborative, digitally enabled urban systems that use resources efficiently, eliminate waste, support local renewable cycles, improve quality of life while maintaining economic prosperity and equity across all sectors. The Circular City Centre [36] extends this definition to the urban built environment by labelling it as a living system that respects the planetary boundaries, preserves the resource value, and ensures the well-being of its inhabitants. Nonetheless, there is a lack of guidance on how these common definitions can be implemented in real-life cases.

One particular example for testing the implementation of CE at an urban scale is urban living labs (ULLs). ULLs offer a promising methodological and governance approach for translating the conceptual definitions of circular urban development into practice [37]. Typically situated within real neighbourhoods or districts, ULLs function as collaborative testbeds where municipalities, researchers, citizens, and businesses experiment together with new technologies, policies, and business models under real-life conditions. Their emphasis on co-creation, iterative learning, and multi-stakeholder governance provides a structured environment to address complexity and uncertainty while fostering innovation capacity [38,39]. Existing ULLs across Europe and beyond—ranging from mobility and energy transition demonstrators to circular construction pilots—illustrate how these spaces can bridge the gap between theory and implementation by enabling experimentation, building shared ownership, and accelerating the systemic transformation toward circular and sustainable cities.

In conclusion, there are several scales of circularity in the built environment. As introduced in Fig. 2, there is a need to extend the existing scholarly and practice-based literature and frameworks to understand circularity on larger scales. The following questions focus on the neighbourhood scale, which is defined as the optimal scale to develop and test innovative solutions for sustainability and circularity concepts [40].

## 2.2. Question 2: what are the current state of the art and best practices in the field of circularity in the built environment?

The current state of circularity in the built environment is less well-advanced than often expected, mainly focusing on large-scale and rather severe downcycling works such as demolition. For instance, existing walls are crushed into smaller pieces to be used for road foundations or landfill. Having said this, to describe the current state of the art, different approaches can be discussed using one of the most internationally-recognised frameworks for circularity in the built environment, the R-ladder hierarchy [41] (see Question 1). Based on this hierarchy, circular practices can be systematically categorised according to ten principles: Refuse, Reduce, Rethink, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. These principles represent a graduated hierarchy rather than equivalent alternatives, as each implies a distinct level of material retention and, typically, material value. At the top of this hierarchy, Refuse and Reduce strategies aim to minimise material consumption per unit of product or service [42]. Such strategies can be applied across all scales of the built environment, from individual products to buildings and cities.

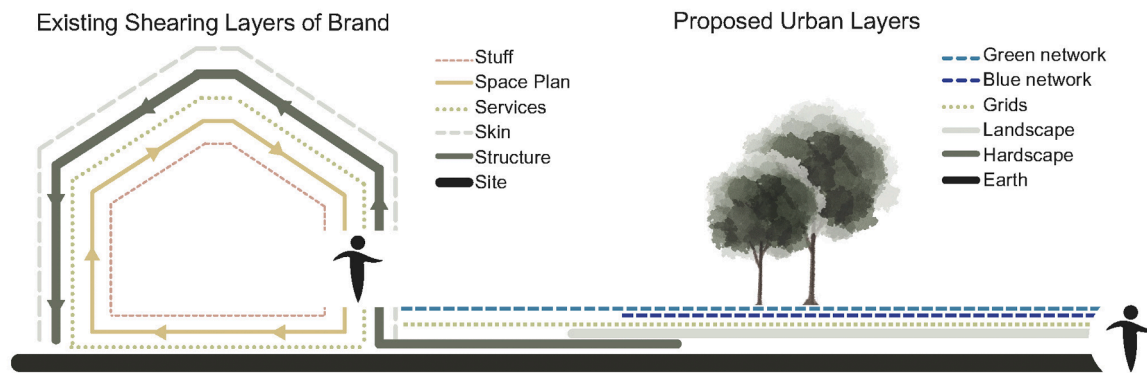


Fig. 2. Extension of shearing layers of Brand to urban context (adapted by Kayaçetin from Brand [28]).

Following these strategies, priority should be assigned to interventions that preserve product integrity and functionality. Specifically, Rethink involves redesigning products and systems to facilitate circularity from conception [42], while Reuse, Repair, Refurbish, Remanufacture, and Repurpose maintain products or components in effective use with varying degrees of intervention. These strategies can be applied across all scales superior to material-level, as they can preserve embodied energy, labour, and material value, potentially even enhancing the latter through upcycling. Only when superior levels of circulations are no longer feasible should material-level strategies be employed. Recycling enables materials to re-enter production cycles, albeit with some loss of quality that may lead to thermodynamic, functional or economic downcycling effects [43]. Recovery, typically through energy generation from waste incineration, occupies the lowest tier and is normally excluded from CE by some scholars [42]. The R-ladder hierarchy, therefore, suggests that the primary performance criterion is material preservation as not all circular practices achieve equivalent outcomes. Nevertheless, within each tier of the R-ladder, it is possible to identify ‘best practices’ and their effectiveness can be evaluated using criteria beyond material preservation alone (see Question 9).

There is not always a consensus on how to define the boundaries of the CE and what qualifies a circular practice. While the concept originally refers to the context of the built environment, more recent frameworks have broadened its scope to include the natural environment. For example, the Ellen McArthur Foundation framework proposes a third principle to regenerate nature, thereby extending circular practices into ecosystem restoration and natural capital rebuilding [11].

In terms of scales, as the aforementioned Brand model (1995) [28] suggests, circular practices can be applied at various levels of the built environment, from the product scale to the building scale. Material or product-level practices to implement circularity include material passports and digital product databases, product-as-a-service (PaaS), urban mining, and material sorting technologies. Other practices, such as adaptive reuse, design for adaptability and disassembly, can be extended to the building level. These circularity practices can be combined with other tools to inform about the technical and environmental performance of the products involved and even the entire building. For instance, environmental product declarations (EPDs), maintenance records, and serialised component IDs can be integrated into building information modelling (BIM) platforms, producing a digital passport of the product. Open standards, such as IFC and ISO 22057:2022 for EPDs in BIM [44] are increasingly used so environmental data can be interpreted by different platforms. All of these practices can be implemented in one project. When enhancing current practices through innovation, best practices can be tested and showcased through circular prototypes at the building scale, for example: Mobble [45] and CBCI Living Lab Gent [33], which apply Rethink principles through design for disassembly, enhancing Reuse and facilitating Repair; and BAMB, a digital

tool for circular building assessment supporting BIM-based design [46]. Other cases include initiatives from the building sector, such as the Upcycle Studios project by Lendager in Copenhagen, Denmark.

Even though there are initiatives to investigate circular practices at larger scales, in the form of living labs [47] or experimental sites [48], there are still relatively few best practice examples at urban scales [49] noted that some of these include Evora in Portugal, Alkmaar in the Netherlands, Reykjavik in Iceland, Augustenborg in Sweden, L’Innesto, Milan in Italy, and South Wales in the United Kingdom. Regarding planning for the future, Amsterdam has emerged as a global leader in setting a circularity agenda through its Circular Strategy 2020–2025, which mandates 50 % of all building refurbished and maintained following the principles of circular construction by 2025 (Municipality of Amsterdam [50]) following the Dutch programme ‘Circular Economy in the Netherlands by 2050’ setting 50 % reduction in raw material use by 2030 and full circularity by 2050 [51]. Collaboration across the value chain remains essential, integrating architects, engineers, developers, and material suppliers, though often insufficiently considered [52]. An assessment of trends and behaviours towards circularity among different stakeholders is needed.

Finally, within the plurality of circularity visions [53], circular practices represent feasible implementation pathways, though their implications require continued examination. Examples of current circular strategies with economic, social, environmental, and technological implications, specifically, are provided in the answers to Questions 5 to 8, respectively.

### 2.3. Question 3: what are the challenges and potential benefits of/to implementing circularity in the built environment?

Although implementing circularity in the built environment has substantial positive impacts on the environment and the economy, there are numerous obstacles and difficulties, some of which have been critically discussed in the scholarly literature [54]. One of the main obstacles is the lack of harmonised frameworks for evaluating circularity at the product level (see Question 2), which makes performance evaluation and decision-making more difficult [55]. A common problem with emerging frameworks is the lack of validated indicators and quality datasets to measure circularity (see Question 9). Existing indicators are local, case-specific and generally clustered around quantitative material flows, and there is a clear lack of indicators for other social or technical dimensions. Meanwhile, the existing dataset used in studies attracted criticism due to lack of transparency and consistency.

The implementation of CE methods is also hampered in the construction sector by a plethora of behavioural, sociological, governmental, technical, environmental, and economic obstacles [56]. For example, common challenges include large upfront expenses, low levels of knowledge and aversion to change related to the implementation of CE principles in the built environment. Furthermore, these problems are

accentuated by the lack of encouraging laws and incentives, which makes it challenging for interested parties to switch from conventional linear models to circular approaches [57]. Another challenge is that circularity interventions may have unforeseen material, social, or energy rebound effects, as the striving for eco-efficiency does not necessarily align with eco-effectiveness [58]. For example, the enhancement in resource and energy efficiency of a building practice might inadvertently boost overall material use by the continual increase of habitable surface area. Therefore, a holistic approach is necessary to understand the impact of circularity strategies in the built environment [59,60]. Such a holistic approach should consider cultural and geographical differences as local frameworks tend to fail when a global harmonisation is required.

In the economy, circularity seeks to minimise waste, prolong product life cycles, and preserve the value of materials, components and resources for as long as feasible [61]. Higher-order strategies, like Rethink, Reuse, Repair, Refurbish, Remanufacture, and Repurpose, which preserve material functionality and value more effectively than lower-tier options such as recycling or recovery, are given priority, as explained by the R-ladder hierarchy in Question 2 [62]. In terms of the environment, these superior methods enhance material productivity throughout value chains while lowering waste production, pollution, and dependency on the exploitation of virgin resources [63]. In terms of the economy, they facilitate new business models such as leasing, remanufacturing PaaS and take-back programmes, encourage supply chain and material innovation, and improve long-term resource efficiency [64]. Additionally, social advantages are concentrated at upper R-ladder tiers, where circular practices strengthen business sustainability pledges, encourage responsible consumption, and create jobs in repair and refurbishing operations [65].

Despite these advantages, there are ongoing operational, social and economic obstacles to implementing the CE that differ depending on the R-ladder tiers. In addition to unclear returns and possible opposition to non-ownership models like sharing or leasing, higher-order solutions frequently call for significant upfront investments in product development, supply-chain restructuring and traceability systems [66]. As circular systems transition to closed-loop configurations, operational complexity rises, necessitating sophisticated logistics, infrastructure for collection and sorting, and technological integration to balance resource efficiency, environmental performance and economic viability [67]. Socially, in order to guarantee the equal involvement of smaller players and lower-income groups, the transition calls for changes in consumption patterns, worker reskilling and attention to distributive justice [67]. These challenges contribute to the explanation of why there are still few solid examples at the urban scale, despite the emergence of best practices at the product, building, and experimental stages.

A complex ecosystem of stakeholders operating across interrelated stages of production, consumption and resource recovery is necessary to realise circularity. While designers and engineers help integrate circular ideas into goods, services and systems, manufacturers and suppliers are crucial in reorganising operations to facilitate closed material loops and effective resource use. Retailers who encourage product life extension, sharing and take-back programmes help consumers impact the transition through changes in their purchase and usage patterns [68]. The material recovery process is managed by waste managers, recyclers and resource hubs, with the help of legislators who establish guidelines, rewards and rules to encourage circularity. While investors and financial institutions supply the funding required to scale circular business models, non-governmental and civil society organisations raise awareness and promote fair and sustainable practices. Lastly, the practical realisation of circular concepts in the broader economy is reflected in the rise of new job opportunities in reuse, repair, remanufacturing and recycling.

Policy frameworks supporting circularity in the built environment reflect these differentiated priorities and uneven implementation across R-ladder strategies (see Question 4 for details). The EU Circular

Economy Package, national roadmaps and lifecycle-based building standards are just a few of the comprehensive regulatory and strategic frameworks that Europe currently leads in promoting higher-order circular practices through binding regulation, monitoring and integration with climate and urban sustainability policies (SDGs 11 and 13) [69,70]. On the other hand, a lot of lower- and middle-income countries continue to concentrate on lower-tier measures like resource efficiency, waste reduction and informal recycling, which reflect more pressing development goals: employment, infrastructure and energy access (SDGs 6, 7, 8, and 9). Regional variations emphasize industrial resilience, urban regeneration and partnerships (SDG 17), while international cooperation, voluntary programmes and pilot projects are frequently used to advance these policies instead of strict legislations [71,72].

The potential advantages of adopting circularity are significant, notwithstanding these obstacles. Implementing circular strategies can enhance economic growth by increasing competitiveness in markets that prioritise sustainability, as well as creating new job opportunities in the recycling and reuse sectors [57]. Furthermore, circularity encourages creativity and early collaboration in the planning and building processes, which results in the creation of resilient and flexible structures that are better able to tolerate shifting environmental circumstances [55]. Thus, even if there are many obstacles in the way of incorporating circularity into the built environment, the long-term benefits to the environment and economy make it crucial to get over them. One crucial step for dealing with these challenges is the harmonisation efforts in policies and regulations toward circular construction practices. Yet the benefits to the local region compared to the global contexts warrant further investigation to prevent the ‘Pollution Heaven’ effect.

The advantages and difficulties of circularity discussed in Question 2 (and later with social and economic perspectives in Questions 5 and 6) become especially apparent at the building and neighbourhood scales, where higher-order R-ladder strategies can improve quality of life, lower whole-life costs and embodied carbon, as well as bolster urban economic resilience—but only if they are backed by circular funding and policy frameworks that can recognise long-term value retention while addressing higher upfront investments and uneven environmental outcomes (see Table 1).

Overall, by separating growth from resource depletion and waste production, the shift to circularity offers significant environmental, economic, and social benefits. Nonetheless, it also poses behavioural, institutional and structural issues that call for systemic transformation and coordinated governance. In order to achieve circularity, cooperation between value chains and sectors is necessary, backed by coherent policies and incentives that balance the need for long-term sustainability and resilience with immediate economic demands.

#### 2.4. Question 4: which policy plans and regulations exist around circularity in the built environment?

Circularity in the built environment is largely shaped by regional policy maturity and economic context. Martínez Moreno et al. [73] highlight that the EU remains a global pioneer through its Circular Economy Action Plans (2015–2020 and 2020–2024), which integrate circularity into regulatory, financial, and monitoring frameworks. These plans emphasize material preservation through recycling and down-cycling, supported by measures such as eco-design directives, waste reduction targets, and funding from the European Green Deal and NextGenerationEU.

Policy frameworks supporting circularity in the built environment are evolving unevenly across global contexts. Although the ISO 59000 series complements policy frameworks by translating high-level circularity goals into operational guidance for organisations, still global inequalities exist. ISO 59,004, part of this series, is detailed in Questions 1 and 9. Fitch-Roy et al. [69] highlight that while Europe leads with comprehensive regulatory and strategic frameworks, such as the EU Circular Economy Package, national roadmaps (such as Finland and the

**Table 1**  
Benefits and challenges of CE strategies.

Dimension	CE Strategies	Key Benefits	Key Challenges
<b>Environmental</b>	<ul style="list-style-type: none"> <li>- Reuse, repair, remanufacturing, recycling</li> <li>- Adoption of recycled and renewable materials</li> <li>- Whole life cycle thinking</li> </ul>	<ul style="list-style-type: none"> <li>- Reduced waste generation and pollution</li> <li>- Lower virgin resource extraction</li> <li>- Increased material productivity</li> <li>- Regenerative material cycles</li> <li>- Long-term cost efficiency</li> <li>- New business models and markets</li> <li>- Increased competitiveness in sustainability-oriented markets</li> <li>- Innovation in materials and logistics</li> </ul>	<ul style="list-style-type: none"> <li>- Rebound effects (eco-efficiency ≠ eco-effectiveness)</li> <li>- Increased total material use</li> <li>- Lack of holistic impact assessment</li> </ul>
<b>Economic</b>	<ul style="list-style-type: none"> <li>- PaaS</li> <li>- Leasing and sharing models</li> <li>- Take-back schemes</li> <li>- Closed-loop supply chains</li> </ul>	<ul style="list-style-type: none"> <li>- New employment opportunities</li> <li>- Stronger corporate sustainability commitments</li> <li>- Empowered and aware consumers</li> </ul>	<ul style="list-style-type: none"> <li>- High upfront investment costs</li> <li>- Long and uncertain payback periods</li> <li>- Market resistance to non-ownership models</li> <li>- Risk of uneven local vs global benefits</li> </ul>
<b>Social</b>	<ul style="list-style-type: none"> <li>- Job creation in reuse, repair, recycling</li> <li>- Consumer engagement in responsible consumption</li> </ul>	<ul style="list-style-type: none"> <li>- New employment opportunities</li> <li>- Stronger corporate sustainability commitments</li> <li>- Empowered and aware consumers</li> </ul>	<ul style="list-style-type: none"> <li>- Behavioural resistance and low awareness</li> <li>- Need for workforce reskilling</li> <li>- Risk of social inequity and exclusion of low-income groups</li> </ul>
<b>Technological</b>	<ul style="list-style-type: none"> <li>- Design for disassembly</li> <li>- Material traceability systems</li> <li>- Closed-loop logistics</li> <li>- Industrial symbiosis</li> </ul>	<ul style="list-style-type: none"> <li>- Extended product and material lifetimes</li> <li>- Improved value retention</li> <li>- Resilient and adaptable buildings</li> </ul>	<ul style="list-style-type: none"> <li>- Lack of validated indicators and harmonised frameworks</li> <li>- Poor-quality, non-transparent datasets</li> <li>- High logistical and technological complexity</li> </ul>
<b>Governance and Policy</b>	<ul style="list-style-type: none"> <li>- Circular construction regulations</li> <li>- Incentives and standards</li> <li>- Cross-sector coordination</li> </ul>	<ul style="list-style-type: none"> <li>- Policy-driven acceleration of circular adoption</li> <li>- Better coordination across value chains</li> </ul>	<ul style="list-style-type: none"> <li>- Fragmented and localised frameworks</li> <li>- Insufficient incentives and supportive legislation</li> <li>- Difficulty in global harmonisation</li> </ul>

Netherlands) and lifecycle-based building standards, most emerging economies are still in early stages, focusing on waste reduction, informal recycling and resource efficiency [71,72], as mentioned above. According to Huovila and Iyer-Raniga [70], circularity -in Europe- is most connected to urban sustainability and climate policies (Sustainable Development Goals (SDGs) 11 and 13), emphasizing energy efficiency, low-carbon infrastructure, and material footprint reduction through binding regulation and monitoring. On the other hand, middle-income countries prioritise resource access, infrastructure, and production efficiency, with a stronger emphasis on SDGs 6, 7, 8 and 9. Policies are often driven by international cooperations, voluntary programmes and pilot projects rather than strict legislation. African and Asian respondents particularly valued energy access, industrial resilience and employment, while Latin American efforts often focus on urban regeneration and partnerships (SDG 17). Dziedzic et al. [74] studied 37 policy instruments from 19 countries across six world regions dividing them

into five main types: regulatory, economic, technical, operational, and communicative. In high-income regions (such as EU, Japan, South Korea, Canada), strong regulatory frameworks, such as the EU Circular Economy Action Plans, Japan’s Construction Materials Recycling Law and mandatory BIM adoption, drive construction and demolition waste recovery. These are complemented by economic incentives (such as subsidies for green buildings) and technical standards promoting DfD and material reuse.

Overall, while high-income regions employ mature policy instruments integrating circularity into regulatory frameworks, lower- and middle-income countries rely on indicator-based approaches and global partnerships to align circularity with broader sustainable development goals. In high-income economies, circularity is embedded in binding legislation, green public procurement and advanced metrics assessing lifecycle impacts of materials and buildings. These countries often integrate design for adaptability and deconstruction, supported by strong institutional and research capacity. Conversely, middle- and low-income countries tend to pursue circularity through urban sustainability and waste management policies, often supported by international initiatives or development aid rather than national regulation. Implementation is constrained by fragmented governance and lack of data. In contrast, other high- and middle-income countries such as China and Canada show varying levels of advancement. China enforces circularity through strong industrial decarbonisation and resource-efficiency policies, while Canada is still developing a coherent national strategy despite growing institutional commitment.

Looking closer to specific instruments, the European Commission adopted the Circular Economy Action Plan (CEAP) in March 2020. By including various initiatives along the entire life cycle of products, the plan aims to reduce pressure on natural resources, decrease waste, create new jobs, and contribute to the EU’s 2050 climate neutrality target. The construction and building sector is among those with the highest resource consumption and circularity potential. In this sector, the European Commission also introduced the Level(s) framework [75] to assess and report on the sustainability performance of buildings and, consequently, to promote the application of CE principles.

Albeit in an indirect way, the revised Energy Performance of Buildings Directive (EU/2024/1275) is also starting to steer designers towards a careful choice of materials in buildings, since it includes the requirement to progressively calculate whole-life-cycle carbon emissions for all new buildings, starting from 2028 [76]. The estimations are that this will lead to the choice of materials with lower embodied carbon emissions, including those with circular origin. At the national level, one way to promote circularity in the public sector is the adoption of Green Public Procurement (GPP) policies, which typically include requirements about the choice of materials. As an example, since 2016, all public works in Italy must comply with minimum environmental criteria (Criteri Ambientali Minimi, CAM) [77], which include provisions about the selection of construction materials such as the minimum thresholds of certified recycled content for several categories of products. This is part of the National Strategy for Circular Economy adopted in Italy in 2022.

All the countries in the study have already implemented solid waste policies, emission targets and green building certifications. Density and height bonuses for green buildings are only present in countries with the highest gross domestic product (USA, Canada, China, Japan, India, Australia, South Korea and Germany). Each country interprets and operationalises these requirements differently based on institutional capacity, governance structures, and market maturity. For instance, in Poland, circularity in the public sector is facilitated primarily through the broader legal and administrative framework that concerns environmental measures, public procurement, and compliance with EU directives. The Constitution requires ecologically sound public policy, and statutory instruments (for instance, environmental law, construction law, public procurement law) provide checks on circular requirements. Furthermore, as a member of the EU, Poland is required to put in place

instruments like the Digital Product Passport and conduct market surveillance, including penalties if terms are not met [78]. Overall, these frameworks allow Polish authorities to enact circularity criteria to the public procurement process, material standards, and administrative surveillance.

In Türkiye, circularity has been facilitated by zero waste initiative and regulation until a broader framework is proposed in the National Circular Economy Strategy and Action Plan published in 2025 [79]. The plan provides a cross-sectoral approach and defines circular products. The aim for the construction sector is to align the existing national regulations with the EU construction products regulation declared in 2024. The document is a roadmap that highlights the need to develop guidelines on recycle and reuse, and strategies for demolition waste.

Overall, policies and regulations are the construction blueprints for a circular built environment. They provide detailed engineering instructions for a solid transition; establish the desired outcome (circularity by 2050), standardise the tools for construction (Life Cycle Assessment (LCA) and Level(s) [75]), provide the necessary financial and informational scaffolding (procurement and Digital Product Passport) and the obligation to deconstruct existing paradigms to maximise material harvesting in future builds.

Synthesising all above, policy transfer relating to circularity and sustainable development occurs through multiple frameworks of cooperation, regulatory alignment and knowledge networks that facilitate the spread of circular practices, institutional learning and alignment of sustainability standards between geographic and governance contexts. Coordination and harmonisation in policies regarding the CE and sustainability yield manifold benefits. Harmonisation provides a means to guarantee common goals and standards when monitoring outcomes, enhancing coherence and, in turn, efficiency. Transnational cooperative arrangements facilitate the innovation and sharing of knowledge through shared learning and open-access learning materials. Many such approaches have a social purpose and provide frameworks for inclusive work opportunities, as in the case of continuing education in Finland as climate law and an initiative for workforce inclusion [80]. Future research should focus on how policy alignment, standards and learning networks interact across governance contexts to enable effective circularity, with particular attention paid to institutional capacity, social inclusion, and measurable outcomes.

### 2.5. Question 5: what are the economic implications of circular strategies applied on the building and neighbourhood levels?

CE strategies at the building and neighbourhood levels can improve inhabitants' quality of life, promote sustainable urban development, and increase economic resilience [81]. Economic resilience depends on preserving and enhancing value in several urban layers: socio-economic and technical infrastructure and production [82]. Circular strategies can create net economic value at the building level while reducing embodied carbon, and transition to a CE is estimated to provide new sources of economic growth in all sectors by 2030 [83]. When life-cycle costs are considered, including multiple use cycles, value retention and secondary markets, circular strategies show lower whole-life costs than linear options [84]. For sustaining such whole-life values through a circular strategy, there is a need to adopt a circular funding framework that can recognise the benefits obtained from the R-Ladder. New CE frameworks are emerging for this purpose, which can capture values throughout the lifetime impacts [85]. Some studies show that more circular activities do not necessarily result in better environmental impacts even though they provide higher profits and social gains [86]. In order to evaluate the economic implications of CE, it is important to review the impact of circular practices. Several circular practices (harvesting materials, certification, BIM/material passports, modular design) require higher initial investments for new knowledge and skills and to coordinate a new circular supply chain. This implies a need for new financing frameworks and incentives to align with private and social benefits [87]. Examples of

such frameworks are revolving funds based on subsidy retention [88] and circular economy service companies (CESCO). Such revolving funds aim to improve the living conditions of low-income neighbourhoods via a revolving fund that generates additional value for the residents via renovation. The integration of a circular and bio-based approach with a revolving fund yields the necessity for an entity that is similar to a CESCO. Some of the basic characteristics of such an entity were previously analysed by Reich et al. [89]. The CESCO concept is used for maintaining and reusing the building components in a PaaS approach [90]. Werrel et al. [91] provided a circularity assessment of PaaS (for instance, leasing rather than purchasing, service-based contracts) that displays promising results relevant to the construction industry. Assessment of such economic strategies generally utilises life cycle costing (LCC) [92] and total cost of ownership approaches [84]. Challenges to the implementation of these techniques include the lack of stakeholder awareness, significant upfront expenses, and regulatory restrictions [92]. Financial incentives, tax relief, cooperative planning among stakeholders, and supporting legislation are necessary to overcome these challenges.

Recent studies put emphasis on development of circular supply chain [59] with a focus on internal drivers (such as BIM and the Internet of Things (IoT) -based logistics) and external drivers (material certification, incentives, market maturity and social engagement) that assign new roles to all supply chain actors and require improved infrastructure. Existing circularity assessment approaches (including indicators and frameworks) often emphasize the role of emerging circular business models within the supply chain. This includes PaaS and buy-back or take-back schemes. Tokazhanov et al. [93] developed a circularity scoring tool for construction projects and found that, among its nine assessment categories, the circular business model category was rated as having high significance in stakeholder surveys.

Circular supply chains and green infrastructures (GIs) are closely related since they both place a strong focus on resource efficiency. In order to foster long-term resilience, both concepts aim to go beyond the conventional linear "take-make-dispose" model and adopt a more cyclical strategy that emulates natural processes [62]. Urban woods, wetlands, green roofs and permeable surfaces are examples of green infrastructures, which manage natural resources to provide ecosystem services and restore ecological balance [94]. GIs offer the ecological framework that allows circular systems to function efficiently, guaranteeing that cycles of materials and energy continue to be compatible with the environment's carrying capacity. Through processes including water reuse, nutrient recovery and energy conservation, the incorporation of GIs into CE initiatives facilitates more effective resource usage and waste reduction.

The integration of circular strategies and GIs at the urban level promotes closed-loop systems, such as decentralised wastewater treatment, biomass-based renewable energy generation and the use of recyclable materials in green building [95]. Both strategies produce more extensive social and economic co-benefits. GIs improve public health, climate resilience and quality of life, while the CE promotes innovation, resource optimisation, and the creation of green jobs [96]. (Table 2).

### 2.6. Question 6: which social circular strategies are applied on the building and neighbourhood levels?

Besides circular environmental and economic indicators implemented at the building and neighbourhood level, transformative social innovation strategies shape circular ways of organising, living, and interacting in urban communities [97]. The social aspects that shape the circular environment have been studied to a much lesser extent than the technical aspects [35]. For example, preserving neglected places and heritage sites contributes to circularity, demonstrating that the human factor plays an important role. Also, place narratives and collective memory regarding places and buildings are part of the community identity and influence people's willingness to be part of the circular

**Table 2**  
Implications of circular economy mechanisms.

Economic mechanism	Circular strategies involved	Value creation logic	Economic implications
Whole-life value optimisation	LCC, TCO, multi-use cycles, secondary markets	Retains value over multiple life cycles	Lower whole-life costs and longer asset value
Circular business models	PaaS, leasing, take-back, CESCOs	Shifts revenue from sales to services and recovery	Stable long-term income and reuse incentives
Circular finance and investment	Revolving funds, subsidy retention, circular funding	Reinvests savings into further circular upgrades	Enables self-financing neighbourhood regeneration
Supply-chain value recovery	BIM, material passports, IoT, certification	Makes components traceable and reusable	Supports secondary markets and asset liquidity
Risk and cost reallocation	Modular design, component harvesting	Moves risk from waste to planned recovery	Improves investment security
Innovation-driven competitiveness	Circular design, bio-based materials, symbiosis	Generates new circular products and services	Strengthens sustainability-based competitiveness
Green infrastructure integration	Water reuse, biomass, green roofs, wetlands	Aligns resource flows with ecosystems	Reduces long-term infrastructure and environmental costs
Social value generation	Renovation funds, repair and reuse	Creates jobs and improves housing quality	Supports inclusive urban development

strategies [98]. In addition, industrial symbiosis and reorganisation enable collaborative networks of communities, institutions and businesses, by embedding circular practices in everyday life as part of systemic change [97]. The ability to recycle, co-design and share space, tools and resources not only extends circularity but also generates behavioural changes in the sharing of knowledge and skills [99]. This, in turn, can pave the way for circular ‘commoning’, where communities collaboratively manage shared resources of their neighbourhood [100]. Thus, managing social assets is necessary for driving innovation, developing circular products and services and fostering inclusive, sustainable practices that are accessible to all. In this question, strategies aimed at revaluing human capabilities, strengthening social ties and creating inclusive, resilient, and healthy neighbourhoods will be discussed, and it will be shown that circular strategies such as changes in relations, human behaviour, institutional and professional norms, policy, well-being and a systematic understanding of how the built environment is embedded in cultures, societies and the natural world, can serve as a platform for deep, socially embedded transformations.

A truly circular built environment must prioritise social inclusion and equity to enhance community well-being. Without deliberate attention to human needs and justice, even efficient circular strategies fail to deliver key social benefits such as better health and reduced inequalities [101]. Ensuring that buildings and services remain affordable and accessible for vulnerable groups, including older adults, people having mobility problems and low-income residents, allows everyone to share in the benefits of circularity. A just circular transition links environmental and social justice by addressing unequal pollution burdens and anticipating labour impacts [102–104]. The social CE framework explicitly focuses on community resilience and inclusivity [105]. Integrating circular strategies into social housing can improve living conditions by lowering energy costs, enhancing indoor health, and strengthening resilience [99]. Contemporary definitions of a circular built environment now include these social aims, coupling environmental quality with social well-being [106]. By embedding affordability, accessibility and care into design, cities can ensure that everyone enjoys safer, healthier neighbourhoods as part of a fair and sustainable transition [101,107]. In summary, circular built environments that put people first will foster community health, cohesion, and fairness, marrying ecological sustainability with social well-being [101,105].

A key social circular strategy concerns the higher-order R-ladder strategy of “Rethink”, which encourages reconsidering how societal needs for buildings and neighbourhoods can be met [108]. Rather than focusing solely on making construction more efficient and effective, this approach adopts a systems-perspective on building(s), questioning the necessity of new construction altogether. It challenges hegemonic assumptions about sufficiency, spatial norms and the size of dwellings and plots. It invites a critical reflection on the financialisation of housing and construction and the socio-spatial norms that shape how people live and cohabitate. Ultimately, it promotes a shift away from large, single-family homes on individual plots toward more compact living

arrangements, denser neighbourhoods and shared use of buildings. A concrete example is the concept of circular commoning developed by Egger et al. (2025). Circular commoning refers to the everyday, often informal, spatial tactics through which communities collectively manage and adapt built environments to meet shared needs in sustainable ways. It emphasizes the integration of resources, people and governance in a way that reclaims space from market-driven logics and reorients it toward collective use, sufficiency, and care. For the construction sector, this implies a fundamental shift: from producing ever more buildings to supporting adaptive reuse, shared spaces and community-led spatial practices. Rather than viewing housing as a commodity, circular commoning encourages a perspective of the built environment as a commons, a shared resource co-created and maintained by its users.

Embedding collaborative design and participatory planning in circular construction has emerged as a key social strategy for empowerment and innovation. Rather than implementing top-down development, co-design invites residents and end-users to actively shape their buildings and neighbourhoods, fostering community ownership and ensuring that solutions truly meet local needs [109]; Huang, 2021; [110]). Meaningful participation extends beyond superficial consultation: when people have real voice and influence over decision-making, trust, satisfaction and long-term commitment to the project rise significantly [111,110]. Co-design within the circular built environment encourages collective experimentation, trust-building and systemic learning [106,112]. Ultimately, co-design and participatory planning anchor circular practices in their social milieu by treating communities as partners in innovation, yielding more inclusive, accepted and resilient outcomes, from user-designed housing that adapts to residents’ lives, to neighbourhood plans that foster stewardship and longevity [113,110].

Bottom-up circular strategies are developed to address systemic socio-environmental inequities by combining simple but effective aims such as circulating materials with strong social objectives, often referred to as Social Circular Economy (SCE) [114,105]. This SCE approach ensures that the transition to a sustainable economy prioritizes the needs and resilience of communities, especially those historically marginalised or known as “frontline communities” [115] and directly links to Question 3 on job creation, as SCE initiatives frequently generate local, inclusive employment opportunities through repair, reuse, recycling and community-based circular activities. The neighbourhood scale is recognised as a powerful leverage point because it is large enough to represent community behaviour and interactions with urban systems, but small enough to mobilise local stakeholders and clearly define project ambitions. These localised projects are easier to implement logistically, financially, and socially than citywide programmes, and their tangibility allows residents to experience the benefits directly. The success of circular initiatives is closely linked to social licensing, where public acceptance and trust influence implementation outcomes. Insufficient societal engagement or perceived unequal distribution of costs and benefits can lead to public opposition, highlighting the need for

transparent decision-making, participatory processes, and clear communication of shared social and economic benefits. However, human factors pose major challenges to the adoption of circular practices.

To overcome such challenges and facilitate the transition to circularity, the establishment of collaborative networks is fundamental. Collaborative networks operate as vital catalysts of co-creation, knowledge sharing, resource sharing, policy action, and alignment among diverse stakeholders and sectors across scales from local to (and international) contexts. Collaborative networks support the process of the systemic change needed for the shift from linear to circular through engagement of new forms of collaboration from broader policy initiatives (for example the EU Climate Pact, mobilises citizens towards a sustainable Europe). The Circular Economy Action Plan puts the priority on multi-stakeholder collaboration, and is centred around co-creation between economic actors, consumers, citizens and civil society organisations. Collaborative networks bridge fragmentation of knowledge through accepted norms of mutual respect and working together for a common purpose [116] more than we see in more linear economy models (particularly within construction), while promoting implementation locally, scaling up innovative and sustainable practices, and encouraging a shared vision for future practice. In doing so, they contribute towards the establishment of strong circularity between businesses, their consumers and citizens, and other civil society actors, and government policy.

Collaborative networks are also imperative in connecting circularity to societal goals to enable a just and equitable transition [117]. They foster fairness and inclusion, drawing marginalised communities into circular strategies. Hybrid collaborative models that bring together public, private and civic partners, such as the temporary use project, create multi-value dimensions for the construction of communities, supportive networks and co-learning resource systems among diverse stakeholder groups [118]. These networks also stimulate sharing and re-use under conditions that facilitate the use of digital-based platforms connecting citizens and businesses together in CE influence activities related to industrial symbiosis, rental, repair, and reuse services. Coordination in circularity is especially important for enacting circularity and reducing fragmentation. The success of all appropriateness practices to reuse is dependent on coordination and the sharing of information among demolishers, contractors and customers; a crucial part of shared decision making in the harvesting and redistribution of materials, is to have stakeholders engaged in the project early on. Collaborative networks create spaces where people can experiment, learn, and innovate together, as seen in the development of the SimFORCE methodology, where more than 30 experts across the circular value chain co-designed new ways of assessing building reusability [116].

Circularity is not only essential for environmental sustainability but also for social sustainability, protecting heritage and preserving cultural heritage [119]. Circularity transforms cultural heritage by privileging the maintenance, extension and functional adaptation of existing buildings and buildings components. In this way, circularity values both the material resources and the historical and cultural value of built heritage. One of the primary ways it does this is by embedding preservation goals directly into circularisation strategies, such as adaptive reuse. Adaptive reuse allows repurposing the existing buildings, reducing CO<sub>2</sub> emissions associated with built heritage, while maintaining historic value. Through functional reuse, cultural heritage becomes an activator of circular urban dynamics, supporting social, environmental and economic regeneration [120]. Reusing structural materials achieves the significant and reputable benefits of reversing environmental damage, whilst intentionally preventing the loss of the historical and functional significance of the region.

Furthermore, circularity is influencing architectural practice by developing new skills and educational trajectories that focus on existing buildings. Educational programmes like the "Circular Studio" at the Norwegian University of Science and Technology frame disciplinary

topics such as building conservation, heritage, material reuse and design development, equipping students with relevant and integrative skills for working with the existing built environment [121]. Hence, it is possible to support (future) professionals to consider a lifetime-based approach to buildings rather than relying solely on the original design. Overall, from the point of circularity, cultural heritage buildings are seen as potential or positive cultural and physical assets rather than burdened or abandoned assets. Circularity, through adaptive reuse, extended life, and consideration of heritage in planning and education, provides a valuable context for maintaining environmental and cultural values over time. In architecture firms, circularity in the design of buildings is slowly taking off [27], and valuable lessons are drawn from the first projects, such as the need to gain knowledge about circular revenue models, to know the lifespan of materials and to ensure that your knowledge of construction systems, products and materials is up to date. And finally, the lesson that architects need to understand is that circular design leads to a different aesthetics but not inferior quality.

Cities have two distinct roles in supporting circular collaboration: they act as both actors and platforms [122]. Concerning their enabler role, local authorities can facilitate partnerships, pilot projects and data-sharing systems regarding circular construction and industrial symbiosis. Their positioning as urban systems "hotspots" gives them the potential to lead public-private partnerships to develop circular strategies together with research organisations and other local actors, engage in developing circular products and services, and collaborate with transnational organisations to share best practices among all stakeholders.

## 2.7. Question 7: what are the environmental implications of circular strategies applied on the building and neighbourhood level?

The construction sector is a major component of the global economy but is also one of the largest contributors to material depletion and greenhouse gas emissions [123]. Over the past four decades, global material use has tripled, with a pronounced acceleration in the extraction of concrete, steel and other construction materials [124]. The residential building stock alone consumes 30–50 % of global resources, creating significant environmental burdens but also opportunities for CE strategies [125]. The construction industry also faces challenges like low productivity and fragmented value chains, leading to inefficiencies and high construction and demolition waste (CDW) generation.

Circular strategies aim to close material loops (see Question 2) but the extent of their environmental implications depends on how they are implemented and at what scale. Haas et al. [126] observed that common circular strategies, such as recycling, have only limited effects on reducing waste flows when implemented at insufficient scale and when material and fossil-fuel consumption continue to grow at current rates. This is supported by a recent study [127] which highlights that circular strategies should be complemented by energy-efficiency measures and a shift toward renewable energy in order to reduce greenhouse gas emissions and contribute to climate change mitigation. To further accelerate mitigation, circular strategies should also apply sufficiency principles at the product and construction materials levels [128]. On the contrary, an uncontrolled implementation of circular strategies in construction may generate undesired environmental burdens. This is the case of the concrete paradox, where the risk of increase of cement demand, up to 20 %, is observed when using a high share of recycled concrete aggregates (RCA) in new concrete [129]. Specifically, while recycled concrete can contribute to circularity and reduce the pressure on primary resources, it often leads to higher carbon emissions due to higher dosage of cement required to reprecipitate the water-to-cement ratio due to higher water absorption of RCA [129].

CE strategies at the building level primarily aim to extend the service life and enhance the adaptability of individual building elements as well as the building as a whole [130]. Other strategies target specific components to facilitate design for disassembly, high-value reuse and the

incorporation of secondary or recycled materials. The environmental impact reductions associated with these circular strategies arise directly from decreased extraction and processing of raw material and energy sources. Indirectly, these strategies contribute to lower emissions to air, land and water by decreasing resource depletion, waste generation and related pollution throughout the life cycle. This includes the reduction of land use for materials' extraction and construction. This can be measured through several indicators such as LCA impact categories (including global warming potential, acidification, eutrophication, particulate matter) (see Question 9).

Nevertheless, the effectiveness of circular strategies in mitigating environmental impacts depends on their position within the R-ladder. For example, strategies at the higher levels of the ladder can preserve the stock of construction materials by adapting and renovating existing buildings. Research shows that circular design strategies focusing on preserving existing structures will have the most significant impact on environmental protection [32]. A significant portion of the carbon savings achieved by preserving an existing structure comes from the greenhouse gases released when demolishing and constructing a new one [131]. Building renovation, which is currently a key focus in the European building system, has the potential to not only significantly improve buildings' environmental performance by reducing operational energy consumption, but also to save virgin materials and minimise emissions embedded in building materials [132].

Strategies at the lower levels of the R-ladder, such as reuse and recycling, yield variable reductions in environmental impacts, largely depending on the processing and treatment required to reintegrate materials and components into a new life cycle. For example, reuse generally requires less energy and generates lower carbon emissions compared to recycling, which often involves energy-intensive reprocessing [133]. When using new materials, locally sourced and low-impact bio-based materials should be used to reduce the environmental impacts associated with transportation, the use of new materials, and land-use competition with agricultural produce.

The widespread use of bio-based materials in construction is a valuable opportunity that can bring several advantages. Particularly, fast-growing bio-based materials can be quickly regenerated in nature by naturally capturing CO<sub>2</sub> from the atmosphere as they grow [134]. The sequestered CO<sub>2</sub> is stored as biogenic carbon during its use as a construction product.

Circular strategies at the neighbourhood level can also optimise the use of material and energy resources, reduce the generation of waste and emissions, promote sustainable urban development and establish long-term environmental resilience. Such strategies are closely linked to other policy drivers, including the EU Green Deal, the Fit-for-55 package and net-zero targets, which show an increased emphasis on decarbonisation and sustainable resource use [135]. At the building and neighbourhood scale, LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method) and mechanisms like whole-building zero carbon, bio-based materials and nature-based solutions, provide tangible actions that lead to climate neutrality [136,137]. Environmental circular strategies vary significantly based on cultural and institutional factors, which create challenges to the worldwide application of circular strategies. They also provide rich examples of context-specific adaptations.

Integrating green and blue spaces within neighbourhoods increases biodiversity, improves microclimates, supports water management and strengthens the cyclical relationship between natural resources [138]. This approach represents a viable approach towards establishing local, accessible, environmentally sound and economically viable circular systems that are also ecologically sustainable. Each geographical location has its own ecology, therefore, when developing circular solutions, these solutions need to reflect the local ecological environment. Generalised solutions are not sufficient, as each locality will have unique pressures that create distinct ecological constraints or opportunities. There is great variability when it comes to biomass production, the state

of soils and water availability within and between different areas. Where access to sustainably produced biobased materials is limited, circular design should focus on creating long-lasting building systems, encouraging the reuse of high-value materials and enabling recyclable building technologies rather than relying on biobased alternatives [139]. Conversely, if the landscape is suffering from soil depletion, circular neighbourhood strategies will need to focus on improving the landscape through the implementation of regenerative landscaping techniques, increasing site permeability and reducing soil sealing [140]. Finally, the goal of CE strategies in the built environment is to minimise a building's and other infrastructures' impact on the environment through actions such as eliminating waste, lengthening the life of materials, and lowering resource usage. When applied at both the building and neighbourhood levels, such strategies have the potential to significantly enhance the environmental performance of buildings and neighbourhoods, but only if proactively managed regarding trade-offs (such as bio-based substitutions, biodiversity, and land use); otherwise, circular strategies could lead to adverse effects.

### 2.8. Question 8: which technological circular strategies are applied on the building and neighbourhood level?

Recent reviews have examined both digital and industrial technologies as enablers of circularity in the built environment, although most focus predominantly on digital solutions, such as the development of conceptual frameworks linking digital technologies to circular strategies [141,142], mapping of digital enablers across life-cycle stages [143], analysis of regional research trends to assess integration levels along the building life cycle [144,145], and clustering digital technologies according to circular functions [146].

Digitalisation plays a key role in accelerating transitions toward climate neutrality and CE, particularly within the context of Industry 4.0 and the development of Cyber-Physical Systems and Digital Twins [147]. Its relevance for smart cities has further highlighted the need for applied research on digital data, tools, and organisational processes [148]. Alongside established instruments such as Environmental Product Declarations, Material Passports, and LCA [149], digital tools like BIM, Augmented Reality, and sensing and scanning technologies are being enhanced and increasingly used to support material tracking and circular construction practices ([150]; Piaia et al., 2025; [151,152]). Together, circular economy principles, circular design, and digitalisation form a coherent framework for sustainable innovation at both product and spatial scales [57].

However, information artefacts such as material passports, digital twins, and construction logbooks serve different purposes and user groups and should be understood as components of broader information systems that include people and processes, not only software and data [153]. Current debates often overlook these aspects, as well as the importance of clearly defining information requirements. Without explicitly embedding circularity metrics and user needs, digital tools cannot effectively support circular construction [154].

Finally, digital tools cannot compensate for insufficient or low-quality data. Their effectiveness depends on robust data generation mechanisms, often requiring physical measurements, sensors, or testing [155]. Without such integration, digitalization risks becoming an administrative and environmental burden rather than a genuine driver of circularity.

Quantitative analysis of global resource requirements for future urbanisation shows that, without a new approach, material consumption by cities will rise from 40 billion tonnes in 2010 to around 90 billion tonnes by 2050 [156]. The contribution of materials to anthropogenic emissions is becoming more and more critical as a large quantity of new construction materials will be demanded in the coming decades to cover the housing and infrastructure deficit in lower- and middle-income countries, as well as to support the urban transformation for the energy transition in higher income countries [157]. At the same time,

construction and demolition activities produce a significant fraction of global waste (around 30–40 % worldwide), and, under conventional linear practices, a significant proportion of this waste has historically been disposed of in landfills in the EU and other countries such as Australia [158,159].

The implementation of “urban mining” strategies, which consists in a wide use of recovered and reused materials from a city, coming from buildings, infrastructure, or obsolete consumer products [160], can turn this contradiction into an opportunity to limit the pressure on natural resources [161,13] thanks to the reduced use of raw materials, the reduced need for landfills, and an increased availability of locally sourced materials, with smaller transport-related impacts.

Some challenges and barriers that are still slowing down a wide implementation of urban mining practices can be at least partially overcome thanks to the use of digital tools. Among them:

- i) Difficulty in tracking the location of existing materials and their availability over time, often requiring data-intensive and time-consuming bottom-up built environment stock models [162]. Linking these with life-cycle assessment or circularity indicators adds another layer of complexity [163,164]. Looking ahead, the progressive deployment of BIM-based, continuously updated digital twins of buildings and infrastructures [165] linked to material or building passports [166] can be a key enabler of CE strategies [167].
- ii) Quality assurance of elements recovered from existing buildings is necessary to reduce uncertainty when assessing the residual performance [168,169]. Digital twins and material passports are potentially useful to improve confidence in second-use decisions, although CE aspects must be explicitly required to make them actually useful [169]. Despite these technological advances, regulatory frameworks that prioritise primary materials and often categorise reclaimed components as waste limit their market uptake and inhibit high-quality recycling or reuse [170]. A modernised regulatory framework is, therefore, required to recognise reclaimed elements as legitimate construction products.
- iii) Lack of effective value chains that can make demand and supply meet, through the establishment of hubs for second-life materials and the availability of information for stakeholders of the design and procurement process.

On the other hand, the goal of matching material demand and the availability of secondary-source materials opens interesting design perspectives to achieve the desired, or requested, circularity levels.

The DfD approach ensures that buildings and their parts are dismantled, rather than demolished, at the end of their life cycle [171], increasing the availability of circular materials in the urban mining perspective. Digital tools will only prove environmental effectivity when integrated into this overarching DfD approach to construction.

During the design phase, components that can be assembled with reversible connections should be specified, so that their parts are not damaged during disassembly, and materials are easy to separate for their next life. DfD can thus reduce demolition waste, the amount of material sent to landfill and the use of virgin resources, but also nuisance during dismantling and a healthier environment for workers [172].

The DfD potential is related to the type of connections (for instance, dry connections versus wet bonds), their accessibility, material independency, and geometry of the product edge [173]. The implementation of DfD principles will require a major shift from on-site, labour-intensive technologies to industrialised systems that are fabricated off-site and then quickly dry-assembled on site, such as complex facade and floor elements and entire volumetric assemblies [174,175]. The dry connections make it easier, in principle, to dismantle the components at the end of their useful life and reuse or recycle their elements.

Moreover, since the assembly of these modular components takes

place in a factory or workshop, the whole material flow can be managed efficiently thanks to easier sorting, reusing and recycling of byproducts.

It is, however, necessary to highlight that industrialised components are currently selected for economic, operative, and time-related reasons, while not much attention has been paid so far to the actual dismantling process [171]. Part of the reason is that it is difficult to predict the circularity technologies and regulations that will exist decades after design and construction. This once again points at the importance of a coherent and reliable information flow about the building components and their assemblies, that can support decisions about deconstruction and the second life of materials in the future.

Trustworthy digital information systems, combined with enabling regulation, can enable circularity in the built environment, cutting across constructive, material, and process-related domains as shown in Table 3. However, it must be once again underlined that their existence alone is not guaranteed for success, unless they are properly integrated into an overarching information management framework oriented towards CE.

2.9. Question 9: how is the circularity of the built environment measured or assessed?

The CE transition in the built environment is inherently systemic and multilevel. It spans from the micro-level of building materials and products, through the meso-level of individual buildings, to the macro-level of urban configurations and infrastructure networks [13]. Assessing circularity across these levels presents significant challenges. Circularity assessment has been defined in ISO 59004:2024 [16] as the evaluation and interpretation of results and impacts derived from a circularity measurement [176]. Prior to its release, there were no internationally recognised standards specifically guiding CE implementation and assessment. To date, no ISO standard has been

**Table 3**  
Summary of key technologies as circular strategy enablers.

Technology Area	Enabler	Primary Resource Principles	Exemplary Circular Strategy Enabled
Digital	Artificial Intelligence and Machine Learning (AI/ML)	Regenerate, narrow, slow	Life-cycle-based asset optimisation
	Big Data and Analytics (BDA)	Regenerate, narrow, slow	Resource flow management
	Blockchain Technology (BCT)	Narrow, close	Traceability-based value retention
	Building Information Modelling (BIM)	Narrow, slow, close	Integrated life-cycle information management
	Digital Twins (DT)	Narrow, slow	Feedback-driven adaptive circularity
	Digital Platforms / Marketplaces	Slow, close	Collaborative networks
	Material Passports (MPs) and Databanks	Regenerate, slow, close	Residual value recovery
Constructive	Internet of Things (IoT) – Sensors, RFID, Cloud/ Edge Computing	Slow, close	Lifetime extension
	Spatial Data Acquisition (GIS, LiDAR, SLAM, TLS, UAV)	Slow, close	Urban mining
	Augmented and Virtual Reality (AR/VR)	Narrow, slow	Collaborative decision-making
	Off-site Industrialised Construction	Narrow, slow, close	PaaS
	Reversible / Mechanical Joints	Slow, close	Design for disassembly (DfD)
	Dry Construction	Slow, close	Design for disassembly (DfD)
	Selective Deconstruction Technologies	Narrow, close	High-value resource recovery

established that specifically addresses the circularity assessment of buildings and the built environment. Consequently, a variety of approaches emerged across academic research, industrial practice and regional or policy frameworks, each developing its own methods to measure and assess circularity in the built environment across material, building, neighbourhood and community, and city and beyond scales.

Assessing circularity in the built environment requires robust, reliable, and context-specific data across material, component, and building life cycles. Circularity assessment involves a wide range of stakeholders with distinct information needs. As a result, no single indicator can serve all users. Effective indicators therefore require a clear definition of the target audience and explicit communication of their intended purpose. To date, however, developmental activities in CE monitoring mostly follow a data-driven approach: data are collected, transformed into indicators, and published with the assumption that stakeholders will act accordingly. However, the effective uptake of circularity indicators remains limited in practice, as has been recently demonstrated from the perspective of regional policy making [177]. Rather than proliferating indicators, indicators should be developed from a user perspective and be conceptualised as components of information systems that connect data to decision-making and provide clear affordances for action [154].

Digital innovations have often been cited as promising pathways for CE monitoring. Tools such as digital building logbooks, BIM, and material and building passports (such as Madaster) are gaining traction, supported by emerging legislation and market uptake. These tools can theoretically enhance data availability and traceability. However, their contribution to circularity assessment is not automatic. Indicator development must be explicitly embedded in the design of such tools from the outset. Moreover, existing tools have been criticised for a lack of holistic governance models and insufficient focus on value creation beyond compliance [178]. Without addressing these limitations, digitalisation alone is unlikely to substantially improve the effectiveness of circularity assessment.

An additional challenge is related to the development of robust methods to reflect circularity impacts and potential benefits across multiple dimensions. The common bottom-up aggregation approach often falls short in capturing the systemic nature of the CE transition. Besides, it is hindered by key data gaps such as material quality and modularity. To complement this, a top-down perspective is essential. Frameworks such as need-satisfier systems (for instance, [179]) essentially draw on development economics (such as Max-Neef, see [108]) and have been adapted for regional CE monitoring. These frameworks introduce indicators that are able to reflect systemic dynamics, such as the percentage of land area occupied by buildings, which highlights the tension between urban expansion and ecological limits. Moreover, the need satisfier approach integrates social dimensions, emphasizing that circularity in housing must also address issues like homelessness and building vacancy. A built environment cannot be considered circular if it fails to equitably meet basic human needs.

Building on this foundation, indicators and measurement frameworks play a crucial role in translating data into actionable insights. At the material and product level, the Ellen MacArthur Foundation introduced the Material Circularity Indicator (MCI) [180] to assess product circularity on a scale of 0 (fully linear) to 1 (fully circular), based on factors such as virgin material input, non-recoverable waste output, use intensity and service life. The indicator has since been widely adopted for assessing material-level circularity within the built environment.

At the building level, more diverse circularity assessment methods have been developed. Indicators can be categorised as quantitative, semi-quantitative and qualitative, and are applied either individually or as part of indicator sets within assessment frameworks [20]. The European regulatory framework Level(s) [75] provides a set of quantitative indicators for circularity assessment, such as the bills of materials and quantities of construction and demolition waste. Semi-quantitative assessments are commonly applied within the Green Building Rating Systems. Kubbinga et al. [181] proposed six semi-quantitative indicators

for possible integration into BREEAM. Each indicator is evaluated through a credit-based scoring system. In academia, researchers have been focusing more on quantitative methods. Verberne [173] developed the Building Circularity Indicator based on the MCI through a four-step aggregation process. This indicator and its subsequent adaptations [182–186] have been extensively applied in recent research, either individually or in sets with other indicators such as the Global Warming Potential and Net Present Value.

At the neighbourhood level, circularity assessment is conducted using sets of indicators within quantitative, semi-quantitative, and qualitative frameworks. For instance, the German Sustainable Building Council (DGNB) [187] incorporated five CE bonus indicators (i.e., water cycle systems, resilience and adaptability, social and commercial infrastructure, resource management, and construction site) within its DGNB Urban District certification. Each of these indicators is eligible for up to ten bonus points, encouraging the integration of circular principles into urban-scale design and management practices. At the city and beyond scale, quantitative assessments are more prevalent, either based on a single indicator or sets of indicators. Lederer et al. [188], for example, calculated the indicator mass of raw materials saved to assess and compare different strategies for construction and demolition waste management in the city of Vienna. Likewise, the Green Building Council Australia through its Green Star Community rating system explicitly addresses and incorporates CE principles. The rating system awards an “Innovation Challenge” credit to projects that implement CE initiatives such as digital material tracking [189].

While building level dominates current practice, larger scales, such as neighbourhoods, cities, and beyond, are significantly less explored. Circularity assessment methods vary by spatial scale. Quantitative approaches are the most widely used, supported by relatively well-established methods such as LCA and Material Flow Analysis (MFA). In contrast, semi-quantitative and qualitative assessments remain less developed, often challenged by methodological ambiguities, particularly inconsistencies in scoring systems. This is evident in academic frameworks, where researchers developed their own frameworks that are rarely re-applied by other researchers, such as those qualitative frameworks for assessing adaptive reuse [190,191].

Existing circularity assessment indicators and frameworks collectively address environmental, economic, social, technical, and managerial dimensions. Among these, the environmental dimension is the most extensively explored [192], aligning with the strong emphasis on emission reduction, material efficiency, and energy performance in current research and policy agendas. The technical dimension is represented through indicators related to DfD, design-for-adaptability, design-for-longevity, and innovative construction methods. In contrast, the economic, social, and managerial dimensions remain underexplored, despite their important role in ensuring the feasibility and success of circular transitions.

Overall, the field is characterised by a large number of fragmented indicators and frameworks, which complicates consistent and comprehensive assessments. Future research should build upon existing approaches, focusing on refining and adapting current indicators and frameworks. This includes extending building-level approaches to larger urban scales, integrating environmental, economic, social, technical and managerial dimensions within a single holistic assessment framework, and enhancing methodological clarity, alignment and standardisation across approaches to improve their transparency, replicability and comparability. Moreover, these assessment methods should be implemented, tested and validated in different geographies using mixed techniques (LCA, questionnaires, etc.) via emerging platforms such as ULLs.

## 2.10. Question 10: what are the future trends for circularity in the built environment?

Data-driven strategies, sustainable materials and technology

integration are progressively influencing future circularity trends in the built environment. One notable advancement is the use of CE concepts in BIM, commonly known as CircularBIM. This method promotes resource optimisation throughout the building life cycle by improving life cycle evaluations, assisting with disassembly planning, and facilitating more effective material recovery [193]. As the quantity of available data increases, utilising emerging Artificial Intelligence (AI) tools should enhance the optimisation processes.

Developing thorough and standardised approaches that successfully include circularity concepts throughout the design process should be the main goal of future research on circular design. This involves developing quantifiable metrics and evaluation instruments that can analyse circular performance at the system, service and product levels [194]. To create logical frameworks that direct designers in real-world implementation, more research is required into the combination of LCA, DfD, and design for reuse. In order to maximise circularity at the early stages of design, it is also worthwhile to investigate emerging digital technologies like artificial intelligence, digital twins, and data-driven design systems. In addition, material innovation remains a critical research frontier, with emphasis on developing bio-based, recyclable, and self-healing materials that support multiple life cycles, alongside enhanced material traceability through technologies such as blockchain and the IoT.

From an industrial and systemic standpoint, future studies should examine how circularity can be integrated into other industries, including electronics, fashion, mobility, and building. It is crucial to comprehend and get above organisational, monetary and cultural obstacles that stand in the way of the shift to circular processes. Additionally, scalable circular business models, such as remanufacturing, product-service systems, and material recirculation strategies, should be developed [195]. The social and behavioural aspects of circularity are equally significant, requiring a closer look at how consumers engage in value-retention processes collectively as well as in repair, reuse and sharing activities. In order to develop a generation of professionals who can promote regenerative and restorative economic models, educational strategies should also incorporate circularity and systems thinking into their curricula. In the study of Jacobs et al. (2022), several blueprints for courses on circularity at a building level were proposed based on a learning-by-doing approach.

Future research should look at how circular design can be used successfully in a variety of industries, such as electronics, fashion, mobility and construction, from an industrial standpoint. Finding and removing organisational, financial, and cultural obstacles that prevent widespread adoption is very important. Scalable business models like product-service systems and remanufacturing techniques should also be investigated [195]. The social and behavioural aspects of circular design are as significant and necessitate further study of consumer behaviour in repair, reuse, and sharing contexts as well as user participation and co-design methodologies. To develop a new generation of designers focused on sustainability, educational approaches that include circularity and systems thinking into design curriculum should also be studied.

At the systemic level, research should deepen understanding of the policy, governance and regulatory mechanisms that can accelerate the transition toward circularity [196]. Research on multi-stakeholder ecosystems, cross-sector cooperation, and urban and regional circular systems may provide strategies to integrate circularity into larger socio-technical and territorial frameworks. Additionally, there is an urgent need for empirical and longitudinal studies that evaluate the practical effects of circularity, taking into account social justice, ethical considerations, system resilience and environmental and economic performance [197]. Such multifaceted inquiry will be crucial for advancing circularity from a conceptual framework to a transformative paradigm that drives systemic change and meaningfully contributes to sustainable development.

Research should expand knowledge of the governance, regulatory

and policy mechanisms that can hasten the shift to circularity at the systemic level. Research on multi-stakeholder design ecosystems, cross-sector collaboration and urban and regional circular systems may show how to incorporate circular design concepts into larger socio-technical systems [198]. Lastly, longitudinal and empirical studies are required to evaluate the practical effects of circular design, including social equality, ethical issues and system resilience, in addition to environmental and economic results. To move circular design from a conceptual framework to a revolutionary practice that significantly advances sustainable development, such multifaceted inquiry will be crucial.

At the same time, low-carbon and bio-based materials like hempcrete, mycelium composites, and wood are becoming increasingly popular. These materials support circularity objectives by providing regenerative advantages and lowering embodied carbon [199]. Such low-carbon materials should be preferred in building components that are DfD and suitable for PaaS to extend the number and duration of reuse cycles. DfD improvements will also require an extended network of production lines for standard building components. This research line may lead to standardised, modular and mobile buildings that are less dependent on land use.

At the neighbourhood scale, integrated systems for energy, water and waste, such as district heating, green infrastructures and localised renewable generation, are emerging as scalable circular strategies that support self-sufficient and low-impact communities [17]. Additionally, digital twins and sensor-based monitoring systems are being used to track material performance and usage in real-time, enabling predictive maintenance and informed refurbishment strategies [56]. Such tracking systems may enhance the use of urban mining to achieve a local self-sufficient system. Rich data are generated throughout the circular design, construction and operation. There is an urgent need to capture such data and ensure transparency and validity throughout the supply chain. As circularity becomes increasingly data-intensive, effective data governance and interoperability across stakeholders will be essential. Overall, these trends point toward a built environment that is adaptable, low-carbon, and technologically responsive, with circularity embedded from design through to operation and end-of-life.

### 3. Conclusions and recommendations

The Ten Questions (Fig. 1) framework demonstrates that circularity in the built environment is not a single technical fix but a systemic transition that unfolds across concepts, practices, and measurement. By structuring the literature and emerging practices into ten questions about 1) the foundational framework, 2) strategies in practice, and 3) evaluation and outlook. The paper thereby exposes critical gaps between ambition and implementation, and between implementation and robust evidence.

#### 3.1. Questions 1,3 and 4: foundational framework

The answers to Questions 1, 3 and 4 show that conceptual clarity has improved, but fragmentation remains a defining feature of the field. Definitions of circularity, CE, circular design and circular urbanism converge around value retention, regenerative cycles and system resilience, yet frameworks tend to be partial environmental and technical dimensions are well developed, while social and economic dimensions are still underrepresented. The extension of Brand's shearing layers to neighbourhood scale and the emphasis on the R-ladder hierarchy offer an important multiscale structure, but operational guidance on how to navigate trade-offs between scales, regions and policy regimes is still limited.

These findings imply that circularity is at risk of becoming an umbrella label that obscures normative choices (for instance, sufficiency versus efficiency, and local versus global impacts). A key contribution of Questions 1, 3 and 4 are, therefore, to make these assumptions explicit and to argue for neighbourhoods as a productive meso-scale where

technological, social and institutional experiments can be aligned.

### 3.2. Recommendations

- Develop integrative conceptual frameworks that explicitly connect material, social and organisational circularity, and clearly distinguish between value preservation of materials and of functions (such as, housing, care, mobility).
- Promote (the use of) interdisciplinary standards and glossaries (building on ISO 59,004) that are co-produced by engineers, planners, social scientists and policy makers, to reduce semantic fragmentation.
- Use the neighbourhood scale as a reference level for linking interventions on the scale of components, buildings and cities, and for embedding circularity in everyday practices.

### 3.3. Questions 2 and 5 to 8: strategies in practice

These questions highlighted that economic, social, environmental and technological strategies are proliferating, but their implementation is uneven and often experimental. Economic instruments such as revolving funds, circular business models and CESCO-type entities show that value can be retained across multiple life cycles, yet they currently rely on niche financial expertise and are rarely integrated into mainstream construction and infrastructure programmes. Social strategies commoning, co-design, and social CE initiatives demonstrate that circularity can support inclusion, place attachment and community resilience, but they remain underrecognised in dominant policy and assessment frameworks.

Environmental strategies confirm that prioritising high-order R-ladder actions (Refuse, Reduce, Rethink, Reuse) yields the largest environmental benefits, especially when renovation and adaptive reuse avoid demolition and new construction. At the same time, examples such as the concrete paradox show that poorly designed recycling strategies can increase embodied emissions, underlining the need for life-cycle and sufficiency perspectives. Technological strategies BIM, digital twins, material passports, urban mining platforms are powerful enablers but depend on data quality, governance and clear information requirements. Without these, they risk becoming costly administrative burdens rather than catalysts of circularity.

### 3.4. Recommendations

Scale up proven economic instruments (revolving funds, PaaS, CESCOs) through alignment with public procurement, social housing programmes and green finance, explicitly accounting for distributional effects.

Systematically integrate social circular strategies, participatory planning, circular commoning, heritage-based reuse into urban regeneration and housing policies, treating them as core rather than peripheral components.

Prioritise high-order strategies (sufficiency, adaptive reuse, design for longevity) over end-of-pipe recycling, and explicitly analyse rebound effects in material, energy and land use.

Co-design digital tools with their intended users; define who needs which information, for what decision, before investing in passports, logbooks or twins, and ensure that data governance and maintenance responsibilities are clear.

### 3.5. Questions 9 and 10: evaluation and outlook

These questions showed that assessment and future trends are both the glue and the bottleneck of circularity. The current indicator landscape is fragmented, heavily material-centric and dominated by environmental metrics, with economic, social and governance dimensions underdeveloped. Existing frameworks often aggregate data bottom-up

from materials to buildings and cities but struggle to capture systemic dynamics such as spatial consumption, vacancy or housing inequality. Emerging top-down approaches (for instance, need satisfier systems) demonstrate how circularity and basic human needs can be evaluated jointly but remain largely experimental.

Looking ahead, data-driven approaches, CircularBIM, AI and digital twins offer opportunities to link design decisions, material flows and performance indicators in near real time. Bio-based and low-carbon materials, regenerative landscapes and green blue infrastructure can reinforce circular strategies, provided that local ecological limits are respected. Yet the paper also highlights that technological optimism must be tempered: digitalisation does not automatically solve data gaps, and circularity cannot be reduced to optimising existing linear demand.

### 3.6. Recommendations

- Move from indicator proliferation to consolidation by building modular, user-centred assessment frameworks that: (1) integrate environmental, economic, social, technical and governance dimensions; (2) distinguish between material and functional circularity; and (3) are explicitly tailored to decision contexts (design, policy, investment, community action).
- Combine bottom-up and top-down monitoring: couple material-flow and LCA-based indicators with metrics on land take, living space per capita, accessibility and affordability, so that circularity is evaluated against planetary boundaries and social foundations.
- Use urban living labs and neighbourhood-scale pilots as test beds where assessment methods, digital tools and business models are co-developed, iteratively refined in the local context and transparently reported.
- Embed circularity and systems thinking in education and professional training across disciplines, so that future practitioners can navigate the interdependencies highlighted in all three clusters.

Overall, the Ten Questions paper shows that advancing circularity in the built environment requires simultaneous progress in conceptual alignment (Question 1, Question 3 and Question 4), robust and just implementation (Question 2, Question 5, Question 6, Question 7 and Question 8), and meaningful evaluation and learning (Question 9 and Question 10). Only by treating these questions as interdependent rather than sequential can circularity become a transformative pathway rather than a new label on business as usual.

### CRedit authorship contribution statement

**N. Cihan Kayaçetin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Rengin Aslanoglu:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Chiara Piccardo:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Yasemin Afacan:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Gabriele Masera:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Formal analysis. **Qiuxian Li:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Carlo Andrea Biraghi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Francesco Pittau:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Dirk Saelens:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Veronica Soebarto:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Jian Zuo:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Ruidong Chang:** Writing – review & editing, Writing – original draft,

Investigation, Formal analysis. **Hanne Vrebo**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Karel Van Acker**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Rizal Sebastian**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Jeroen Dikken**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Loredana Ivan**: Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Luc Alaerts**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Duygu Aral**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Liliya Terzieva**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Joost van Hoof**: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Nuri Cihan Kayaçetin** is an assistant professor at Bilkent University, Department of Interior Architecture and Environmental Design. He conducted his PhD on life cycle impact assessment of mass-housing projects. His current research areas are integrated sustainable design, energy efficiency, circular and bio-based construction, and socio-ecological life cycle assessment of the built environment. He is leading multiple research projects and is the main coordinator of the DUT2023 Urban-CoLLaR project.

**Rengin Aslanoglu** is an assistant professor in the Department of Systems Research at Wrocław University of Environmental and Life Sciences, Poland. Her works focus on the domains of socio-environmental systems, including adaptation of urban space to climate change, nature-based solutions, ageing society, and visual perception of the built environment. She has wide scientific cooperation in projects at the international level. She is a Management Committee Member in COST Action: Building Opportunities for Participation and Accessibility through Lifelong Community Mobility.

**Chiara Piccardo** is an assistant professor in the Department of Civil Engineering at KU Leuven, Campus Ghent, Belgium. She is a member of the research group Building Physics and Sustainable Design, where she currently leads research on circular and low-carbon construction technologies through a holistic approach, supported by Life Cycle Assessment methods, in the context of building and urban regeneration. She is the principal investigator of several research projects at the regional and international levels.

**Yasemin Afacan** is a full professor in the Departments of Neuroscience and Interior Architecture and Environmental Design at Bilkent University. She is the department chair of Interior Architecture and dean of the Faculty of Art, Design and Architecture. She has won the Young Scientist Award from the Science Academy of Turkey (BAGEP-2017) and the Outstanding Young Scientist Award from the Turkish Academy of Sciences (GEBİP-2018). Her research interest has been focused on environmental gerontology and sustainable architecture. She has also been a member of the International Society of Gerontechnology since 2014.

**Gabriele Masera** is a full professor of Building Technology at Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering. Holding a PhD on the topic of energy-efficient homes, he currently conducts research about innovative construction technologies for sustainable, low-carbon buildings and enabling digital tools for multi-disciplinary design. He worked on several research projects at the national and European levels on these topics.

**Qiuxian Li** is a researcher in the Building Physics and Sustainable Design research group at the Department of Civil Engineering, KU Leuven, Belgium. She holds a Master's degree in Integrated Building Systems and conducts research on the sustainable built environment, with a focus on energy-efficient building renovations at various spatial scales, life cycle assessment, energy communities, renewable energy integration, and circular resource flows. She is also an active member of the IEA EBC Annex 89 project - Ways to Implement Net-Zero Whole Life Carbon Buildings.

**Carlo Andrea Biraghi** is a researcher with a multi-disciplinary attitude and a hybrid background (architecture and geomatics) at Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering. After a PhD in urban optimisation and a PostDoc on Citizen Science, he now focuses on GIS-based urban analytics and

the development of maps, metrics, and algorithms to support decision-making for sustainable urban development. He's also a computational designer and, together with a mathematician, he started and runs the Applied Mathematics for Parametric Architecture course at Politecnico di Milano.

**Dirk Saelens** is a Full Professor in "Energy in Buildings" and is head of the Building Physics and Sustainable Design Section within KU Leuven's Department of Civil Engineering. At EnergyVille, he co-coordinates the Buildings and Districts Research Line and is a member of the Operational Steering Committee. His expertise is in energy and comfort assessment in buildings and urban environments, supported by simulations and field measurements. He received his MSc in Architectural Engineering from KU Leuven, Belgium, in 1997, followed by a PhD in Civil Engineering in 2002. His doctoral research focused on ventilated double-skin facades within the Building Physics Section. In 2002, he received a Postdoctoral Fellowship from the Flemish Agency for Innovation by Science and Technology (IWT).

**Veronica Soebarto** is a Professor in the School of Architecture and Built Environment, Adelaide University. Her background is architecture and architectural science with expertise in sustainable architecture, environmental performance assessment of the built environment, building energy use and monitoring. She also conducts research relating to older people and the built environment, both in relation to housing and green spaces, and how the built environment impacts the well-being of older people.

**Jian Zuo** is a Professor of sustainable construction, School of Civil Engineering and Construction Management, Adelaide University. He is the chief investigator of several projects commissioned and funded by governments in China and Australia such as the Australian Research Council and Australian Housing and Urban Research Institute. His main research interest relates to achieving good health, safety and sustainability at both building and urban levels. His other main research interests include environmental management and monitoring, construction and demolition waste management, health and well-being of construction workers, smart construction, productivity of building users, indoor environmental quality in buildings, and the mechanisms for generation and mitigation of dust across the life-cycle of buildings.

**Ruidong Chang** is an Associate Professor in the School of Civil Engineering and Construction Management, Adelaide University. He has a PhD in sustainable construction and studies environmental monitoring and modelling of construction. Chang is also a co-author of the Springer book, *Circular Economy for Buildings and Infrastructure- Principles, Practices and Future Directions*.

**Hanne Vrebois** is an interdisciplinary postdoctoral researcher at the Team of Sustainability Assessments of Materials and Circular Economy (SAM), Department of Material Engineering, KU Leuven. She combines a background in architectural engineering, urban ecological planning, and international urban development with a PhD in social sciences, focusing on socio-spatial methods in neighbourhood development. Her current research is on the dynamics of circular cities and specifically the circular construction ecosystem.

**Karel Van Acker** is a full professor in Circular Economy with a joint mandate at the Department of Materials Engineering and at the Centre for Economics and Corporate Sustainability. His research is on developing strategies to realise the circular economy (CE) and on sustainability assessments of these CE strategies, including, amongst others, recycling, materials substitution, sharing economy. He has built up experience in lateral and interdisciplinary research, and in research close to the industry and society in many international collaborations. He holds a PhD in Materials Science and has been working in the industry, at VITO, and as an industrial valorisation manager. He has been for 12 years coordinator of the KU Leuven Materials Research Centre (>500 researchers) and is now head of the division SeMPEr. He also leads the policy research centre "Circular economy"

for the Flemish government and is a member of the steering committee of Circular Flanders. He is currently the chairman of the Sustainability Council of KU Leuven.

**Rizal Sebastian** is a Chair Professor of Future Urban Systems at The Hague University of Applied Sciences and a Senior Advisor on Digitalisation for Sustainable Built Environment at The Netherlands Enterprise Agency (RVO). He also supports the European Commission and the Dutch Research Council as a scientific expert. He has a PhD in management of collaborative urban design, an MSc in construction management, and a BSc in architecture.

**Jeroen Dikken** is an associate professor with the Research Group of Urban Ageing and a principal lecturer of nursing with The Hague University of Applied Sciences in the Netherlands. He is a Registered Nurse (RN), holds a Master's degree in both Health Sciences as well as Gerontology, and a doctoral degree in Nursing Science.

**Loredana Ivan** is a Professor at the National University of Political Studies and Public Administration, Communication Department, Bucharest, Romania. She has a PhD in Sociology and a post-doctorate in Social Psychology. Her areas of interest include ageing and digital communication; sociology, participatory approaches and methodology.

**Luc Alaerts** is the Centre Manager of the Policy Research Centre Circular Economy (CE Center), funded by the Flemish government since the beginning of 2017. He is connected to KU Leuven as a senior researcher leading research on the challenges in monitoring sustainability transitions with an emphasis on circular economy and data. He is a team member of the operational team of Circular Flanders, a public-private cooperation between the Flemish government and diverse actors involved in the circular economy transition. He has managed the data and knowledge programme of Leuven 2030, a public-private urban initiative, between 2019 and 2022. Before, he worked in research and development in the chemical sector.

**Duygu Aral** is a researcher at Izmir Institute of Technology, Department of Architecture, and a professional architect leading sustainability in public buildings and urban design projects, with a background in building performance analysis and a master's degree in environmental life cycle impact assessment. Her PhD research focuses on circular economy assessment and implementation in the built environment, with emphasis on urban regeneration, a life cycle approach, and the use of digital enablers to support the transition toward climate-neutral and resource-efficient buildings and urban environment.

**Liliya Terzieva** is Professor Designing Value Networks at the Hague University of Applied Sciences, the Netherlands. Her PhD is in the field of Economic and Organisational Sciences of Leisure and Tourism. Within her career pathway of around 20 years of international experience (Bulgaria, China, France, Malta, Vietnam, the Netherlands, etc.) she worked in non-governmental, public, as well as educational and business organisations, related to the domains of (among others): entrepreneurial learning and mindset, value generation, leadership, tourism, leisure, strategic and human-centred design. Her research interest is in the impact and value that diverse multi-stakeholder collaborative interactions lead to, and the role design plays in fostering and nurturing the above.

**Joost van Hoof** is a full professor of Urban Ageing with the Centre of Expertise Governance of Urban Transitions of The Hague University of Applied Sciences in the Netherlands. He has a background in building physics and services and holds both a DSc (habilitation) and a PhD degree in the design of housing facilities for older people. He is also affiliated with the Wrocław University of Environmental and Life Sciences in Poland as a full professor of social sciences in the discipline of socio-economic geography and spatial management.