

Luís Bragança · Viorel Ungureanu
Katerina Tsikaloudaki
Adriana Salles Editors

Circular Built Environment

From Conceptual Design
to Digital Implementation



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Implementation

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Preface

The transition towards a circular built environment has become one of the defining challenges facing the construction sector. Achieving this transition requires far more than the adoption of new materials or isolated technical solutions. It calls for a fundamental rethinking of how buildings are conceived, designed, delivered, operated, adapted, and ultimately transformed throughout their entire lifecycle. Such a transformation can only be achieved through close collaboration between researchers, designers, engineers, policymakers, and industry.

This book is the outcome of collaborative research within the COST Action CA21103 CircularB “Implementation of Circular Economy in the Built Environment.” CircularB brings together researchers, practitioners, and experts from across Europe to develop shared knowledge on how circular economy principles can be applied systematically to buildings and construction.

The urgency of this transition towards a circular built environment is evident. The construction sector accounts for more than one-third of global waste and one-third of greenhouse gas emissions. At the same time, the building stock represents a repository of valuable materials, components, and embodied carbon and labour that, with better design and management, could be recovered and reused.

This book aims to advance an architectural and engineering approach that equips designers and construction teams with targeted solutions to incorporate circularity principles across multiple lifecycle stages of both new and existing building stock. It examines how circularity can be embedded into building practice, not through isolated technical fixes, but through a systematic approach that connects design thinking, decision-making frameworks, and digital tools across the entire building lifecycle.

The volume is organised around three complementary perspectives:

- Chapter “[Design Strategies and Solutions for Circularity Across the Building Lifecycle](#)” presents evidence of successful implementations. Through analysis of international case studies and built projects, it demonstrates that circular design strategies are systematic and transferable. Rather than experimental exceptions, the analysis shows patterns that recur across different building types, geographies,

and climates, providing a necessary bridge between outstanding projects and real-world buildings;

- Chapter “[Embedding Circularity in Conceptual Building Design: A Functional Framework for Data-Driven Decisions During the Earliest Architectural Design Stages](#)” focuses on the earliest phases of the design process, where the greatest opportunities to influence circular performance exist. It provides frameworks and guidance for practitioners working in the earliest design stages, where decisions about architectural forms, materials, structural systems, adaptability, and disassembly have the greatest impact. This chapter operationalises the patterns identified in Chapter “[Design Strategies and Solutions for Circularity Across the Building Lifecycle](#)” into actionable decision support;
- Chapter “[BIM for Circular Built Environments: Data, Indicators, and Implementation Frameworks](#)” examines the role of digital technologies in enabling circular construction. It presents findings from practitioners across Europe and assesses the readiness of Building Information Modelling (BIM), data standards, and organisational capacity to enable circular practice. It also proposes a conceptual BIM enabled circularity simulation workflow for how simulation and scenario testing could improve circular design choices.

Together, these three chapters show a clear path: from validated evidence to practical guidance to an honest assessment of the digital tools and organisational structures needed to make circularity the norm rather than the exception.

The book speaks to three audiences:

- For researchers, it provides a synthesis of existing knowledge, analyses of real projects, and practitioner data on barriers and opportunities. This work can guide future research into circular building practice;
- For practitioners (architects, engineers, facility managers), it offers practical frameworks and transferable approaches that can be applied immediately in early design stages;
- For policymakers and public authorities, it identifies the specific gaps between aspiration and practice, and points to regulatory, standardisation, and capacity building actions that could accelerate the transition.

We recognise that this book will not solve all the challenges. Circular economy principles in buildings require changes to business models, supply chains, and governance structures that extend beyond design and digital tools. By integrating evidence from practice, structured design methodologies, and digital perspectives, this book aims to contribute to a more informed, practical, and scalable implementation of circular economy principles within the built environment.

We hope that the ideas presented in this volume will stimulate further research, foster interdisciplinary collaboration, and support practitioners in transforming circular economy from an emerging aspiration into standard practice for the buildings of tomorrow.

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Contents

Design Strategies and Solutions for Circularity Across the Building Lifecycle	1
Adriana Salles, Mirjana Miletic, Ivan Lukačević, Raluca Buzatu, Alicia Zaragoza-Benzal, Philip Griffiths, Hafize Büşra Bostancı, Vlatka Rajcic, Amaryllis Iliadi-Manou, Kleoni Ntouvli, Joana Maia, Michaela Gkantou, Daniel Ferrández, Rocío Pastor Lamberto, Viorel Ungureanu, and Luís Bragança	
Embedding Circularity in Conceptual Building Design: A Functional Framework for Data-Driven Decisions during the Earliest Architectural Design Stages	59
Maria Beatrice Andreucci, Marco Delli Paoli, Vanessa Tavares, Ivan Lukačević, Genesis Camila Cervantes Puma, and Viorel Ungureanu	
BIM for Circular Built Environments: Data, Indicators, and Implementation Frameworks	101
Vanessa Tavares, Ana Rute Costa, Genesis Camila Cervantes Puma, Hafize Büşra Bostancı, Ihab Al-Qazzaz, Joana Maia, José Gonçalves, Kenza Belkhiri, Marco Delli Paoli, Marta Maria Sesana, Mehmet Emiroglu, Milena Rajić, Moses Itanola, Pelin Sertyesilisik, Sefa Guntepe, and Viorel Ungureanu	

Design Strategies and Solutions for Circularity Across the Building Lifecycle



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Abstract The built environment is one of the most resource-intensive sectors globally, yet progress towards circularity remains constrained by fragmented implementation, limited lifecycle integration, and insufficient governance frameworks. This chapter examines design strategies and solutions for circularity across the entire

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building lifecycle, drawing on a systematic comparative analysis of 45 international case studies. Using a matrix-based analytical framework, circular strategies are mapped across six dimensions: design for circularity, materials and products, construction practices, building operations and maintenance, end-of-life and deconstruction, and business models and policy support, and aligned with the 10R circular economy hierarchy. The findings reveal a clear concentration of circular maturity at the design and material levels, with strategies such as adaptability, flexibility, design for disassembly, and low-carbon material selection widely present across the dataset. In contrast, operational circularity, advanced end-of-life planning, digital traceability, and enabling business models remain significantly underdeveloped in mainstream practice. Cross-case analysis identifies five building clusters and six transferable circular design patterns, ranging from reuse-first approaches and design for disassembly as a system, to procurement-driven circularity and use-based strategies. The evidence consistently demonstrates that high circular performance is achieved through integrated, multi-lifecycle-stage approaches rather than isolated interventions. Policy and practice recommendations are derived directly from the pattern analysis, targeting design regulation, public procurement, operational management, and end-of-life governance. The chapter concludes that scaling circularity requires moving beyond project-based experimentation toward systemic frameworks that connect design intent, supply chain mechanisms, and institutional conditions across the full building lifecycle.

Keywords Circular economy · Design for circularity · Design for disassembly · Adaptive reuse · Material passports · 10R framework

1 Introduction

The built environment is a critical sector for implementing circular economy principles, given its high material intensity, long asset lifetimes, and systemic influence on resource consumption patterns [1, 2]. Buildings account for a substantial share of global material extraction and embodied greenhouse gas emissions, making lifecycle-oriented approaches essential for reducing environmental impacts at scale [3].

The construction sector is one of Europe's most resource-intensive industries, responsible for approximately 35% of total waste generation [4]. Despite the introduction of policy instruments such as the European Green Deal and the Renovation Wave, progress towards circularity remains slow: the EU circularity rate increased only marginally from 10.8% in 2010 to 11.7% in 2021, still far below the 24.3%

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target for 2030 [5]. At the same time, the sector continues to consume large quantities of virgin materials and generate 25–30% of Europe's annual waste [6]. This combination of low circularity performance and high material dependency underscores the need for an accelerated transition towards circular design strategies that reduce embodied carbon, minimise waste, and extend building lifecycles.

The urgency of a systemic shift is highlighted by recent data indicating that the global economy is currently only 7.2% circular, a decrease from 9.1% in 2018 [7]. This decline is particularly alarming for the built environment, as key construction materials—specifically steel, cement, aluminium, and plastics—are responsible for nearly 20% of global carbon emissions [3]. Shifting toward a circular model provides a “win-win” benefit, enabling the optimisation of decarbonisation while fostering economic development. Within this framework, waste is no longer viewed as an inevitable byproduct but rather as a “design error” that can be eliminated through superior planning and material selection [8].

To fully appreciate the urgency of transitioning to circularity, it is essential to recognise the environmental pressures associated with material extraction and construction. Conventional construction practices drive substantial carbon emissions from extraction, processing, manufacturing, and transport. Global warming trends intensify these concerns: modern lifestyles contribute to excessive energy consumption in urban areas, with buildings playing a central role [9]. According to the Intergovernmental Panel on Climate Change (IPCC), 33% of global energy-related GHG emissions are attributable to building use [10], and these have continued to rise since 2019 [11]. The application of measures such as the Energy Performance of Buildings Directive will see further reductions in operational energy, but this exposes the embodied carbon from construction and ongoing maintenance, which is expected to rise to 50% of the total embodied carbon over the lifecycle by 2050 [12], consuming a large part of the remaining carbon budget.

Despite increasing awareness of these challenges, construction practices remain largely rooted in linear models in which buildings are conceived as static end products, and demolition is treated as the default end-of-life scenario. Circular economy frameworks challenge this paradigm by prioritising value retention through strategies such as reuse, repair, refurbishment, remanufacturing, and recycling, while also emphasising higher-order strategies such as refusal and rethinking of unnecessary construction [13]. Within the built environment, the effectiveness of these strategies depends strongly on early-stage design decisions, which shape buildings' capacity to adapt, be reconfigured, or be disassembled over time [14].

Achieving sustainability in the built environment requires a profound and systematic reduction in both greenhouse gas emissions and primary resource consumption. Studies show that increasing recycled content in construction materials can reduce energy use by up to 85% and CO₂ emissions by up to 90% [15]. One of the most effective pathways to this objective is the direct reuse of building components, which preserves structural integrity and extends material lifecycles. Empirical research demonstrates that component-level reuse can reduce life-cycle carbon emissions by approximately 38%, while reclaimed elements such as windows, façade cladding, and structural steel can achieve carbon savings approaching 99% [16]. Circularity

is therefore approached as a systemic design methodology spanning conceptualisation, detailing, procurement, construction, in-use adaptation, and end-of-life scenarios. Key enablers include modular and interoperable components, reversible joints, material passports, and adaptive spatial planning that maintains potential for future reconfiguration.

Circularity in the built environment extends beyond design to encompass material selection, construction practices, building operation and maintenance, end-of-life planning, and enabling business models. Material-related strategies include the use of recyclable, bio-based, low-carbon, and non-hazardous materials, as well as reducing unnecessary components and avoiding composite assemblies that obstruct reuse [17, 18]. Construction-phase strategies such as prefabrication, lean construction, local sourcing, and environmentally responsible waste management influence both construction efficiency and the feasibility of future disassembly and reuse [14].

Implementing these principles requires a fundamental reclassification of materials into “technical” and “biological” cycles [1]. Technical materials, such as metals and polymers, are designed for continuous reuse and recovery, while biological nutrients are intended to return safely to the biosphere [1]. To operationalise this, the 10R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) provides a nuanced hierarchy for resource value retention [13]. This hierarchy prioritises “short loops,” such as reuse and repair, over “long loops,” like recycling and energy recovery, to ensure that components are maintained at their highest utility and value at all times [13, 19]. Design for circularity, therefore, emerges as a key leverage point for enabling circular outcomes. Strategies such as design for adaptability and flexibility, design for longevity and increased utilisation, design for disassembly, and design for reversible solutions enable buildings to accommodate changing functional and technical requirements while preserving material value [20]. The use of digital tools, particularly Building Information Modelling (BIM), further supports these strategies by enabling coordination, modularisation, and long-term documentation of building systems and components [19].

Structural systems play a decisive role in determining the circularity potential of buildings, as they represent one of the largest contributors to material consumption and embodied carbon. Conventional structural design practices typically optimise performance for a single service life and may rely on irreversible joints, composite assemblies, and demolition-oriented end-of-life scenarios. These approaches significantly limit the direct reuse of structural components, which are materials with high technical durability and strong reuse potential, resulting instead in downcycling or disposal and the loss of substantial material value and carbon investment. From a circular economy perspective, component-level reuse is one of the most effective short-loop strategies, delivering far greater environmental benefits than recycling alone. Numerous studies show that reusing structural steel elements can reduce life-cycle carbon emissions by up to 60% compared with structures made from new steel elements. While recycling aluminium can reduce energy use and greenhouse-gas emissions by around 95% relative to primary aluminium production. Realising these benefits requires circularity to be embedded at the design stage through reversible

connections, adaptable and non-composite structural layouts, and design strategies that anticipate future disassembly, reconfiguration, and long-term material recovery.

Delivering circular outcomes requires combining low-carbon, recyclable, and durable materials with designs for non-destructive disassembly. A Life Cycle Assessment (LCA) should prioritise materials that reduce embodied carbon, maintain repairability, and preserve component value for subsequent life cycles. Designing interfaces to allow intact dismantling is essential to close technical loops and avoid downcycling, thereby supporting regenerative material flows. Operational strategies, including predictive maintenance and monitoring systems for energy and water efficiency, play a critical role in extending building service life, while end-of-life strategies such as selective deconstruction, material recovery, reuse networks, and reverse logistics determine whether materials retain value beyond a single use cycle [20]. The implementation of these strategies is strongly shaped by business models and policy frameworks, including product-as-a-service models, extended producer responsibility schemes, and supportive regulatory environments, which remain underdeveloped in mainstream building practice [7, 21].

Construction products are underpinned by robust standards for dimensional precision, quality, and EU regulatory compliance, including Regulation (EU) No 305/2011—Construction Products Regulation [22]. Factory-controlled manufacturing improves quality consistency and supports low-impact design. However, current applications remain concentrated in new construction and façade retrofits, with limited uptake in adaptable housing or modular expansion of existing buildings. While reused materials are increasingly integrated into retrofit projects, their incorporation into modular, plug-and-play components remains limited.

Within this context, this chapter analyses design strategies and solutions for circularity across the entire building lifecycle. Together with the following chapters (Chaps. 2 and 3), circular building design strategies and best practices are examined by establishing what works with evidence from built cases (Chapter 1), translating this into when and how to decide through early-stage guidelines (Chapter 2), and investigating whether digital infrastructure exists to operationalise these decisions at scale (Chapter 3). Based on a systematic analysis of 45 international case studies, this chapter adopts a matrix-based approach that maps circular strategies across six lifecycle dimensions— design, materials, construction, operation, end-of-life, and business models—while aligning them with the 10R circular economy framework. The emphasis is on design for disassembly, reversibility, adaptability, and spatial transformability, ensuring that buildings can be adjusted, upgraded, or dismantled with minimal waste and maximum value retention. In parallel, the chapter addresses strategies for the circular re-design of existing buildings, extending functionality and usability to increase overall circularity within the current building stock.

The analysis of 45 case studies shows that circular principles are well-established in exemplary and iconic projects, particularly through adaptability, reuse, and design for disassembly. Yet, everyday buildings still underutilise these proven strategies. Bridging the gap demands a shift from isolated material fixes to integrated, lifecycle-based circular design, supported by enabling business models, policy frameworks,

and stakeholder capacity building. This synthesis provides a foundation for translating shining examples into scalable, mainstream practices by identifying transferable strategies that support the transition from pioneering circular projects to everyday building practice.

2 Materials and Methods

The study adopts a qualitative, comparative case study methodology, which is particularly suited to investigating complex and context-dependent phenomena such as circular design implementation in the built environment [23, 24]. Case-based approaches are widely used in circular construction research to explore how design strategies, material choices, and organisational conditions interact across different project contexts [8, 14].

The comparative approach is grounded in “replication logic” rather than sampling logic, treating each case study as an independent experiment that either confirms a pattern (literal replication) or offers contrasting results for predictable reasons (theoretical replication). This allows the research to move beyond descriptive summaries toward an analytical generalisation, where findings from iconic projects can be tested for their scalability to everyday building practices [24]. By focusing on these “critical cases,” the methodology activates more basic mechanisms and actors, providing richer information on the deeper causes of circular success or failure [23].

The research was conducted in two main phases:

1. systematic collection and documentation of 45 international case studies, and
2. cross-case analysis using a structured strategy matrix.

2.1 Case Study Collection and Documentation

A comprehensive survey identified 45 circular construction projects worldwide. The selection process was based on a targeted review of academic literature, professional reports, project databases, and exemplary built projects frequently cited in circular economy and sustainable construction discourse.

Case studies were selected using purposive sampling to capture a broad range of building types, scales, and geographical contexts, as well as varying levels of circular ambition. Projects were included if they explicitly addressed one or more circular strategies across the building lifecycle, such as adaptability, reuse, disassembly, modularity, lifecycle-based material management, or innovative business models [19, 20].

Each case study was documented using a standardised template, presented in Appendix 01, that captured project metadata, circular strategies across lifecycle

stages, structural and construction systems, material choices, adaptability and disassembly mechanisms, the use of digital tools, stakeholder roles, and reported challenges. Data were collected from peer-reviewed literature, EU research project reports, professional publications, and publicly available project documentation. Where possible, information was triangulated across multiple sources to enhance reliability and validity [24]. The use of a structured template ensures consistency, comparability, and transparency across cases. The survey aimed to capture both iconic reference projects and more replicable examples, allowing insights into best practices as well as implementation challenges. For each case, qualitative and quantitative data were collected, including design strategies, structural systems, material choices, adaptability mechanisms, and end-of-life considerations.

2.2 *Strategy Matrix and Analytical Framework*

The documented case studies were analysed using a strategy matrix that served as the central analytical tool of the research. The matrix enabled the comparison of circular solutions across lifecycle stages, design, construction, use, adaptation, and disassembly, allowing recurrent patterns, gaps, and transferable strategies to be identified. This methodological framework supports the identification of scalable design strategies that bridge the gap between iconic circular projects and everyday building practice.

In the matrix, each row represents an individual case study ($N = 45$), while each column corresponds to a specific circular strategy grouped into six lifecycle-related dimensions:

- (a) design for circularity,
- (b) materials and products,
- (c) construction practices,
- (d) building operations and maintenance,
- (e) end-of-life and deconstruction, and
- (f) business models and policy support.

In addition, all case studies were mapped against the 10R circular economy framework (R0–R9), enabling alignment between project-level strategies and broader circular economy hierarchies [13]. The presence or absence of each strategy was qualitatively coded, allowing systematic cross-case comparison and identification of recurring patterns and gaps. Figure 1 represents the matrix proposed.

The matrix enabled a systematic cross-case comparison of the selected case studies, allowing the identification of recurring patterns and structural differences in the application of circular strategies across the building lifecycle. Through this comparative approach, it was possible to distinguish which circular strategies are most commonly implemented in current practice and which remain rare, experimental, or limited to a few pioneering projects. The analysis reveals a clear concentration of efforts on material-related and design-oriented strategies, while more

Case Study N.	Design for Circularity (a)						Materials Products (b)					Construction Practices (c)					Building Operations & Maintenance (d)					End-of-Life & Deconstruction (e)					Business Models & Policy Support (f)					Circular Strategies – 10R Framework (g)													
	1	2	3	4	5	6	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9						
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Fig. 1 The matrix

advanced operational, end-of-life, and business-model approaches are applied less frequently and often on a project-specific basis.

In addition to identifying the relative prevalence of individual strategies, the matrix enabled observation of interdependencies among different circular measures. Certain strategies consistently appear in combination, suggesting that their implementation relies on supporting technical or organisational conditions. For example, the use of material passports and long-term material traceability is closely linked to the availability of digital design and information management tools, such as BIM-based data environments. Similarly, design for disassembly and selective deconstruction are more likely to be present in projects that also apply modular construction systems and prefabrication.

Overall, the matrix supports understanding of circularity not as a set of isolated interventions, but as an interconnected system of strategies whose effectiveness depends on coordinated implementation across multiple lifecycle stages. This insight is particularly relevant for this study, as it highlights the importance of integrated design approaches and enabling infrastructures in advancing circular construction from experimental applications toward more robust and scalable solutions.

3 Results & Discussion

The cross-case analysis of 45 international case studies reveals a clear concentration of circular economy strategies at the design and material levels of the building lifecycle (refer to Appendix 1). Design-related measures such as adaptability, flexibility, extended building lifespan, and design for disassembly are present in a significant share of the analysed projects, often supported by the use of digital design tools such as Building Information Modelling. In contrast, strategies that explicitly prioritise the refusal of new construction or the application of fully reversible design solutions appear only sporadically. Figure 2 indicates the applied strategies throughout the case studies.

Material-related strategies show the highest degree of consistency across the dataset. Most case studies include the use of recyclable, bio-based, low-carbon, or non-hazardous materials, as well as efforts to reduce unnecessary components and apply modular construction systems. However, advanced material management practices, including material passports and systematic data logging, are documented in only a limited number of cases, as indicated in Fig. 3.

Construction-phase strategies are moderately represented (see Fig. 4). Waste management measures and prefabrication appear more frequently, while lean construction approaches and smart construction technologies, such as robotics or additive manufacturing, are rarely reported.

Strategies related to building operation and maintenance are weakly represented overall, as indicated in Fig. 5. Although monitoring systems for energy and water efficiency are present in some projects, predictive maintenance, digital twins, and operational resource recovery systems are largely absent.

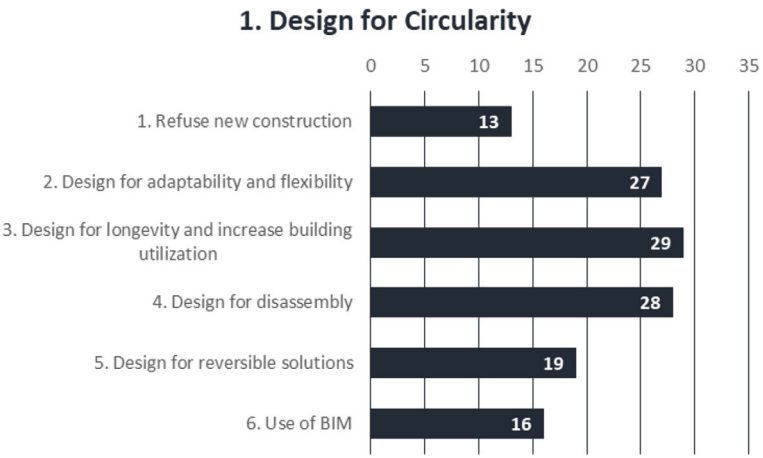


Fig. 2 Design for circularity strategies

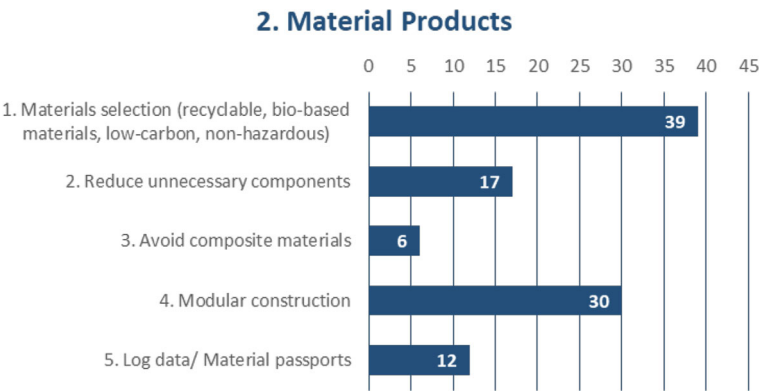


Fig. 3 Material-related strategies

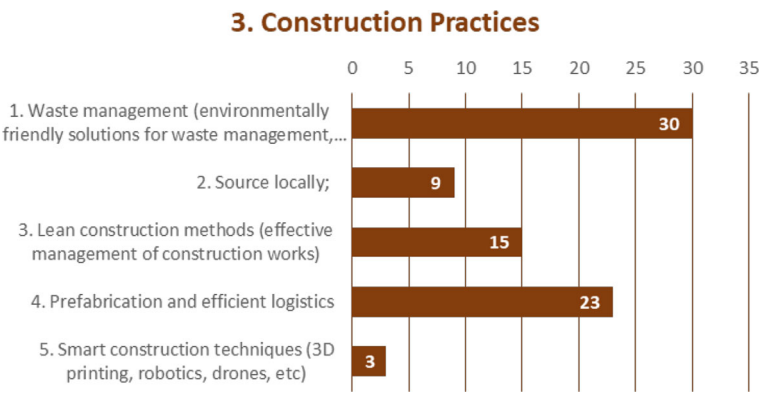


Fig. 4 Construction practices

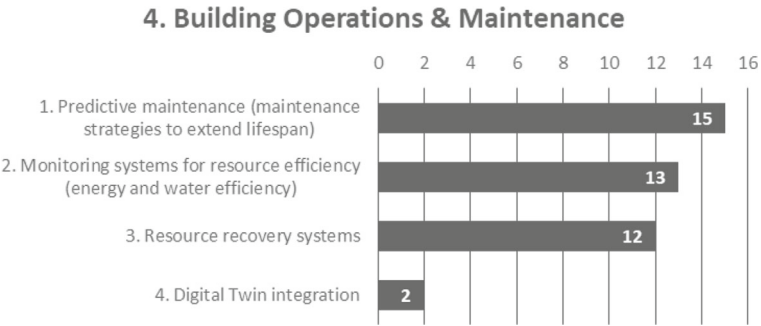


Fig. 5 Building operations & maintenance

End-of-life and deconstruction strategies are documented in a limited subset of cases, primarily in the form of selective deconstruction and material recovery. Reuse networks, urban mining practices, and reverse logistics systems are rarely identified, as illustrated by Fig. 6.

Business models and policy support mechanisms represent the least developed dimension, with only isolated references to product-as-a-service models, extended producer responsibility, or supportive regulatory frameworks (see Fig. 7).

When mapped against the 10R framework (see Fig. 8), the results indicate a strong emphasis on mid-level strategies such as reduce, reuse, and recycling, while higher-order strategies, including refusal and rethinking, as well as advanced remanufacturing and repurposing, remain marginal.

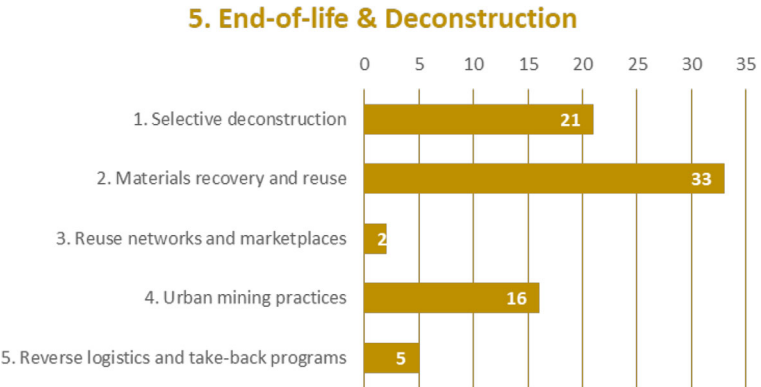


Fig. 6 End-of-life & deconstruction



Fig. 7 Business models & policy support

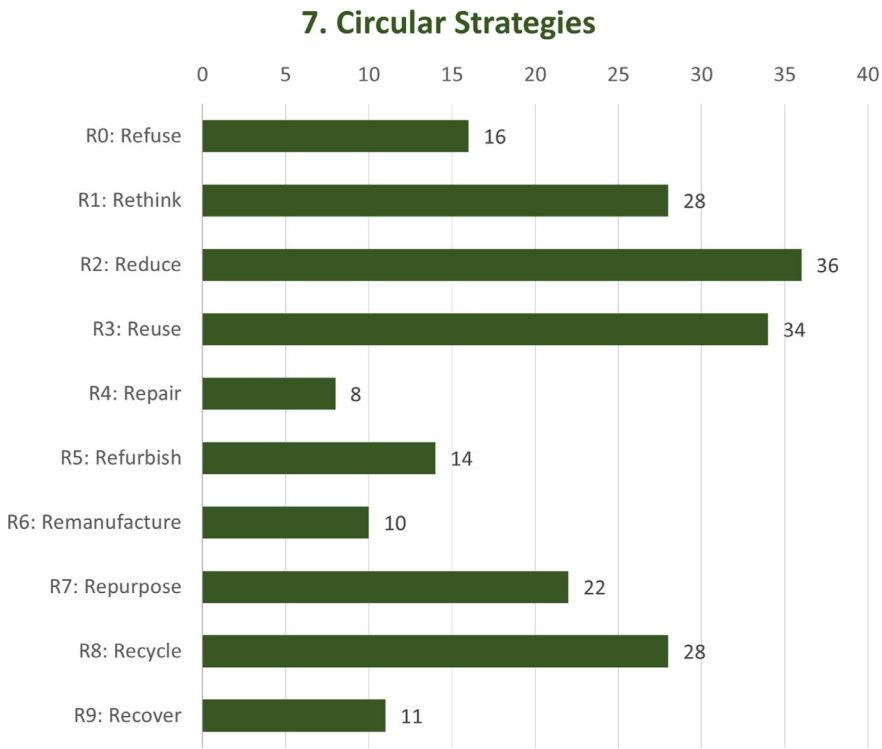


Fig. 8 Circular strategies

3.1 Most Common Circular Economy (CE) Strategies Identified

Analysis of the 45 case studies indicates that the most used methods for implementing Circular Economy in the built environment are those that emphasise the preservation value of existing resources, extend the building’s lifespan, and lower the need for

new construction. Overall, the results align with the R-strategy method hierarchy, which states strategies at the higher priority end, those that emphasise prevention, reuse, and life extension above recycling or recovery, are primarily responsible for achieving circularity.

Some of the most widely used circular economy strategies in the examined case studies are R3 (Reuse), R4 (Repair), and R5 (Refurbish). Particularly, they appear on existing structures and building components, such as in projects involving renovation, energy upgrading, and adaptive reuse. These projects demonstrate that using the existing building stock often provides greater environmental and functional value compared to demolition and reconstruction. The aim is to increase the value of existing structures, reduce waste generation, limit the extraction of new resources, and mitigate the environmental impacts of construction.

The strategies at the top of the R-strategy hierarchy dominate: R1 (Rethink), R2 (Reduce), R3 (Reuse), R4 (Repair) and R5 (Refurbish). However, strategies R6 (Remanufacture), R7 (Repurpose), R8 (Recycle) and R9 (Recover) appear less frequently. These strategies are applied when higher value options are no longer possible, as they often require a lot of process and energy. This pattern follows the circular economy hierarchy, where keeping the original function and value of materials is preferred over transforming materials or recovering energy.

Across the examined case studies, design for circularity appears as one of the most prominent circular economy strategies. This includes principles such as system flexibility, longer lifespans, reusability, adaptability, and ease of maintenance. Rather than limiting their focus only to material choices, many projects adopt design decisions that support future changes, and in this way, circular design ensures that buildings remain functional over time, thereby limiting the need for extensive renovations or complete replacement.

A commonly appearing strategy in the examined projects is designing buildings with a flexibility and adaptability concept. Many projects incorporate features that allow future expansion, reconfiguration, or changes in use without requiring major interventions. This design approach supports longer building lifespans and structures that can respond to shifting market conditions or user needs, thereby maximising their value. This way, buildings can change use and evolve over time, the need for unnecessary construction.

A strong emphasis is placed on material efficiency and low-carbon material choices across the case studies. Many projects enable the use of renewable, waste-derived, bio-based, or recycled materials. This helps reduce dependence on natural resources, limit their excessive use, and make use of the large waste streams generated by construction and demolition activities. Also, many of the projects adopt lean construction methods and more efficient structural design in order to minimise the overall material consumption.

Selective deconstruction involves disassembling components, separating hazardous elements, and sorting materials on-site so that valuable components can be reintegrated into supply chains or reused in future projects. This strategy not only retains the intrinsic value of building materials by allowing higher-grade recovery

and reuse of elements such as lumber, metals, and fixtures, but it also significantly reduces waste sent to landfill and encourages circular material flows.

Reducing superfluous components and simplifying construction systems are essential strategies for increasing circularity in the built environment as they improve material efficiency and durability. Simplified assemblies with standardised components could reduce the range and complexity of materials required. Thus, reducing waste generation and allowing for eventual design for disassembly and reuse of building elements, a major principle of circular construction.

Modular and prefabricated construction has emerged as a critical strategy for improving circularity in the built environment by connecting industrialised building processes with the circular economy's key concepts. Prefabrication is the process of manufacturing components or systems off-site and then assembling them on-site, resulting in controlled production conditions that significantly improve quality control and reduce material waste compared to conventional construction. However, findings reveal that limited case studies used these strategies.

Digitalisation, business models, and policy mechanisms could significantly improve circularity by providing traceability, reuse planning, lifetime analysis, and post-use material flows. However, case studies findings highlight that digitisation is currently underutilised relative to its potential: most implementations focus on design and construction efficiency, rather than incorporating circular lifecycle needs into digital systems. On the other hand, circular business models are recognised as essential drivers of industry transition, but practical adoption and supportive regulations are still lagging behind research interest.

Finally, maximising circularity in the construction industry involves tackling several lifecycle stages in an integrated manner, including design, construction, operation, maintenance, and end-of-life, rather than focusing on isolated phases.

3.2 Circular Economy Strategies Mapped to the Matrix (Evidence-Based)

The cross-case analysis of 45 international case studies reveals a highly uneven distribution of circular economy strategies across lifecycle stages (please refer to Appendix 2 for the case studies list). When mapped through the structured strategy matrix, a clear pattern emerges: circularity is most mature at the design and material levels, moderately represented during construction, and significantly weaker in operation, end-of-life systemisation, and enabling business models.

For example, strong design- and material-led circularity is evident in projects such as case CS11 (Circular Retrofit Lab), case CS12 (Stadskantoor building at Rotterdam's City Hall), case CS18 (CASA QUATTRO), case CS28 (Super Circular Estate–SUPERLOCAL) and case CS31 (ReCreate–H2020 Project), where adaptability, structural reuse, reversible detailing, or bio-based/low-carbon materials are

core project drivers. In contrast, comprehensive operational circularity and business-model innovation remain limited to a smaller subset of cases, such as case CS27 (Sloan Square House–reclaimed steel reuse workflow) and case CS45 (Reallabor Space Sharing), where digital coordination or systemic reuse logistics are addressed more explicitly.

Design-related measures such as adaptability, flexibility, extended building lifespan, and design for disassembly are present in a significant share of the analysed projects, often supported by the use of digital design tools such as Building Information Modelling. Clear examples include case CS11 (Circular Retrofit Lab), which tests dry and reversible envelope assemblies; case CS12 (Stadskantoor building at Rotterdam’s City Hall), where modular spatial planning enables functional transformation; case CS28 (Super Circular Estate–SUPERLOCAL), which embeds reuse-driven transformation logic; and case CS42 (Koodaaram Kochi-Muziris Pavilion), explicitly designed for full dismantling and component reuse.

In contrast, strategies that explicitly prioritise the refusal of new construction or the systematic application of fully reversible design solutions appear only sporadically, primarily in adaptive reuse or experimental contexts such as case CS28 (Super Circular Estate–SUPERLOCAL) and case CS42 (Koodaaram Kochi-Muziris Pavilion) rather than across mainstream permanent building projects.

Material-related strategies show the highest degree of consistency across the dataset. Most case studies use recyclable, bio-based, low-carbon, or non-hazardous materials, as well as efforts to reduce unnecessary components and adopt modular construction systems. Representative examples include case CS18 (CASA QUATTRO) with mono-material bio-based systems (wood, cork, straw), case CS31 (ReCreate–H2020 Project) demonstrating structural reuse of precast elements, case CS35 (Eco-sustainable ceiling panels incorporating recycled polyurethane insulation derived from refrigerator waste) applying industrial symbiosis through waste-derived insulation panels, and case CS21 (Scuola di via Milano, Pesaro) integrating circular material and procurement criteria in a public building context.

However, advanced material management practices, including material passports, digital matching of components, and systematic data logging, are documented in only a limited number of cases, notably case CS27 (Sloan Square House–BIM-enabled reclaimed steel integration) and case CS31 (ReCreate–H2020 Project–digital inventory and structural matching), indicating that traceability infrastructures remain research, or innovation-driven, rather than mainstream practice.

The main finding of the case studies is that circularity succeeds best when methods address several lifecycle stages simultaneously. The most robust circular outcomes are observed in projects that integrate design strategies (adaptability and disassembly), material selections (low-carbon and reusable systems), construction techniques (prefabrication, selective deconstruction), and explicit end-of-life planning. This systemic integration is particularly evident in cases CS11 (Circular Retrofit Lab), CS28 (Super Circular Estate–SUPERLOCAL), CS31 (ReCreate–H2020 Project) and CS42 (Koodaaram Kochi-Muziris Pavilion), where circularity is not confined to a single intervention but embedded across multiple lifecycle phases.

This result supports the idea that isolated interventions, such as material substitution without design adaptability, or recycling without disassembly planning, are insufficient to achieve high circular performance. Rather, the evidence from the analysed cases calls for a comprehensive framework that incorporates decisions made during the design, building, operation, renovation, and final disassembly phases, ensuring that circular intent is translated into long-term material value retention.

- (a) **Dominance of Design for Circularity.** Design for circularity represents the most consistently implemented dimension. Strategies such as Design for adaptability and flexibility, Design for longevity and increase building utilisation, Design for disassembly and Design for reversible solutions appear in a significant share of cases. Adaptability is often embedded at spatial and structural levels rather than treated as an afterthought. Projects that demonstrate long-term flexibility typically incorporate modular grids, accessible service zones, and non-composite assemblies that enable future transformation without destructive intervention.

Design-for-circularity strategies are the entry point for most projects and are present regardless of building type or budget. Across the dataset, “design for circularity” rarely appears as a single, isolated tactic; rather, it functions as a system property that depends on how spatial planning, structural logic, and specification choices reinforce one another. For example, adaptability and flexibility are most robust where they are “locked in” through modular grids, separable layers, and non-destructive detailing, as demonstrated by the Circular Retrofit Lab’s emphasis on dry-assembled envelope solutions (CS11). In addition, “refuse new construction” in practice is often implemented not as a full avoidance of building activity, but as a reframing of value around what already exists (e.g., deconstruction-driven transformation and high-value reuse in Super Circular Estate, CS28).

A critical pattern emerging from these examples is that design-phase ambition is easiest to sustain when it is coupled with explicit end-of-life assumptions (future dismounting, future reconfiguration, future relocation) and when those assumptions are translated into choices about connections, assemblies, and access. This explains why projects that claim adaptability but do not address disassembly or reversible detailing tend to remain “partially circular” (circular intent without guaranteed circular outcomes).

- (b) **Materials and Products: strong technical maturity, weak traceability.** Material-related strategies show a high consistency across the dataset. The majority of projects include the use of low-carbon, recycled, or bio-based materials and modular construction. These strategies align primarily with mid-level 10R categories (R2–R5), emphasising reduction, reuse, and refurbishment over recycling. Material circularity is strong at the component and material level, but traceability tools (material passports, databases) remain limited to research-driven projects.

More advanced material management tools, such as material passports, long-term digital traceability and structured material banking, appear only in a

limited number of research-driven or flagship projects. This reveals a structural gap: material circularity is technically feasible, but its systemic tracking infrastructure is not yet common.

The material-focused “maturity” visible across the cases is partly explained by feasibility: substituting or optimising materials can often be achieved within existing procurement routines and compliance pathways, whereas strategies requiring long-term responsibility (take-back, leasing, verified traceability, multi-owner data governance) demand institutional change. This divide is visible when contrasting bio-based/mono-material systems with known recovery routes (CASA QUATTRO, CS18) with digitally enabled structural reuse (ReCreate, CS31): both are “material strategies,” but the latter requires a coordinated value chain and verified performance data to be viable at scale.

A second finding is that “recycled content” alone is not a guarantee of circularity. The most transferable examples treat materials as assets with an exit route, meaning they are selected and assembled to preserve future value (e.g., design-for-disassembly plus material choices that can be separated without contamination). This logic is explicit in the Eco-sustainable ceiling panels case (CS35), where a new product pathway is created for waste-derived insulation and delivered in prefabricated panels that can be dismantled.

In the end, the matrix analysis shows that traceability tools correlate strongly with the presence of BIM-based workflows. Where digital documentation is absent, the potential for future reuse becomes uncertain.

- (c) **Construction Practices: uneven but transferable.** Construction-phase strategies are moderately represented within the case studies. Common practices include waste management, prefabrication, efficient logistics, lean construction methods and local sourcing. Where construction practices perform strongly, the driver is often processing discipline (logistics, separation, sequencing, and documentation) rather than advanced technology. Advanced “smart construction” technologies (robotics, additive manufacturing, automated disassembly systems) are rare. A concrete illustration is the Italian school case in Pesaro (CS21), where circularity is operationalised through tender requirements and the systematic sorting of demolition/construction streams according to the European Waste Catalogue, with obligations to route materials into recycling chains. This shows how procurement can shift circularity from “optional design intent” to “contractual delivery condition,” reducing reliance on individual project champions.

Another construction-stage enabler visible in practice is prefabrication as a precondition for disassembly: when assemblies are standardised and quality-controlled off-site, it becomes easier to ensure repeatable joints, limit irreversible fixing, and create predictable “reverse logistics” later (CS14 and CS26). The implication is that construction-phase circularity is best interpreted as an implementation layer that either enables or undermines the design-stage circular intent.

The case studies demonstrate that construction circularity depends less on technological innovation and more on procurement models, contractual requirements and tender specifications. Where circular criteria are embedded in public procurement, construction-phase circularity becomes enforceable rather than voluntary, demonstrating that construction circularity is primarily a governance challenge rather than a technological one.

- (d) **Building Operations & Maintenance: the weakest dimension.** Strategies related to building operation and maintenance are significantly underrepresented. Although some projects include energy and water monitoring systems, increased space utilisation models, and flexible interior systems (The Edge - CS9), advanced operational circularity mechanisms, such as predictive maintenance, digital twins, or integrated resource recovery systems, are rarely implemented.

The strongest operational examples treat circularity as use optimisation rather than physical material cycling. The Reallabor Space Sharing case (CS45) demonstrates how multi-use, space sharing, and digital coordination can “refuse” new floor area demand by unlocking underutilised capacity: effectively shifting circularity upstream to the question of *whether* construction is needed at all.

Operational decisions determine whether buildings remain adaptable or become prematurely obsolete. Yet, circularity is still predominantly conceptualised as a design-phase issue, not as a long-term management strategy. A critical barrier is that operational data (occupancy, component condition, maintenance history) is rarely structured to support future recovery decisions. This helps explain why the “digital twin/passport” direction appears in the draft as an opportunity space rather than mainstream practice: the dataset contains only limited, research-driven or pilot examples where digital workflows are explicitly mobilised for reuse and disassembly planning. In the end, the limited presence of digital twins confirms that “Material Passport 2.0” approaches (dynamic, sensor-linked material data) remain experimental rather than widespread practice.

- (e) **End-of-Life & Deconstruction: Demonstrated but Not Systematically Embedded.** Selective deconstruction and material recovery appear in a subset of projects, particularly temporary and demonstrator structures. When implemented, these strategies show high circular maturity: mechanical reversible connections, planned dismantling, reuse of structural components and take-back systems for specific materials. However, end-of-life planning is rarely embedded in early design stages in conventional buildings. In most everyday projects, demolition remains the default scenario

End-of-life strategies appear most clearly where projects are conceived as pilots, temporary structures, or research demonstrations, and where “future disassembly” is treated as a core performance criterion rather than a secondary benefit. The cases indicate that end-of-life circularity becomes credible when it is designed-in and tested, not simply stated. Koodaaram Pavilion (CS42)

is instructive because the project's temporary nature makes dismantling non-negotiable; the consequence is a coherent alignment between structural concept, connection strategy, and the intended second life of components. In contrast, for conventional buildings, end-of-life performance depends on whether the project team is willing to invest in up-front detailing, documentation, and reverse logistics planning, elements that often lack immediate payback under current market conditions.

The case studies highlight a systemic inconsistency: Projects demonstrate that disassembly is technically viable, but it is not yet economically or legally standardised.

- (f) **Enabler of the CE infrastructure.** Beyond individual lifecycle categories, the case studies suggest that digital tools are currently most effective when they serve a specific circular function: matching reclaimed stock to design requirements, documenting recoverable components, and reducing uncertainty around quality and compliance. A clear example is the reclaimed-steel workflow in the Sloane Square House vertical extension project (CS27), where reuse is enabled by parametric/BIM-linked assessment and design iterations responding to available stock, highlighting that “designing from availability” is a practical route to scaling reuse. Similarly, ReCreate (CS31) positions digital matching and supply-chain integration as prerequisites for structural reuse beyond one-off bespoke projects. At the same time, the dataset confirms that full traceability ecosystems (material passports with long-term governance, operational updates, and reliable transfer across owners) remain rare and mostly visible in research/pilot contexts rather than mainstream delivery. This shows that some strategies appear “limited” not because they are conceptually weak, but because they require market infrastructure, standards, and responsibilities that are still emerging.

3.3 *Clusters*

Cluster 1: Existing Buildings—Retrofit & Adaptive Reuse. The first cluster represents projects in which circularity is primarily achieved through the reuse, refurbishment, and functional transformation of existing buildings. This cluster encompasses a wide range of everyday building types, including residential, office, cultural, and public buildings, reflecting the central role of the existing building stock in the transition toward a circular built environment. Circular strategies in this cluster focus on extending the service life of buildings, avoiding demolition, and reducing embodied carbon by retaining structural systems and adapting spaces to new or evolving uses.

The dominance of this cluster highlights that retrofit and adaptive reuse are currently the most mature and widely applicable pathways to circularity. Rather than relying on advanced technologies, these projects demonstrate how circular outcomes can be achieved through strategic design decisions, spatial reconfiguration, and selective material replacement. The emphasis on adaptability and low-carbon materials further reinforces the role of design as a long-term enabler of circular performance.

As the largest cluster, it reflects the reality that circular economy principles are most impactful when applied to ordinary buildings and existing urban fabric.

Typical buildings: Offices, residential, cultural, public **Key strategies:** Reuse, refurbishment, adaptability, low-carbon materials

Case studies: CS1, CS2, CS3, CS8, CS9, CS11, CS12, CS13, CS15, CS17, CS19, CS21, CS23, CS25, CS26, CS30, CS32, CS37, CS38, CS41

Main characteristics:

- Refurbishment or adaptive reuse of existing buildings
- Functional reconfiguration without demolition
- Emphasis on extending service life and reducing embodied carbon

Cluster 2: Temporary & Experimental Structures. The second cluster groups temporary and experimental structures, such as pavilions, exhibitions, and demonstrator projects, where circularity is explicitly embedded in the project brief from the outset. These projects typically define a limited lifespan and plan for full or partial dismantling, allowing advanced circular strategies such as reversibility, modularity, and design for disassembly to be tested under controlled conditions.

Within this cluster, circularity is treated as an experimental design challenge rather than a constraint imposed by long-term use. As a result, these projects often achieve a high degree of technical circularity, including complete material recovery and reuse. While their direct transferability to permanent buildings may be limited, their value lies in their role as innovation incubators. They provide proof-of-concept demonstrations, reduce uncertainty around novel solutions, and generate practical knowledge that can inform more conventional building projects.

Typical buildings: Pavilions, exhibitions, demonstrators, temporary works

Key strategies: Design for disassembly, reversibility, modularity

Case studies: CS5, CS6, CS13, CS16, CS20, CS26, CS29, CS33, CS39

Main characteristics:

- Temporary lifespan explicitly stated
- Full or partial dismantling planned
- Testing of advanced circular principles under controlled conditions

Cluster 3: Infrastructure & Structural Systems. The third cluster focuses on infrastructure and structural systems, shifting attention from whole buildings to repeatable components and systems such as car parks, retaining structures, construction pits, and structural frames. Circularity in this cluster is achieved through high levels of standardisation, modularity, and controlled ownership models, enabling strategies such as product-as-a-service, leasing, and take-back schemes.

This cluster demonstrates some of the highest levels of circular maturity across the case studies, largely because structural systems lend themselves to industrial logic

and repeatable use cycles. The focus on reusable steel components, reverse logistics, and standardised assemblies enables scalability and economic viability. Importantly, this cluster illustrates that circularity becomes more achievable when responsibility for components is clearly defined and when reuse is embedded in supply chains rather than left to project-specific decisions.

Typical buildings: Car parks, construction pits, retaining walls, structural frames

Key strategies: Product-as-a-service, reusable components, reverse logistics

Case studies: CS5, CS6, CS18, CS22, CS28, CS34, CS40, CS44

Main characteristics:

- Focus on structural systems rather than whole buildings
- Reusable steel, modular systems, leasing or take-back models
- High standardisation and repeatability

Cluster 4: Material-Driven Innovations. The fourth cluster is defined by projects in which circularity is driven primarily by material innovation rather than by building-scale design strategies. These case studies focus on transforming waste streams into construction products, including bricks, concrete, insulation materials, and retrofitting systems, often through recycling, remanufacturing, or industrial symbiosis.

Circularity in this cluster operates largely at the product level and is frequently independent of a specific building typology. While this enables measurable reductions in waste and embodied carbon, it also limits the systemic impact of circularity unless material innovations are integrated into broader design and lifecycle strategies. This cluster highlights both the potential and the limitations of material-driven circularity, emphasising the need to align product innovation with design-for-reuse and end-of-life planning.

Typical applications: Bricks, concrete, insulation, retrofitting systems

Key strategies: Recycling, remanufacturing, industrial symbiosis

Case studies: CS4, CS7, CS10, CS14, CS24, CS31, CS36, CS37, CS42, CS44

Main characteristics:

- Circularity driven primarily by material innovation
- Waste streams converted into construction products
- Often independent of a specific building type

Cluster 5: Urban-Scale & Use-Based Strategies. The fifth cluster shifts the focus of circularity from physical construction to patterns of use and spatial organisation at the urban scale. Projects in this cluster prioritise space sharing, increased utilisation, and functional reuse of existing buildings, often supported by governance models and digital platforms. Typical examples include multi-use buildings, campuses, and shared facilities.

This cluster demonstrates that significant circular benefits can be achieved by reducing demand for new construction through more efficient use of existing space. Circularity here is less dependent on material or technological innovation and more closely linked to organisational, social, and institutional arrangements. By emphasising how buildings are used rather than how they are built, this cluster plays a critical role in connecting circular economy principles to urban planning and everyday practice.

Typical buildings: Multi-use buildings, shared spaces, campuses

Key strategies: Space sharing, increased utilisation, functional reuse

Case studies: CS2, CS9, CS14, CS17, CS19, CS27, CS35, CS4, CS45

Main characteristics:

Focus on *how* space is used rather than *what* is built.

Shared use, flexible programming, governance models.

Often supported by digital platforms

Overlapping Clusters and Systemic Interpretation. The presence of case studies in multiple clusters underscores the systemic nature of circularity. Projects such as Entopia (CS2) or La Borda (CS14) combine adaptive reuse, material innovation, and use-based strategies, demonstrating that high circular performance is achieved through the integration of multiple approaches rather than through isolated measures. These overlaps confirm that the clusters should be understood as analytical lenses rather than rigid categories, supporting a more nuanced interpretation of circular economy implementation across the built environment.

It is important to note that many case studies belong to more than one cluster, especially:

- CS2 (Entopia) → Clusters 1, 4, and 5
- Cases CS5 & CS6 (steel sheet piling systems) → Clusters 2 and 3
- Case CS14 (La Borda) → Clusters 4 and 5

3.4 Challenges Faced and Lessons Learned

From the analysis of the case studies, it can be concluded that we are currently facing many challenges and barriers in introducing full circularity into wider practice. Different regulatory, technical, financial and cultural challenges to implementation can be identified.

The most common and main *regulatory challenges* are:

- Inflexible building codes: codes often prioritise fire safety and acoustics through permanent, layered assemblies that are antithetical to easy disassembly.
- Storage space: reused materials need to be stored until a new project needs them. Developers rarely have the space or the desire to pay for long-term warehousing.

- Market fragmentation: a lack of a centralised digital marketplace makes it hard for architects to find the specific salvaged parts they need during the design phase.

The most common *technical challenges* are:

- Ensuring performance standards when using reused components.
- Integration of the distinctive sculptural architecture with sustainable construction practices requires careful coordination and specialist expertise.
- Complexity in the structural certification of, for instance, reused steel to meet applicable regulations.
- The use of non-standardised materials requires novel design solutions. This ‘extra’ certification can increase initial costs, along with cleaning and reconditioning processes.
- Limited initial data usage/analytics capacity.

The most common *financial challenges* are:

- Balancing high-quality design aspirations with funding constraints demanded prudent cost management.
- Managing high upfront costs for advanced HVAC systems.
- Managing the high upfront investment for IoT systems.
- Lack of overall financial analysis that implies a cradle-to-cradle approach
- Coordinating distinct firms aligned with circularity purposes, logistic and material supply, regarding the possible insufficient circularity-based market
- High labour costs: deconstruction, taking a building apart piece by piece, for instance, is far more labour-intensive and time-consuming than traditional demolition
- Valuation uncertainty: banks and insurers often struggle to value “used” components or buildings designed for disassembly, leading to higher risk premiums.

The most common *socio-cultural challenges* mentioned in case study analysis are:

- Convincing the stakeholders of the long-term value of a circular retrofit over a new build.
- Privacy concerns over user tracking (GDPR).
- Encouraging acceptance of a non-clinical architectural style within a traditionally clinical hospital environment.

Some of the *isolated lessons learned* from the numerous analysed case studies are as follows:

- Circular retrofit is viable even for complex, older buildings.
- Early design-stage engagement with contractors and suppliers is essential.
- Material passports and reuse networks enhance the practicality of circular strategies.
- Construction of buildings with waste materials and retrofitting buildings with waste-based materials are the cultural barriers. Communities, from past to now, generally use new technologies and buildings. The sustainability concept, in contrast to this, requires the use of things many times, if possible, after repairing

also. Although this approach ensures economic perspectives and has many advantages, and new technical reports have been published, cultural habits change may require time. Educational regulations on sustainability can be a solution for new generations to break barriers.

- Smart technology enhances circular operations but needs long-term maintenance planning.
- Material selection must consider not only carbon but also reuse potential.
- Flexibility and modularity in design improve long-term performance.
- Collaboration between digital and construction teams is crucial.
- Early collaboration between architects, engineers, and sustainability specialists is critical for successfully blending form, function, and circularity.
- Durable, renewable materials can be incorporated effectively in high-profile healthcare settings to enhance wellbeing and environmental outcomes.
- Community engagement during and after construction enriches the project's social value and strengthens local support.
- Transparent documentation and communication around sustainability goals help align stakeholders and inform future projects.
- Treatment sludge originating from different sectors can be evaluated in a similar way. For instance, in countries like Türkiye, Italy, Croatia, Slovenia, and Montenegro, which are in earthquake zones and have a large stock of old buildings, especially in towns, urban transformation applications need to be carried out quickly. There will be an intensive need for building materials within the scope of urban transformation applications. Meeting some of this need with industrial symbiosis applications will reduce both the amount of waste, the use of natural resources and the costs.
- Reusing structural steel directly is viable, safe, and economically competitive, although tests are always necessary to certify the quality of the materials.
- The use of digital tools, like BIM, is essential for integrating non-standardised elements and maximising the material's potential.
- The requirement for certification of reused materials can pose a significant challenge when it comes to reuse.
- Modular systems can be used in the projects since modular units can be added for possible new functions or easily dismantled if needed.

3.5 Transferable Circular Design Patterns for Everyday Buildings

This session reframes the case studies into replicable patterns, moving from iconic projects to mainstream applications.

Pattern 1: “Reuse First, Build Second”.

Observed in: Super Circular Estate—SUPERLOCAL (CS28), Circular Retrofit Lab (CS11)

Applies to: Residential retrofits, public housing, offices

- Prioritise reuse of structures and components before specifying new materials
- Accept material variability as a design input
- Reduces embodied carbon more than material substitution alone

Key takeaway: Circularity starts with *strategic refusal* of unnecessary new construction.

This pattern reflects Reuse (R3) and the ability to use what we have, avoiding demolition and accepting that buildings are a resource that can be reused if we rethink how we use buildings. Beyond the building, some of the projects illustrate how systems from buildings can be reused, such as mechanical and electrical systems and what Stewart Brand (1995) [25] called the ‘stuff’ layer. In other cases, materials are used for temporary works. Only Reduce (R2) appeared across the exemplar buildings more often than Reuse (R3). Often, the reuse of buildings is linked with Refurbish (R5); sometimes, retrofit is required to improve the energy performance. Cheshire (2021) [26] outlines this scenario by quoting Carl Elefante: “The greenest building is the one already built.”

The advantage of reuse is the elimination of a substantial amount of upfront embodied carbon, as demonstrated by the Entopia building retrofit (CS2), where a disused telephone exchange was converted into offices for the Cambridge Institute for Sustainable Leadership, UK. The architects—Architype, and engineers—Max Fordham, sought to maximise the reuse of existing material and deliberately set out to integrate circular design principles, including how the building could be disassembled. They did all this while also delivering a healthy, productive and inclusive workspace. It was certified EnerPHit in August 2022. A significant portion of materials was salvaged and reused from other construction sites, reducing demand for virgin material, including reclaimed timber, raised access flooring, light fittings, reclaimed mineral wool, internal doors and acoustic panels, thereby extending their product lifespans and diverting material from landfill. Built-in features and furniture were sourced from refurbishment suppliers. All reused and recyclable materials were catalogued, creating a building passport of components and material passports to aid with future reuse or repurposing of the fittings and materials.

A 50% reduction in embodied carbon compared with a new build was reported alongside reductions in operational energy through the retrofit measures. 50 t of material were diverted from landfill. However, some issues must be reported. Ensuring performance standards of reused components were met, and central to this was the need to convince the stakeholders of the long-term value of a circular retrofit.

The Circular Retrofit Lab (CS11), at Vrije University, Brussels, Belgium, is another building reuse where circular principles were applied, by focusing upon the repurposing of a former student accommodation into an office. The building was stripped back to its concrete frame and a new facade and interior constructed so that it is de-mountable, adaptable and flexible. A modular approach was taken to parts, with accessible joints to allow for maintenance, repair and disassembly. This has become a living laboratory to demonstrate circular principles to students and has

demonstrated a route for further refurbishment of other buildings on the campus. The challenges included an insufficiently circular market and coordination among firms supplying materials. BIM-enabled material passports were essential.

In Norway, a residential project in Bergen, Nøstebukten Brygge (CS19), studied the effective reuse of construction products. Doors, internal walls, wood frames, and bricks were deemed economically reusable, while other construction products could only be recycled. The principles of urban mining for building components demonstrated the economic benefits through new value creation. Potential extra costs were highlighted if materials needed to be stored and quality tested, which calls for a marketplace to shift such goods onto new uses as soon as they become available. Again, documentation was key, and the lack of information and resultant uncertainty of product performance and life expectancy did raise issues.

The new Elementa residential project (CS24) in Basel, Switzerland, used materials from buildings being demolished in the city. Prefabricated concrete elements, such as panels and structural elements, were reused in their entirety, some for their original use and others for new uses. This reduced embodied carbon, diverted material from landfill, and avoided the extraction of new raw materials.

Holbein Gardens (CS26), a commercial office block in London, UK was a vertical extension of an existing building. The existing structure was retained, as well as elements of the facade of the 1980s constructed building. The extension was facilitated by 13.5 t of reclaimed steel taken from a building being demolished in London. Reclaimed bricks and stone pavers were also used in the project. They claimed that over 99% of the strip-out waste was traded through Globchain. The reused steel saved 60 t of CO₂. The costs were higher due to material re-use, the need for steel testing, and considerable coordination.

The Super Circular Estate–SUPERLOCAL (CS28) in Kerkrade, Netherlands, achieved a 90% material reuse rate through the deconstruction of a 10-storey 1960s social housing building and the construction of new social housing. This was a large project that investigated nine deconstruction and reuse strategies, accounting for 70% embodied energy savings. Load-bearing structures making up apartments in the 10-storey buildings were removed and reused to create two houses, while the remaining block was refurbished and retrofitted. Brick facades were removed and reused along with lightweight concrete partitions and insulation. Through engagement with the tenants, the team persuaded them that kitchens, sinks, and toilet bowls could be reused in the refurbished apartments. The process highlighted that labour was a major cost, resulting in limited financial competitiveness. Also, the dwellings had to be considered existing but retrofitted, because it was difficult to bring them into compliance with the current Dutch building codes if they were declared ‘new build’. They also highlighted the importance of designing buildings for future reuse cycles and implemented designs that would allow for disassembly. The researchers consider that taxation of employment is detrimental to this activity and that it would be better for carbon emissions to be taxed, as this would make such a project financially viable. They also highlight that broader social engagement and awareness-raising are essential for achieving societal adoption of circularity.

Temporary works are perfect for the reuse of materials. RS76 GmbH & Co. (CS5) required temporary works to shore up a construction pit for a new building in Munich, Germany. Sheet steel piles were rented (as a product-as-a-service), manufactured from 100% scrap using 100% renewable energy. At the end of the project, with the temporary works no longer needed, the pit was filled in, and the piles recovered and returned to the supply company.

What comes through in these projects is a prioritising of component reuse and materials above the use of new materials. The project partners went out of their way to reuse buildings and systems, often to demonstrate circular principles and to reduce embodied carbon. The challenges included costs, especially increased labour, logistics, and communication across the project team, as well as re-certifying materials. Significant carbon savings were made in these projects, which helped justify the choices. The building projects, especially, demonstrate that circularity starts with a *strategic refusal* of unnecessary new construction.

Pattern 2: “Design for Disassembly as a System”.

Observed in: Koodaaram Pavilion (CS42), Circular Retrofit Lab (CS11)

Applies to: Schools, offices, temporary buildings

- Dry connections, accessible joints, modular assemblies
- Disassembly considered across façade, structure, and services

Key takeaway: Disassembly must be systemic, not limited to isolated components.

In 1851, the Great Exhibition was held in Hyde Park, London, in what became known as the Crystal Palace, an iron-framed glass building designed by Joseph Paxton. After the exhibition, it was moved to Sydenham, south London, where it stood until destroyed by fire in the 1930s. Using the same principles of a metal frame, Agram Architects designed the Koodaaram Kochi-Muziris Pavilion (CS42) for a Biennial in New Delhi, India, in 2018. The design was purposely light and temporary, using a skeletal frame and a bamboo roof that enabled full disassembly. The weight avoided the need for permanent foundations, further reducing the building’s embodied carbon. Lightweight, modular systems offer good opportunities for disassembly and high reuse rates when circular principles are integrated from the outset.

The Circular Retrofit Lab (CS11) in Brussels, Belgium, utilised modular components to aid disassembly. Dry connections and reversible technical systems, with accessible joints and demountable facade panels makes the facade and internal walls of this concrete frame building adaptable to future needs. A standardised kit of parts was used to aid with modularity and flexibility.

The Stads Kantoor building at Rotterdam’s City Hall (CS12), Netherlands, is an interesting attempt at design for disassembly through designing for modularity. The actual brief was a building that modules could be added to, so it is akin to Lego bricks, where the brick represents the module that makes up the units from which this building is constructed. Construction finished in 2015, and it achieved a BREEAM Excellent rating. The modular system brought cost savings to the project, and, through

the existing design, if extra space is required, modules can be added to the building, making it flexible.

The Bio-Building Gonsi Socrates (CS13) in Barcelona, Spain, was completed in 2020. The aim was to integrate circular economy principles into the design, including enabling disassembly. Considerable pre-fabrication was used with dry systems. The building is fully documented as a 'material bank' and designed so that systems and products can be removed, replaced, or used elsewhere at the building's end of life. This was successfully tested during a tenancy change. This flexibility and adaptability allow tenants to reconfigure spaces without costly renovations. The dry construction methods and 'design for disassembly' required careful planning and coordination between the architects, engineers and contractors, who were unfamiliar with circular techniques. New workflows and digital tools were required to track and manage material passport data. Initial upfront construction costs were higher, but these should be offset by lifecycle savings. Some regulatory barriers were encountered that complicated the approval processes, while cultural opposition and scepticism amongst sub-contractors and suppliers required education and persuasion.

Also in Barcelona, the La Borda Vivienda Cooperativa (CS14) social housing project was constructed in 2018. It incorporates a cross-laminate timber structure that has been erected to enable disassembly, with dry, visible connections between the prefabricated modular systems and the absence of adhesives, all of which help prevent component damage and reduce demolition waste.

The NEST building (CS15) was constructed at the Swiss research institute, EMPA, in Dübendorf in 2016. Its modular construction was deliberately chosen so that research 'pods' could be added and taken away as projects commenced/completed. It provides a test bed for new building materials and systems. The laboratory consists of an open cantilevered series of floors into which modules can be inserted or removed. The Urban Mining and Recycling Experimental Unit was installed between 2017 and 2018 to investigate modular assembly and prefabricated components with reversible joinery that allowed all building components to be removed, separated and sorted without contamination or residue. No glued joints were used, only screws, bolts, or clips. Its circularity potential was calculated to be 96%. It was estimated that disassembly would generate new economic activity, and the explicit inclusion of design for disassembly enables the clean separation of components for future use, thereby allowing the structure to act as a material bank for future reuse. The Sprint units were installed in NEST in 2022, providing 200 m² of office space using pre-fabricated wooden units that could be added or removed as space requirements changed. The project successfully demonstrated the ability to construct and install the individual units, and then remove them.

To facilitate a refurbishment of the Östermalm Market Hall (CS32) in Stockholm, Sweden, a temporary venue was required to allow the market businesses to continue trading. In 2017, a temporary hall was constructed, with the brief to be ecological, temporary, lightweight, cost-efficient and sustainable [27]. A structure of timber glulam columns, steel brackets and veneer beams in prefabricated modules allowed for quick assembly and efficient disassembly with minimal waste. The building was so successful that it saw a 200% increase in footfall, and traders reported a 50%

increase in turnover. In 2020, when the main hall was refurbished, the building was disassembled and moved to Gothenburg. Its new owners converted the building into a Padel sports hall, adapting the structure to remove some columns to install padel courts. What started out as a temporary building has become ‘permanent’, though its re-assembly maintains its ability to be disassembled again in the future.

Design for Disassembly is not new, but has been revitalised by circular thinking. It has been successfully applied to offices and temporary buildings. Avoiding connections that require adhesives or wet connections is a key feature of the exemplar buildings, with disassembly being a main aim of the design process from the start. What is clear is that disassembly must be holistic and not limited to isolated components.

Pattern 3: “Structural Reuse Enabled by Digital Tools”.

Observed in: ReCreate - H2020 (CS31)

Applies to: Concrete and steel buildings

- Digital matching of reclaimed elements
- Enables reuse beyond bespoke, one-off projects

Key takeaway: Digitalisation is a scaling mechanism, not just a design aid.

This pattern is based on the reuse of elements. These elements are usually structural, as they are more durable and resistant and are often protected by other elements or systems, meaning that their properties do not tend to vary greatly during their life cycle. The ReCreate project–H2020 (CS31) exemplifies this change by focusing on the reuse of precast concrete elements from existing buildings for integration into new commercial, residential and public buildings in various EU countries (Sweden, the Netherlands, Germany and Finland). Concrete is one of the most widely used materials in construction today, so this case study is easily transferable to a multitude of projects that use this material.

The key to the applicability of reusing structural elements lies in their digital pairing, which contributes to traceability and control in the management of recovered components. It is very common for information and documentation relating to second-life elements to be lost or scattered, so digital tracking is very beneficial when implementing urban mining. In the case of ReCreate (CS31), BIM technology is used to carry out audits prior to deconstruction. This facilitates the subsequent creation of databases with detailed and more complete information on the available elements, which facilitates their transfer and recovery of value in other construction projects. In this sense, the elements can be labelled using QR, NFC or Bluetooth technologies, and therefore effectively tracked individually. This labelling collects information on the structural properties and quality of each element through standardised laboratory tests, which increases the reliability and flow of recovered materials in the design of new projects.

Current regulatory and technical requirements limit the use of reused structural elements, mainly due to the lack of information regarding their characteristics. The application of digital tools allows this barrier to be overcome, enabling both concrete and steel elements to meet established standards by linking the data for each element

to current calculation protocols. This drastically reduces uncertainty about structural behaviour and safety, giving confidence to the parties involved and facilitating the obtaining of permits and licences. In addition, the use of advanced digital tools, such as Revit add-ons for automated carbon footprint and life cycle calculation, ensures that design decisions are based on quantifiable and verified environmental benefits.

Digitisation in the construction sector within a circular system should be understood as a mechanism for scalability and implementation, not merely as design tools. The use of these tools, from ‘urban mining’ activities to reverse logistics management, enables the effective reuse of components. In this sense, traceability through digital tools transforms a discarded item into a reliable resource, helping to standardise the circular economy and apply it to any type of building on a more everyday basis.

Pattern 4: “Circular Materials with Known Exit Routes”.

Observed in: CASA QUATTRO (CS18)

Applies to: Housing, small-scale buildings

- Mono-material systems
- Avoid composite layers that block reuse

Key takeaway: Circular materials must be chosen based on future recovery, not only current performance.

This pattern is based on the selection and use of materials, taking into account not only their use, performance, or aesthetics but also the disposal options for the material once it has reached the end of its useful life. It must be ensured that this exit from the system is as sustainable as possible, understood as a high rate of recovery, reuse, recycling, or degree of biodegradation. Materials of natural and local origin facilitate the implementation of these measures and add positive environmental values.

At CASA QUATTRO (CS18), this pattern is clearly evident, with systems that avoid the use of composite materials or layered materials that are difficult to separate at the end of life and limit selective recovery. Using single (non-composite) materials, implemented through industrialised construction, facilitates the dismantling and subsequent recovery of each component independently. In addition, limiting the use of chemicals in naturally sourced materials promotes the safe and sustainable disposal of materials. Taking all these aspects into account at the design and material selection stage ensures that their value and functionality are preserved over time. By choosing materials with clear “end-of-life routes” from the design phase, the project achieves the nZEB (nearly zero energy building) standard, combining operational efficiency with a low embodied carbon footprint.

The materials used in circular systems must be chosen based on their likelihood of recovery, not just on their performance. CASA QUATTRO (CS18) demonstrates that these materials can deliver high performance and low cost while advancing sustainability. The success of this model in conventional residential construction highlights its high replicability, showing that circularity and energy efficiency do not

require complex solutions but rather a coherent selection of materials with clear exit routes and well-integrated renewable technologies.

Pattern 5: “Increase Use Before Increasing Floor Area”

Observed in: Reallabor (CS45)

Applies to: Universities, offices, public buildings

- Space sharing and flexible programming
- Governance and digital platforms are key

Key takeaway: Circularity includes how buildings are used, not just how they are built.

In this case, the Refuse (R0) and Rethink (R1) strategies take precedence over any other circularity proposal. The best way to implement circularity is not to build better and more consciously, but to use what already exists efficiently and optimally. This concept can be applied to buildings with different uses, constituting an essential methodology for effectively implementing circularity in buildings such as universities, offices and public buildings. By intensifying land use, resource consumption and land occupation can be significantly reduced. The Reallabor (CS45) is paradigmatic in that it has an effective plan to open up and expand the availability of existing spaces in buildings to users of all kinds. The goal here is to avoid new construction at all costs.

Technically, this model is developed through appropriate space planning, prioritising flexibility. The management of this planning must be based on digital tools that streamline and optimise operations. In this regard, the creation of digital booking platforms and shared space catalogues that align underutilised space capacity with social needs is essential. Likewise, this system can be supported by flexible furniture and equipment designs that allow a classroom to be transformed into a co-working space or community centre in a reversible manner and with minimal material impact, thus extending the functional life of the property.

This model generates direct environmental and social benefits, such as increased energy efficiency and reduced transport, by centralising functions in a single building, particularly relevant in established urban locations. By prioritising functional reuse over demolition and new construction, waste generation is drastically reduced. Furthermore, this pattern creates economic value by generating savings for users and owners and providing access to affordable spaces, fostering social interaction that segregated-use models do not allow.

In this case, circularity is achieved not through the material itself but through the use made of the spaces that are inhabited. The success of this model depends mainly on governance and collaboration among public agents, institutions, and networks of local actors. Digital tools play a crucial role in this regard, promoting scalability and transparent, accessible management of spatial resources, transforming the concept of ownership into one of shared access. In this way, spaces are re-densified, enabling comprehensive management of all existing resources in cities. However, one of the

main drawbacks could be users' perception of moving from a private space to a shared one.

Pattern 6: "Procurement as a Circular Lever"

Observed in: Italian public projects (CS21)

Applies to: Public sector, social housing

- Circularity embedded in tenders and contracts
- Shifts responsibility from designers alone

Key takeaway: Without procurement alignment, circular design remains experimental.

In this model, the public sector's power is used to drive circularity in buildings. The public sector can transform the circular economy from a niche experiment into standardised market practice. To achieve true circularity, it cannot be left to chance or the goodwill of the designer or builder, but must be an essential part of the specifications and tender contracts. By applying this pattern in sectors such as social housing or public infrastructure, the state acts as a catalyst, compelling the entire supply chain to adopt sustainability criteria to access contracts, thereby moving the market towards sustainability.

The operational mechanism of this model is based on the inclusion of mandatory technical criteria in tenders. These criteria are effective in ensuring compliance with regulated standards for recovered or recycled material content or in achieving high energy-efficiency standards. Responsibility for implementing circular measures thus falls on builders and suppliers interested in obtaining public contracts, whereas traditionally, decision-making in favour of sustainability tended to fall solely on designers and architects. When certain requirements, such as the use of a stipulated amount of recycled or bio-based materials or low-carbon systems, are mandatory and incorporated into contract clauses, the industry is forced to innovate in logistics and manufacturing processes to comply with the law. This ensures that environmental objectives are maintained throughout the execution of the work and are not diluted by economic pressures or a lack of technical expertise.

Ultimately, without alignment of procurement processes, circular design will remain an experimental and isolated practice. In this sense, green public procurement (GPP) promotes the scalability of proven circular solutions for implementation in the general market. By standardising the use of local, natural and easily recyclable materials through public tenders, market uncertainty is reduced, and economies of scale are promoted, making circular construction the logical and economically viable option for everyday buildings. This creates a market with constant demand, enabling local companies to industrialise these solutions and make them competitive. The application of this pattern is limited by regulatory ambiguity in the classification of recovered materials, especially in structural elements (which have greater technical and safety requirements).

The following tables summarise the Circular Design Patterns across Building Lifecycle Stages (Table 1) and the 10R Framework (Table 2).

Table 1 Circular design patterns across building lifecycle stages

Circular design pattern	Design & planning	Construction	Operation & use	End-of-life
Reuse first, build second	●●●	●●	●●	●
Design for disassembly as a system	●●●	●●●	●	●●●
Structural reuse enabled by digital tools	●●	●●	—	●●
Circular materials with known exit routes	●●●	●●	●	●●
Increase use before increasing floor area	●	—	●●●	—
Procurement as a circular lever	●●	●●●	●	●

Legend ●●● = strong relevance ●● = moderate relevance ● = indirect relevance — = not applicable

Table 2 Circular design patterns × 10R framework

Pattern	Dominant R-strategies
Reuse first, build second	R0 refuse, R1 rethink, R3 reuse, R5 refurbish
Design for disassembly as a system	R3 reuse, R4 repair, R7 repurpose
Structural reuse enabled by digital tools	R3 reuse, R6 remanufacture
Circular materials with known exit routes	R2 reduce, R3 reuse, R8 recycle
Increase use before increasing floor area	R0 refuse, R1 rethink
Procurement as a circular lever	Enables R0–R7 across lifecycle

4 Policy and Practice Recommendations (Derived from the Patterns)

The cross-case matrix and cluster analysis developed in this report demonstrate that circular economy strategies in the built environment do not follow a single best-practice pathway, but rather multiple pathways depending on context, building typology, ownership and supply arrangements, and design intent. The findings reveal that, under current conditions, the most robust and scalable circular output is often achieved through the strategic reuse, renovation, and adaptive reuse of existing building stock; new construction, however, can only make a meaningful contribution to circularity through design and governance frameworks that anticipate adaptability, demountability, and recovery. Therefore, the recommendations aim to institutionalise circularity throughout the entire design-supply-operation-end-of-life chain, rather than reducing it solely to material innovation.

For design and planning, “design for circularity” through permits and specifications should be normalised. Adaptable and demountable are fundamental key points

that enable long-term value preservation across all cases. Therefore, the first goal of policy design should be to transform these two principles from a call for good faith into measurable and verifiable obligations.

Firstly, local governments and relevant ministry units should define adaptability, such as plan scheme flexibility, floor height and service spaces, structural grid rationality, adaptation to changing uses, and demountable criteria, including reversible assembly, standard connections, layered design and decomposable material compositions, as minimum requirements in building permit applications. These conditions should be tested not only through documentation but also with verifiable outputs, such as a demolition scenario and end-of-life plan during the design phase. Thus, circularity becomes an integral component of the permit process, not just a claim reported upon project delivery.

Secondly, as the analysis highlights, circular maturity is most strongly scaled by the reuse of existing buildings. Therefore, zoning decisions and public authority investment approval processes should require the first proof of reuse and adaptive reuse options, rather than accepting new construction as the default mode. In practice, this means making the reuse-first principle a mandatory pre-feasibility standard, especially for public projects. Not approving new construction without evaluating adaptation options for the existing building stock is one of the most direct levers for circular goals.

Followingly, capacity building and standard guidelines for design teams are required for various stakeholders. Architects, engineers, and consultants often tend to confine circularity to the heading of material selection. However, the findings show that design purpose, procurement mechanism, and governance framework are more decisive than technological innovation. Therefore, professional associations, municipalities, and universities should collaborate to produce adaptability and demountability guidelines, type detail libraries, and sample specification clauses, and disseminate them through continuous professional development programs. This is a low-cost but highly effective way to bring best practices that remain experimental in the market into the mainstream.

For construction and procurement, circular obligations through public procurement and contracts should be institutionalised. Cluster analysis shows that high circular maturity often occurs in systems with clear ownership models, standardisation, and reverse logistics; however, in everyday buildings, circularity is strongly linked to the procurement and contractual framework. Therefore, procurement policy should ensure that circularity is a contractual performance area, not an optional one.

The initial focus is to set reuse and recyclable assembly targets. Public procurement is one of the most powerful tools shaping market behaviour. Procurement documents should include clauses such as: (a) reuse targets (minimum reuse rate or percentage of demountable elements per building component/product), (b) recyclable assembly requirements (restriction of permanent adhesives and composites; principles of biodegradable connections), (c) a site waste reduction plan, and (d) a recovery plan. These clauses should be justified not as additional criteria that increase costs, but from a lifecycle cost and risk-management perspective. Demountability and component reuse both reduce future conversion costs and preserve asset value.

Moreover, structural systems and facade components are critical items in terms of material density and embodied carbon. Supporting product-service systems (leasing, buy-back guarantee, performance contract) in these items systematises reverse logistics and reuse. Policy-level equivalents include:

- Encouraging take-back and second-life guarantee clauses in contracts,
- Frameworks in tax regulations that make the use of second-hand components defined rather than risky,
- Adapting insurance and liability mechanisms to reuse components.

This approach reduces the problem of ownership uncertainty, one of the most challenging links in circularity. Keeping the component tied to the manufacturer or service provider strengthens standardisation and traceability.

Consequently, incentives and marketplace infrastructure for supply chain actors can increase the potential for circularity. For contractors and suppliers, reuse is often limited due to uncertain supply and demand conditions and quality concerns. Public authorities and industry associations should support infrastructure such as reuse depots, digital component inventories, and regional material banks, and develop standard contract templates that will reduce the time and cost risks of reuse. Thus, reuse becomes institutional market behaviour rather than individual, well-intentioned projects.

Circularity is not just the cycle of materials; the functional cycle of buildings and spaces is at least as effective as the cycle of materials, within the operation and urban policy focus. The distinction emphasised in the report shows that in everyday buildings, circularity is strengthened not through technology but through management and usage design.

Firstly, local governments should facilitate mixed-use, adaptable plan schemes, shared operation of common areas, and daily and time-based usage scenarios through zoning plan notes and building regulations. For example, parking requirements, rigidly increased space demands during use changes, or plan provisions that lock to a single function, weaken the functional reuse aspect of circularity. Therefore, regulations should evolve into a framework that facilitates controlled use changes, rather than bureaucratically penalising them.

Secondly, circularity is often reduced to recycling rates in policy documents and performance frameworks. However, functional reuse, such as adapting a building or space to a different function, increasing usage intensity, and sharing-economy models, all reduce the need for new construction and preserve the low embodied carbon. Therefore, national and local circular economy strategies should recognise functional reuse as a clearly defined circular output and develop measurement indicators.

The circular performance of buildings is significantly affected by maintenance, change management, and user behaviour during the operation phase. For facility management units and building owners, practices such as modular renovation protocols, updating maintenance plans on a component basis, preserving demountable elements, and keeping inventories for reuse should be encouraged. While digital traceability tools are critical at this point, given the limited deployment indicated

in the report, a start could be made with a minimum data standard in the short term. Hence, practical documentation, including minimal fields such as component identification, assembly type, manufacturer information, maintenance history, and disassembly instructions, should be prioritised to inform various stakeholders.

The circular economy necessitates a selective dismantling approach rather than demolition at the end-of-life stage. However, the widespread adoption of selective dismantling is not only about construction site techniques but also about market maturity, responsibility, and trust relationships.

Within this perspective, local and national regulations should require selective dismantling plans and mandatory inspections for buildings of a specific scale, age, and function. This requires the separation and documentation of recoverable components, such as structural elements, facade systems, doors and windows, and technical equipment. While selective dismantling requires higher organisation in the short term, in the long term, it reduces both waste management costs and the need for new products.

Thirdly, one of the main bottlenecks to scaling up reuse is uncertainty about quality and responsibility. Therefore, frameworks should be established that clarify the classification, testing, and certification processes for second-hand building components, as well as the sharing of warranties and responsibilities. The insurance sector, standards organisations, and professional associations are critical stakeholders in this framework. Certification should encompass not only technical conformity but also traceability and performance declaration. In this way, reuse becomes a reliable supply option rather than an exception.

Lastly, the findings show that the limited dissemination of material passports and digital traceability tools restricts the systemic scalability of circularity at the material level. A viable approach is a targeted, phased, mandatory approach: first, a minimum data standard is mandated in public buildings and large-scale projects; then, the passport is expanded to specific component groups. To ensure the data infrastructure can operate on-site, incentives for compliance with digital processes can be provided to the contractor and manufacturer.

Implementing the recommendations requires multi-stakeholder coordination:

- Public authorities (ministries, municipalities): define licensing and regulatory conditions; guide the market through public procurement; establish oversight capacity for selective decommissioning and data standards.
- Design professionals (architects, engineers, consultants): implement adaptability/decommissioning principles into the project; translate design intent into contracts; generate end-of-life scenarios.
- Contractors and suppliers: implement reversible assembly and selective decommissioning operations; plan reuse logistics; provide quality assurance documentation.
- Manufacturers and service providers: offer buyback and second-life guarantees with product-service systems; develop standardisation and modularity.

- Building owners and facility managers: manage occupancy intensity and space sharing strategies; preserve component value through maintenance and inventory processes.
- Insurance/finance and standards organisations: make reuse risks manageable; build market confidence through certification and accountability frameworks.
- Academia and civil society: generate measurement metrics, impact assessments, and policy learning, which speeds up the transfer of best practices.

The findings demonstrate that circularity in everyday building production essentially stems from a combination of design intention, supply mechanism, and governance, and that material innovation can only amplify its impact when integrated into this systemic framework. Therefore, the proposed recommendation set aims to strengthen renovation and adaptive reuse as the most urgent and dominant path, while also securing the circular performance of new construction through licensing, supply, and end-of-life mechanisms. When selective decommissioning, certification, and digital traceability are considered together, circular strategies can move from experimental examples to mainstream practice; thus, the conservation of embedded carbon in the built environment, waste reduction, and the long-term sustainability of asset value can be achieved simultaneously.

5 Concluding Remarks and Future Outlook

The cross-case matrix, cluster structure, and derived circular design patterns collectively demonstrate that the implementation of the circular economy in the built environment is neither uniform nor linear but follows multiple, context-dependent pathways. The analysis confirms that the most robust and scalable circular outcomes are currently achieved through the strategic reuse and adaptation of existing buildings, positioning retrofit and adaptive reuse as the dominant and most immediately actionable pathway toward circularity.

Furthermore, the results confirm that the implementation of the circular economy in the built environment is currently driven primarily by strategies that can be integrated into existing design and construction paradigms. The predominance of reuse, refurbishment, adaptability, and material efficiency across the analysed case studies indicates that circularity is most mature where it aligns with familiar architectural practices, regulatory frameworks, and professional competencies. This is particularly evident in retrofit and adaptive reuse projects, which form the largest cluster and demonstrate the highest degree of circular maturity while addressing everyday building typologies.

The strong presence of R1–R5 strategies across the matrix highlights a prevailing focus on extending the life of buildings and components rather than on advanced recovery or remanufacturing pathways. While this reflects a pragmatic and context-sensitive approach to circularity, it also reveals a structural limitation: higher-order strategies beyond reuse and refurbishment remain difficult to implement

without dedicated infrastructures, markets, and governance mechanisms. The selective appearance of R6–R9 strategies suggests that these approaches are currently viable mainly in controlled or experimental contexts, such as infrastructure systems or material-driven pilot projects.

Design for circularity emerges as the most consistent and transferable entry point across all clusters. Strategies such as adaptability, flexibility, reversibility, and design for disassembly are present regardless of building type, scale, or budget, confirming their role as foundational enablers of lifecycle circularity. Importantly, the evidence shows that these strategies are most effective when embedded at the level of spatial organisation and system logic rather than treated as add-on technical solutions. Projects that integrate circularity into planning concepts and structural layouts demonstrate greater resilience to uncertain future uses and material availability.

Across all clusters, design for circularity emerges as the critical entry point, with adaptability, flexibility, and disassembly enabling long-term value retention regardless of building type or scale. Material innovation plays a significant supporting role, particularly in reducing embodied carbon and closing material loops, yet its impact remains limited when not integrated with design strategies that anticipate future reuse and recovery. The limited diffusion of material passports and digital traceability tools further constrains the systemic scalability of material-level circularity.

The cluster analysis highlights a clear distinction between experimental and mainstream applications. Temporary structures and infrastructure systems demonstrate high circular maturity under controlled conditions, benefiting from clear ownership models, standardisation, and reverse logistics. However, these conditions are rarely present in everyday buildings, where circularity depends more strongly on design intent, procurement mechanisms, and governance frameworks than on technological innovation alone.

The identification of overlapping clusters further demonstrates that circularity does not follow a single linear pathway. Many of the most advanced case studies combine strategies across multiple clusters, integrating material innovation, adaptive reuse, and use-based approaches. This overlap suggests that high levels of circularity are achieved not through isolated measures, but through the strategic combination of design, material, operational, and governance-related interventions.

Urban-scale and use-based strategies reveal an often-overlooked dimension of circularity, showing that significant resource savings can be achieved by intensifying the use of existing space rather than by improving building performance alone. These strategies underline the importance of organisational, social, and policy instruments in reducing demand for new construction and aligning circular economy principles with urban practice.

Taken together, the findings indicate that circularity in the built environment is most effective when multiple lifecycle stages are addressed simultaneously. Projects that combine reuse, adaptable design, material innovation, and supportive procurement or governance mechanisms consistently demonstrate higher circular performance. Conversely, isolated interventions, whether material-driven, technological, or design-focused, tend to remain limited in impact.

This synthesis underscores the need to move beyond project-based experimentation toward integrated, lifecycle-oriented frameworks that connect design decisions to construction practices, building operations, end-of-life planning, and to enabling institutional conditions. For this work, the results provide a clear evidence base for promoting circular design strategies that are not only technically feasible, but also transferable, scalable, and applicable to everyday buildings and urban contexts.

Finally, the derived circular design patterns provide a critical bridge between exemplary projects and everyday building practice. By reframing complex case studies into transferable patterns, the analysis shifts the focus from iconic solutions toward scalable strategies applicable to mainstream residential, public, and commercial buildings. These patterns emphasise that circularity is not solely a matter of technological advancement, but of strategic decision-making, design prioritisation, and institutional alignment across the building lifecycle.

5.1 Recent Developments and Future Directions in Design for Circularity

The future outlook for design strategies and solutions for circularity in the building sector indicates a strong shift from the linear “take-make-waste” model toward systems that treat buildings as “material banks.” Future development is focused on integrating digital tools and innovative construction methods throughout the entire lifecycle. The integration of Design for Disassembly (DfD) and Material Passports (MPs) has shifted from a niche “sustainability” goal to a core industrial strategy. The upcoming opportunities lie in moving beyond just “tracking” materials to creating “active” systems where buildings function as dynamic material banks.

Below are the key opportunities for integrating these innovations into upcoming projects and emerging trends:

Key Design Strategies.

Design for Disassembly (DfD): Instead of permanent adhesives, mechanical joints are used to allow materials to be separated later without damage, increasing component recovery rates by 30%. It is transforming construction by turning buildings from static structures into mobile and renewable resources.

Examples and Innovations in DfD: In the last 2 years, the focus has shifted from theoretical concepts to large-scale infrastructure projects and innovative fastening systems. Several example projects are:

- **AlMusalla Pavilion (Saudi Arabia/Uzbekistan):** This award-winning work by EAST Architecture Studio was designed for the 2024 Islamic Arts Biennale in Jeddah. Built from local date palm waste, the pavilion was completely disassembled after the exhibition and successfully relocated to Uzbekistan for the 2025 Bukhara Biennial.

- New York International Cricket Stadium (Populous): Built for the 2024 T20 World Cup, this 34,000-seat stadium uses a modular grandstand system borrowed from Formula 1. The entire facility was engineered for rapid assembly (3 months) and subsequent dismantling.
- Wisperweide School (Amsterdam): The first school built using Circlewood's prefabricated timber modular system. Amsterdam selected this system for mass application in primary schools due to the ease of adapting and reusing elements.
- Nordic Pavilion (Expo Osaka 2025): Designed by AMDL CIRCLE for the upcoming World Expo, the structure is entirely focused on a circular approach, allowing the entire pavilion to be dismantled and repurposed after the event ends.

Technological Innovations in Fasteners: Innovations in joint mechanics are crucial for DfD as they replace permanent adhesives and welding. Some examples are:

- RING Connectors (Rothoblaas): The new generation of RING90C connectors allows for joining CLT (Cross-Laminated Timber) structures with just a single screw. The system ensures ductility (earthquake safety) and allows panels to be disassembled without damaging the wood.
- TackScrew® and ClampDisk® (PEM Europe): Innovative fasteners that offer the benefits of "press-in" components (fast assembly) but with the capability for repair and removal using specialized tools, ideal for modular elements and metal frames.
- GHOST™ Magnetic Fastening: A completely hidden joining solution that is activated and unlocked exclusively by a magnetic tool, providing high security and a clean aesthetic without visible screws, while allowing for instant dismantling.

Adaptability and Flexibility: Designing spaces that can be easily reconfigured for new purposes without demolition. Examples, like the Nantes School of Architecture, demonstrate how flexibility extends a building's lifespan.

- Circular logic: By specifying standardised, reversible joints, it can be ensured that components can be "harvested" without structural damage.

Modularity and Prefabrication: Using factory-made modules assembled on-site reduces waste by and allows for easier relocation or reuse of parts. Upcoming projects are increasingly adopting modular adaptability and "light" or non-load-bearing systems.

- Opportunity: instead of permanent interior walls, use modular partition systems that are documented in the Material Passport.
- Benefit: this allows a building to be "reconfigured" rather than "demolished" when the tenant needs to change. A floor plan can be updated in days by unbolting and moving components recorded in the digital inventory.

Digital Solutions and Technology.

Material Passports: Detailed digital records of the origin, properties, and recycling potential of every installed element, enabling their future trade on secondary raw material markets. Digital Material Passports (DMP) function in practice as a dynamic

digital inventory that tracks every building component through its entire lifecycle, from production to deconstruction. They transform buildings into “material banks” by ensuring resources become valuable raw materials for new projects rather than waste. Here is how DMPs work in practical stages:

(a) Design and Production Phase: Creating the “Digital Twin”

- **Data Collection:** Manufacturers input data regarding chemical composition, raw material origin, recycled content, and maintenance instructions into a standardised digital format (often based on XML or IFC).
- **BIM Integration:** Architects link this data to the building’s BIM (Building Information Modelling) model. Every element in the model, such as a steel beam or a concrete slab, receives its own passport.
- **Physical Identification:** Products are tagged with QR codes, RFID chips, or NFC tags, which serve as a “key” to access the digital passport on-site.

(b) Use Phase: Real-Time Tracking

- **Maintenance Log:** All repairs, part replacements, or renovations are recorded in the passport. This ensures a “Golden Thread” of information, which is crucial for safety and future repurposing.
- **IoT Sensors:** Advanced systems use sensors to monitor material health (e.g., moisture in timber structures or stress in steel), enabling proactive maintenance and an accurate assessment of remaining service life.

(c) End of Life: Urban Mining and Reuse

- **Value Assessment:** Before deconstruction, owners can use platforms like Madaster to see the exact quantity and current market value of the materials embedded in the building.
- **Dismantling Instructions:** The passport contains detailed instructions on how to safely dismantle components without damage, which is a cornerstone of Design for Disassembly (DfD).
- **Secondary Raw Material Market:** Data from the passport (e.g., steel load-bearing certificates) is automatically transferred to resale platforms, eliminating the need for expensive laboratory testing of old materials.

Practical Examples of DMP:

- **Matrix ONE (Amsterdam):** This 13,000 m² building tracks over 120,000 individual components via DMP, allowing more than 90% of the materials to be reused.
- **Edenica (London):** A 12-story development project that uses passports to track the geometry and location of structural elements (floor slabs, steel frame) to secure their value for the next 120 years.

Building Information Modelling (BIM) and Digital Twins: These tools ensure resource traceability throughout the lifecycle, from planning to the post-use phase, allowing for precise deconstruction planning. Traditional Material Passports were

often static documents. In 2026, the opportunity lies in Digital Twins—3D digital replicas that are continuously updated with real-time data.

- Opportunity: using sensors and AI, Digital Twins can track the wear and tear of components. This “MP 2.0” allows you to know not just *what* is in the building, but the *remaining service life* of each part.
- Innovation: if a specific joint is nearing failure, the Digital Twin alerts maintenance teams to replace it before it damages surrounding components, facilitating cleaner disassembly later.

Chapter 3 provides a detailed account of the regulatory and policy context underpinning BIM-enabled circularity assessment in the built environment.

Material Innovations.

Bio-based Materials: Increased use of materials based on algae, mycelium (fungi), and agricultural waste, which are biodegradable and have a 30–35% lower carbon footprint. The most significant opportunity is the shift in asset valuation. By using Material Passports, developers can now calculate the residual value of a building’s components (e.g., steel beams, timber beams and panels, or modular facades) at the end of its life cycle.

- Opportunity: projects can be financed as “material repositories,” where the future resale value of materials is factored into the initial investment and loan terms.
- Action: Integrate digital platforms like Madaster or Concular early in the design phase to generate real-time circularity scores

High-Value Material Recirculation: Solutions are being developed for full cement recycling (via aggregate mineralisation) and the reuse of steel and aluminium without loss of quality.

Regulatory and Business Trends.

New Legislation: The EU plans to introduce the Circular Economy Act in 2026, aiming to double the circular material use rate to 24% by 2030. The policy and regulatory context underpinning the strategies presented here is examined in detail in Chapter 2.

Product-as-a-Service (PaaS): Instead of buying lighting or HVAC systems, building owners pay for the service, while the manufacturer retains ownership and handles maintenance and recycling.

This chapter has demonstrated that circular design patterns are systematic and transferable. Chapter 2 shows how to use these patterns in early-stage design decisions. Chapter 3 then examines what digital tools and organisational support are needed to put them into practice at a larger scale. Together, the three chapters show a clear path from evidence to action.

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1. Refuse new construction;
2. Design for adaptability and flexibility;
3. Design for longevity and increase building utilization;
4. Design for disassembly;
5. Design for reversible solutions;
6. Use of BIM.

(b) Material Products:

1. Materials selection (recyclable, bio-based materials, low-carbon, non-hazardous);
2. Reduce unnecessary components;
3. Avoid composite materials;
4. Modular construction;
5. Log data/Material passports.

(c) Construction Practices:

1. Waste management (environmentally friendly solutions for waste management, energy savings, pollution control during construction);
2. Source locally;
3. Lean construction methods (effective management of construction works);
4. Prefabrication and efficient logistics;
5. Smart construction techniques (3D printing, robotics, drones, etc).

(d) Building Operations & Maintenance:

1. Predictive maintenance (maintenance strategies to extend lifespan);
2. Monitoring systems for resource efficiency (energy and water efficiency);
3. Resource recovery systems;
4. Digital Twin integration.

(e) End-of-life & Deconstruction:

1. Selective deconstruction;
2. Materials recovery and reuse;
3. Reuse networks and marketplaces;
4. Urban mining practices;
5. Reverse logistics and take-back programs.

(f) Business Models & Policy Support:

1. Product-as-a-service;
2. Extended producer responsibility;
3. Supportive regulations.

(g) Circular strategies:

- R0: Refuse;
R1: Rethink;

- R2: Reduce;
- R3: Reuse;
- R4: Repair;
- R5: Refurbish;
- R6: Remanufacture;
- R7: Repurpose;
- R8: Recycle;
- R9: Recover.

Case Studies

- CS1 Project Name: Afyonkarahisar Atatürk Cultural Center (Afyonkarahisar, Turkey).
- Şen, Y. D., & Halaç, H. H. Yeniden İşlevlendirme Üzerine Bir Değerlendirme: Afyonkarahisar Atatürk Kültür Merkezi. *Mimarlık ve Yaşam*, 9(2), 327–343.
- CS2 Project Name: The Entopia Building Retrofit—Cambridge Institute for Sustainability Leadership (CISL) (Cambridge, United Kingdom).
- Cambridge Institute for Sustainability Leadership (CISL). (2022) Entopia Building retrofit: short version report. Cambridge: University of Cambridge Institute for Sustainability Leadership: https://www.cisl.cam.ac.uk/files/cisl_entopia_report_short_version.pdf (Accessed: 03/02/2026).
 - Cambridge Institute for Sustainability Leadership (CISL). (2022) Building Entopia: The story behind the ultra-sustainable retrofit of CISL's new home in Cambridge. Cambridge: CISL: https://www.cisl.cam.ac.uk/files/entopia_case_study_12_12_22.pdf (Accessed: 03/02/2026).
- CS3 Project Name: Maggie's Cancer Support Centre at the Royal Free Hospital (Hampstead, London, United Kingdom).
- Expedition Engineering, (2024). Maggie's Centre: <https://expedition.uk.com/project/maggies-centre/> (Accessed: 03/02/2026).
 - Maggie's, (2024). Maggies at the Royal Free—Construction Q&A: <https://www.maggies.org/about-us/news/maggies-at-the-royal-free-construction-qa/> (Accessed: 03/02/2026).

CS4 Project Name: Investigation of the circular use of automotive industry chemical treatment sludge in eco brick production (İstanbul, Türkiye).

- Erdem Uslu, Edip Avşar, İsmail Toröz, 2011. An Investigation Of The Automotive Industry Chemical Treatment Sludge Application On Brick Manufacturing In Terms Of Product Quality, Journal of Engineering and Natural Sciences Sigma 3, 141–148.
- Edip Aysar, İsmail Toroz, Asude Hanedar And Erdem Uslu, 2013. Investigation Of The Usability Of Automotive Industry Chemical Wastewater Treatment Sludge As An Additive To Brick Raw Material In Terms Of Firing Process Stack Gas Emissions, Fresenius Environmental Bulletin, Volume 22—No 8a.
- Erdem Uslu, Edip Avşar, İsmail Toröz, 2009. An Investigation Of The Automotive Industry Chemical Treatment Sludge Application On Brick Manufacturing In Terms Of Product Quality, TÜRKAY 2009, 15–17 June 2009, Yıldız Technical University, Türkiye.

CS5 Project Name: RS76—Temporary construction pit (Munich, Germany).

- Züblin: https://www.zueblin.de/databases/internet/_public/content30.nsf/web30?Openagent&id=nachhaltige-baustelle-baugrube-rs76 (Accessed: 03/02/2026).
- ArcelorMittal: <https://sheetpiling.arcelormittal.com/download-center/new-bvk-headquarters-munich-de-2023> (Accessed: 03/02/2026).
- ADVANCE: <https://www.steelconstruct.com/wp-content/uploads/Factsheet-13-AMBD-Reuse-of-steel-sheet-piles.pdf> (Accessed: 03/02/2026).

CS6 Project Name: Hopmarkt underground car park (Aalst, Belgium).

- ArcelorMittal: <https://sheetpiling.arcelormittal.com/download-center/hopmarkt-underground-car-park-be-2013> (Accessed: 03/02/2026).
- Jan de Nul: <https://www.jandenul.com/our-projects/aalst-hopmarkt-belgium> (Accessed: 03/02/2026).

CS7 Project Name: Seismic Damage Assessment of Sustainable ECC Retrofitted-Natural and Recycled Aggregate Concrete Beam-Column Joints in New and Existing Structures (Istanbul, Turkey).

CS8 Project Name: Pier 47 (Langelinie Pier, Copenhagen, Denmark).

- <https://en.wikipedia.org/wiki/Pier47> (Accessed: 03/02/2026).
- <https://www.ltarkitekter.dk/pakhuset-da> (Accessed: 03/02/2026).
- <https://www.windowmaster.com/project-references/pier47/> (Accessed: 03/02/2026).
- <https://aroundus.com/p/11225493-pier47> (Accessed: 03/02/2026).

CS9 Project Name: The Edge (Amsterdam, Netherlands).

- <https://edge.tech/buildings/the-edge> (Accessed: 03/02/2026).

- <https://breeam.com/web/bre-group/case-studies/the-edge-amsterdam> (Accessed: 03/02/2026).
- <https://plparchitecture.com/the-edge/> (Accessed: 03/02/2026).
- <https://www.designlife-cycle.com/new-page-84> (Accessed: 03/02/2026).
- https://www.cdbb.cam.ac.uk/system/files/documents/TheEdge_Paper_LOW1.pdf (Accessed: 03/02/2026).
- <https://www.slc.philips.com/support/cases/office/edge> (Accessed: 03/02/2026).
- <https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/> (Accessed: 03/02/2026).

CS10 Project Name: Eco-industrial use of waste foundry sand in the production of insulation materials (Bilecik, Türkiye).

- Sabel, W. (1967). Chapter 6 Drying. *Basic Techniques of Preparative Organic Chemistry*, 157–169. <https://doi.org/10.1016/B978-0-08-012307-3.50009-0>
- Tüylü, M. (2019) Research on Reuse of Waste Foundry Sands, Master's Thesis (In Turkish) Republic of Turkey Bursa Uludağ University, Institute of Science, Department of Environmental Engineering, BURSA.
- Yahlı Kılıç, M., & Tüylü, M. (2019). Utilization of waste casting sands as raw material in ready mixed concrete production by industrial symbiosis in Bursa. *Uludağ University Engineering Faculty Journal*, 24(1), 99–110. <https://doi.org/10.17482/uumfd.463234>
- Zanetti, M.C., Fiore, S., Clerici, C. (2004). Reuse of foundry sands for core and glass production *Journal of Solid Waste Technology and Management* 30(1):28–36

CS11 Project Name: Circular Retrofit Lab, Vrije Universiteit Brussel (Brussels, Belgium).

- <https://www.circularactions.be/crl> (Accessed: 03/02/2026).
- Anne Paduart, Stijn Elsen, Niels De Temmerman, 2018. Presentation: Circular Retrofit Lab: A Brussels' renovation experiment on how to re-design existing buildings into circular buildings, TRANSFORM research group. https://www.bamb2020.eu/wpcontent/uploads/2018/06/Circular_Retrofit_Lab_-_A_Brussels_renovation_experiment_on_how_to_redesign_buildings_into_circular__05.06.18_web-2.pdf (Accessed: 03/02/2026).
- <https://www.bamb2020.eu/topics/pilot-cases-in-bamb/retrofit-lab/> (Accessed: 03/02/2026).
- Charlotte Cambier, Jeroen Poppe, Waldo Galle, Stijn Elsen and Niels De Temmerman, 2021. The Circular Retrofit Lab: a multi-disciplinary development of a building envelope according to circular design qualities, *IOP Conference Series: Earth and Environmental Science*, doi 10.1088/1755-1315/855/1/012013. <https://iopscience.iop.org/article/10.1088/1755-1315/855/1/012013> (Accessed: 03/02/2026).

- Buildings As Material Banks (Bamb), 2019. Testing Bamb Results Through Prototyping And Pilot Projects D14—4 pilots built + Feedback report. <https://www.bamb2020.eu/wp-content/uploads/2019/03/20190228-BAMB-D14.pdf> (Accessed: 03/02/2026).
- CS12 Project Name: Stads Kantoor building at Rotterdam's City Hall (Rotterdam, Netherlands).
- <https://www.oma.com/news/oma-presents-proposal-for-rotterdam-city-hall> (Accessed: 03/02/2026).
 - <https://www.oma.com/news/stadskantoor-design-wins-breeam-award> (Accessed: 03/02/2026).
 - <https://www.oma.com/news/oma-wins-competition-for-rotterdam-s-stadskantoor> (Accessed: 03/02/2026).
 - <https://tools.breeam.com/projects/explore/buildings.jsp?sectionid=0&projectType=&rating=&certNo=&buildingName=Stadskantoor+&client=&developer=&certBody=&assessor=&location=Rotterdam&countryID=0&partid=10023&Submit=Search> (Accessed: 03/02/2026).
 - <https://www.arch2o.com/rotterdams-stadskantoor-oma/> (Accessed: 03/02/2026).
 - <https://www.archdaily.com/561465/in-progress-stadskantoor-oma> (Accessed: 03/02/2026).
 - Photos: <https://www.oma.com/search?q=Stadskantoor> (Accessed: 03/02/2026).
- CS13 Project Name: Bio-Building Gonsi Sócrates (Viladecans, Barcelona, Spain).
- <https://www.picharchitects.com/portfolio-items/edificio-gonsi-socrates-arquitectura-sostenible/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/portfolio-items/metodologia-para-el-analisis-completo-del-ciclo-de-vida-de-los-edificios/?portfolioCats=519%2C512%2C506%2C522> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2019/12/10/economia-circular-en-el-sector-de-la-edificacion-en-espana/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2019/10/16/edificio-socrates-una-arquitectura-no-convencional/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2019/11/20/congreso-rebuild-edificio-gonsi-socrates/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2020/01/28/economia-circular-en-el-diseno-arquitectonico/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2020/02/12/gonsi-socrates-el-primer-edificio-en-espana-construido-100-bajo-el-modelo-de-construccion-circular/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2020/05/20/economia-circular-en-el-diseno-arquitectonico-pt-2/> (Accessed: 03/02/2026).
 - <https://www.picharchitects.com/2020/10/27/gonsi-socrates-a-circular-construction-model/> (Accessed: 03/02/2026).

- <https://www.youtube.com/watch?v=lj7rNIVeZSk&t=3s> (Accessed: 03/02/2026).
- <https://www.interempresas.net/construccion-industrializada/307838-Edificio-Gonsi-Socrates-en-Viladecans.html> (Accessed: 03/02/2026).
- <https://ecointelligentgrowth.net/projects/gonsi-socrates-biobuilding-circular-construction-in-action/> (Accessed: 03/02/2026).
- <https://www.springerprofessional.de/circular-material-usage-strategies-principles/50170396> (Accessed: 03/02/2026).
- <https://www.construcia.com/en/socrates-building/> (Accessed: 03/02/2026).
- <https://tectonica.archi/projects/edificio-industrial-adaptable-y-con-criterios-de-economiacircular-de-picharquitects-pich-aguilera/> (Accessed: 03/02/2026).
- https://greengrowthproject.eu/wp-content/uploads/2022/06/CaseStudies_EN.pdf (Accessed: 03/02/2026).
- <https://www.picharchitects.com/wp-content/uploads/2020/11/Building-circular-economy-Socrates-Viladecans.pdf> (Accessed: 03/02/2026).

CS14 Project Name: La Borda Cooperative Housing (Barcelona, Spain).

- <https://maderayconstruccion.com/la-borda-en-a-escala-humana/> (Accessed: 03/02/2026).
- <https://arquitecturaviva.com/obras/lacol-arquitectura-cooperativa-la-borda-28-en-barcelona-zs6o2> (Accessed: 03/02/2026).
- <http://www.laborda.coop/es/proyecto/arquitectura/> (Accessed: 03/02/2026).
- <https://www.archdaily.cl/cl/922182/edificio-la-borda-lacol> (Accessed: 03/02/2026).
- <https://lacol.coop/projectes/la-borda/> (Accessed: 03/02/2026).
- <https://arquine.com/obra/cooperativa-de-vivienda-la-borda/> (Accessed: 03/02/2026).

CS15 Project Name: NEST Building—modular research and innovation building (Dübendorf, Switzerland).

- <https://www.empa.ch/web/nest> (Accessed: 03/02/2026).
- <https://www.empa.ch/web/nest/umar> (Accessed: 03/02/2026).
- <https://dfabhouse.ch/> (Accessed: 03/02/2026).

CS16 Project Name: The case study structure is a steel structure for a retail (Stuttgart, Germany)

- Yüksel, P. E. (2023). A BIM-based building circularity framework: assessment and visualization through 5R strategies (Master's thesis, Middle East Technical University (Turkey)).

CS17 Project Name: The New Istanbul Esenler Arena (Istanbul Esenler, Turkey).

- Topraklı, A. Y. (2024). Enabling circularity in Turkish construction: a case of BIM-based material management utilizing material passports. Smart and Sustainable Built Environment.
- CS18 Project Name: CASA QUATTRO: wood, straw and cork for natural living (Magnago, Milan, Italy).
- <https://www.sciencedirect.com/science/article/pii/S0959652624012010> (Accessed: 03/02/2026).
- CS19 Project Name: Nøstebukten Brygge (Bergen, Norway).
- <https://www.sciencedirect.com/science/article/pii/S0959652624012010> (Accessed: 03/02/2026).
- CS20 Project Name: Modular greening system. Green walls and green roofs. Geogreen system (Beira Interior, Portugal).
- <https://www.sciencedirect.com/science/article/pii/S2352710216300316> (Accessed: 03/02/2026).
 - <https://www.sciencedirect.com/science/article/pii/S0048969718302390?via%3Dihub#bb0120> (Accessed: 03/02/2026).
 - https://www.researchgate.net/publication/327421625_ACOUSTIC_EVALUATION_OF_A_NEW_MODULAR_SYSTEM_FOR_GREEN_ROOFS_AND_GREEN_WALLS (Accessed: 03/02/2026).
- CS21 Project Name: Scuola di via Milano. One of the most sustainable school buildings in Europe (Pesaro, Italy).
- https://www.comune.pesaro.pu.it/novita-in-comune/dettaglio/news/a-pesaro-il-nuovo-edificio-scolastico-piu-sostenibile-deuropa/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=8560b7724d5c2627c1654fa190407b9a (Accessed: 03/02/2026).
 - <https://store.uni.com/uni-tr-11821-2023> (Accessed: 03/02/2026).
 - Italian Standardization Body (UNI). UNI/TR 11821:2023. Collection and Analysis of Circular Economy Best Practices; 2023.
- CS22 Project Name: Wood Bridge in Schleißheim (Schleißheim, Austria).
- <https://www.sihga.com/en/news/largest-timber-bridge-in-upper-austria/> (Accessed: 19/02/2026).
 - <https://www.hmr-jacob.de/en/projects/timber-constructions/roman-foothbridge-over-the-traun-river-in-wels-at> (Accessed: 19/02/2026).
 - <https://ic-group.org/en/magazine/detail/roman-bridge-over-traun-opened-sustainable-infrastructure-project> (Accessed: 19/02/2026).
 - <https://www.heavyliftnews.com/felbermayr-delivers-and-installs-covered-wooden-bridge-sections-for-pedestrian-and-cycle-bridge-over-traun-river/> (Accessed: 19/02/2026).
- CS23 Project Name: The Christophorus House (Stadl Paura, Austria).

- <https://www.chh-miva.at/de/christophorushaus> (Accessed: 03/02/2026).
- CS24 Project Name: Elementa (Basel, Switzerland).
- <https://www.archdaily.com/1008183/parabase-reuses-prefabricated-concrete-elements-for-a-radicalhousing-development-in-basel-switzerland> (Accessed: 03/02/2026).
- CS25 Project Name: Brent Cross Town substation (London, United Kingdom).
- <https://www.arup.com/projects/brent-cross-town-substation> (Accessed: 10/02/2026).
 - <https://www.ifdo.co/projects/brent-cross-town-substation#overview> (Accessed: 10/02/2026).
 - <https://www.creativereview.co.uk/lakwena-brent-cross-town/> (Accessed: 10/02/2026).
 - <https://nla.london/projects/brent-cross-town-electrical-substation> (Accessed: 19/02/2026).
 - <https://www.civictrustawards.org.uk/winners/brent-cross-town-substation> (Accessed: 19/02/2026).
 - <https://brentcrosstown.co.uk/stories/brent-cross-towns-new-landmark> (Accessed: 19/02/2026).
- CS26 Project Name: Holbein Gardens (United Kingdom).
- <https://ukgbc.org/resources/holbein-gardens/> (Accessed: 10/02/2026).
 - <https://asbp.org.uk/case-studies/holbein-gardens-disrupt> (Accessed: 10/02/2026).
 - <https://bargazetas.com/projects/holbein-gardens> (Accessed: 10/02/2026).
 - <https://www.grosvenor.com/property/property-uk/holbein-gardens-v1> (Accessed: 19/02/2026).
- CS27 Project Name: Sloan Square House (Sloan Square, London, United Kingdom).
- <https://asbp.org.uk/case-studies/sloane-square-house> (Accessed: 10/02/2026).
- CS28 Project Name: Super Circular Estate, “SUPERLOCAL” (Kerkrade, Parkstad Limburg Region, Netherlands).
- <https://iopscience.iop.org/article/10.1088/1755-1315/225/1/012048> (Accessed: 10/02/2026).
 - <https://www.uia-initiative.eu/en/uia-cities/kerkrade> (Accessed: 10/02/2026).
 - <https://www.housingevolutions.eu/project/the-super-circular-estate-project/> (Accessed: 10/02/2026).
 - https://uia-initiative.eu/sites/default/files/2019-02/Kerkrade_Journal.pdf (Accessed: 10/02/2026).

- CS29 Project Name: Reuse of Structural Steel at BedZED—Beddington Zero Energy Development. (London, United Kingdom).
- https://web.archive.org/web/20150923190405/www.bioregional.com/wp-content/uploads/2014/10/BedZED_seven_years_on.pdf (Accessed: 10/02/2026).
- CS30 Project Name: Development of the Angus Technopôle Building (Montréal, Quebec, Canada).
- <https://technopoleangus.com/en/neighbourhood/eco-district> (Accessed: 10/02/2026).
 - https://www.cagbc.org/green-building-showcase/green-building-spotlight/case-studies/technopole_angus/ (Accessed: 19/02/2026). <https://use.metropolis.org/case-studies/technopole-angus%2D%2Dmontreal> (Accessed: 10/02/2026).
 - Van Dyck, B. and Verhetsel, A., 2007. Reviving Brownfields into living workplaces: technopole Angus and Trefil Arbed. In Paper for the ISOCARP conference (pp. 1–13).
- CS31 Project Name: Recreate—H2020 Project. Reusing precast concrete for a circular economy—H2020, GA No. 958200. (Across EU. Sweden: Helsingborg, 2022—H22 City Expo pavilion; Netherlands: Arnhem → Heerde: Prinsenhof office building; Germany: Hohenmölsen; Finland: Tampere).
- RECREATE, 2021, Recreate—Reusing precast concrete for a circular economy, <https://recreate-project.eu/> (Accessed: 10/02/2026).
 - Dervishaj, A., Gudmundsson, K. and Malmqvist, T., 2024, October. Digital workflow to support the reuse of precast concrete and estimate the climate benefit. In IOP Conference Series: Earth and Environmental Science (Vol. 1402, No. 1, p. 012026). IOP Publishing.
- CS32 Project Name: Temporary Market Hall, Östermalm, Stockholm, 2017 (Östermalm, Stockholm).
- <https://www.metsagroup.com/metsawood/news-and-publications/articles/ostermalm-temporary-market-hall/> (Accessed: 10/02/2026).
 - <https://hicarquitectura.com/2017/03/tengbom-ostermalms-temporary-market-hall/>
 - <https://en.tengbom.se/project/temporary-food-hall/> (Accessed: 10/02/2026).
 - <https://pefc.org/resources/case-stories/ostermalmshallen-a-wooden-temporary-market-hall-enchants-visitors> (Accessed: 10/02/2026).
- CS33 Project Name: Urban Mining and Recycling (UMAR) Experimental Unit (Dübendorf, Switzerland).
- <https://nest-umar.net/> (Accessed: 10/02/2026).
 - <https://labs.aap.cornell.edu/ccl/umar-unit> (Accessed: 10/02/2026).

- <https://www.wernersobek.com/projects/nest-unit-umar> (Accessed: 10/02/2026).
 - E Kakkos, F Heisel, D E Hebel, R Hischier; Towards Urban Mining—Estimating the Potential Environmental Benefits by Applying an Alternative Construction Practice. A Case Study from Switzerland; Sustainability 12 (12): 5041; (2020)
 - F Heisel, S Rau-Oberhuber; Calculation and Evaluation of Circularity Indicators for the Built Environment Using the Case Studies of UMAR and Madaster; Journal of Cleaner Production 243 (SI Urban Mining): 118482; (2020)
 - E Kakkos, F Heisel, D E Hebel, R Hischier; Environmental Assessment of the Urban Mining and Recycling (UMAR) Unit by Applying the LCA Framework; SBE19 Brussels–BAMB-CIRCPATH “Buildings as Material Banks–A Pathway For A Circular Future;” Belgium (2019)
 - F Heisel, D E Hebel; Pioneering Construction Materials through Prototypical Research; Biomimetics 4 (3): 56; (2019)
 - F Heisel, D E Hebel, W Sobek; Resource-Respectful Construction—the Case of the Urban Mining and Recycling Unit (UMAR); In SBE19 Brussels–BAMB-CIRCPATH “Buildings as Material Banks–A Pathway For A Circular Future”; Belgium (2019)
- CS34 Project Name: RumburskáPackwall Flat Renovation (Prague, Czechia).
- <https://www.archdaily.com/1006538/rumburska-packwall-flat-renovation-papundekl-architects> (Accessed: 10/02/2026).
- CS35 Project Name: Eco-sustainable ceiling panels incorporating recycled polyurethane insulation derived from refrigerator waste (Burgos, Spain).
- <https://www.ubu.es/noticias/sky-techos-ecosostenibles-un-caso-de-exito-en-la-comercializacion-de-materiales-sostenibles-para-la-construccion> (Accessed: 19/02/2026).
- CS36 Project Name: Vertical Timber Extensions on Existing Building: new 10 stories hotel on the top of the existing commercial center (Australia, Melbourne).
- <https://architectureau.com/articles/tallest-timber-adaptive-reuse-building-set-to-open/>
 - <https://www.wsp.com/en-id/insights/vertical-timber-extensions-on-existing-buildings> (Accessed: 19/02/2026).
- CS37 Project Name: FrameUp—Optimization of frames for effective assembling (Multinational project: Germany, Sweden, Belgium, Spain, Portugal).

- <https://www.stb.rwth-aachen.de/cms/stb/forschung/forschungsprojekte/%7Empdp/frameup-optimization-of-frames-for-eff/?lidx=1>
(Accessed: 19/02/2026).
- CS38 Project Name: SUPRIM–Sustainable Preconstructed Innovative Module (Greece, Thessaloniki).
- <https://doi.org/10.3390/en13195026> (Accessed: 19/02/2026).
 - https://link.springer.com/chapter/10.1007/978-3-031-73490-8_8
(Accessed: 19/02/2026).
- CS39 Project Name: People’s Pavilion (Amsterdam, Netherlands).
- <https://bureausla.nl/projects/peoples-pavilion/> (Accessed: 19/02/2026).
 - <https://archello.com/project/peoples-pavilion-by-bureau-sla-overtreders-w> (Accessed: 19/02/2026).
 - <https://www.arup.com/projects/peoples-pavilion/> (Accessed: 19/02/2026).
 - <https://www.overtreders-w.nl/en/peoplespavilion> (Accessed: 19/02/2026).
- CS40 Project Name: Brasserie 2050 (Amsterdam, Netherlands).
- <https://frameweb.com/project/brasserie-2050> (Accessed: 19/02/2026).
 - <https://www.dezeen.com/2018/09/05/overtreders-w-zero-waste-barn-lowlands-festival-brasserie-2050-architecture/> (Accessed: 19/02/2026).
 - <https://restaurantandbardesignawards.com/entry/7734> (Accessed: 19/02/2026).
 - <https://dutchdesigndaily.com/stories/brasserie-2050-lowlands-2018/>
(Accessed: 19/02/2026).
- CS41 Project Name: Triodos Bank (Utrecht, Netherlands).
- <https://www.archdaily.com/926357/triodos-bank-rau-architects>
(Accessed: 19/02/2026).
 - <https://www.theplan.it/eng/award-2020-Office-Business/triodos-bank-netherlands-a-circular-wooden-cathedral-rau-architects#:~:text=Wooden%20floors%2C%20wooden%20shafts%20and,that%20of%20a%20%E2%80%9Ccathedral%22.&text=The%20composition%20and%20form%20of,the%20flight%20paths%20of%20bats.> (Accessed: 19/02/2026).
 - <https://www.dezeen.com/2021/02/21/triodos-bank-remountable-office-rau-architects-ex-interiors/> (Accessed: 19/02/2026).
- CS42 Project Name: Koodaaram Kochi-Muziris Pavilion (New Delhi, India).

- <https://www.archdaily.com/921181/koodaaram-kochi-muziris-pavilion-anagram-architects> (Accessed: 19/02/2026).

CS43 Project Name: Stadium 974 (Doha, Qatar).

- <https://www.fenwickiribarren.com/project/974-stadium/> (Accessed: 19/02/2026).
- <https://visitqatar.com/intl-en/things-to-do/adventure-sports/stadiums/974> (Accessed: 19/02/2026).
- <https://www.sbp.de/en/project/stadium-974/> (Accessed: 19/02/2026).
- <https://www.dezeen.com/2022/11/15/2022-fifa-world-cup-qatar-stadium-architecture/> (Accessed: 19/02/2026).
- <https://www.archdaily.com/884528/a-modular-demountable-stadium-built-from-shipping-containers-will-be-built-for-qatar-2022-world-cup> (Accessed: 19/02/2026).

CS44 Project Name: Urban Mining Konzept Rathaus Korbach (Korbach, Germany).

- <https://www.korbach.de/Stadt/Bauen-Umwelt/Wohnen-Planen-Bauen/Bauprojekte/Rathausneubau/> (Accessed: 19/02/2026).
- https://www.dbz.de/artikel/dbz_Urban_Mining_Konzept_Rathaus_Korbach-3601089.html (Accessed: 19/02/2026).
- <https://urban-mining-index.de/projekte/> (Accessed: 19/02/2026).
- <https://www.beton.org/betonbau/architektur/objektdatenbank/objekt-details/neubau-rathaus-korbach/> (Accessed: 19/02/2026).
- <https://porr.de/en/projects/rathaus-korbach/> (Accessed: 19/02/2026).
- <https://www.heringinternational.com/en/news/detail/n/recycled-concrete-the-future-of-construction/> (Accessed: 19/02/2026).
- <https://www.dgnb.de/en> (Accessed: 19/02/2026).
- <https://www.interreg.europa.eu/good-practices/urban-mining-project-in-korbach-hesse-germany> (Accessed: 19/02/2026).

CS45 Project Name: Reallabor (Stuttgart, Germany).

- <https://www.abk-stuttgart.de/forschung/architektur/reallabor-space-sharing/> (Accessed: 19/02/2026).

Additional documents—useful document and example for Circularity Case Studies:

- Circle Economy, Realdania. (2025). Case Studies in the Circular Built Environment: The 9R Strategies in Action. Amsterdam: Circle Economy. <https://www.circle-economy.com/resources/case-studies-in-the-circular-built-environment> (Accessed: 03/02/2026).

References

1. Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J Clean Prod* 114:11–32. <https://doi.org/10.1016/j.jclepro.2015.09.007>
2. Pomponi F, Moncaster A (2017) Circular economy for the built environment: A research framework 143:710–718. <https://doi.org/10.1016/j.jclepro.2016.12.055>
3. Ellen MacArthur Foundation (2021) Completing the picture: how the circular economy tackles climate change. <https://content.ellenmacarthurfoundation.org/m/3eac8667edd240cc/original/Completing%09the%09picture-How-the-circular-economy-tackles-climate-change.pdf>. Accessed 19 Mar 2026
4. European Commission (2020) Buildings and construction. https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en. Accessed 19 Mar 2026
5. European Environment Agency (2023) How far is Europe from reaching its ambition to double the circular use of materials? In: Publications office of the European union. <https://doi.org/10.2800/599752>. Accessed 19 Mar 2026
6. Dodd N, Donatello S, Cordella M (2020) Level(s) indicator 2.2: construction and demolition waste and materials user manual: overview, guidance and instructions. European Commission, Joint Research Centre
7. World Green Building Council (2023) The Circular Built Environment Playbook. https://worldgbc.org/wp-content/uploads/2023/05/Circular-Built-Environment-Playbook-Report_Final.pdf. Accessed 19 Mar 2026
8. Leising E, Quist J, Bocken N (2018) Circular economy in the building sector: three cases and a collaboration tool. *J Clean Prod* 176:976–989. <https://doi.org/10.1016/j.jclepro.2017.12.010>
9. Enríquez E, Fuertes V, Cabrera MJ, Seores J, Muñoz D, Fernández JF (2017) New strategy to mitigate urban Heat Island effect: energy saving by combining high albedo and low thermal diffusivity in glass ceramic materials. *Sol Energy* 149:114–124. <https://doi.org/10.1016/j.solener.2017.04.011>
10. Robert A, Kummert M (2012) Designing net-zero energy buildings for the future climate, not for the past. *Build Environ* 55:150–158. <https://doi.org/10.1016/j.buildenv.2011.12.014>
11. United Nations Environment Programme (2021) Emissions gap report 2021: the heat is on—a world of climate promises not yet deliberated. <https://wedocs.unep.org/handle/20.500.11822/36990>. Accessed 19 Mar 2026
12. World Green Building Council (2019) Bringing embodied carbon upfront. <https://worldgbc.org/climate-action/embodied-carbon/>. Accessed 19 Mar 2026
13. Reike D, Vermeulen WJV, Witjes S (2018) The circular economy: new or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention. *Options* 135:246–264. <https://doi.org/10.1016/j.resconrec.2017.08.027>
14. Geldermans, RJ (2016) Design for change and circularity—accommodating circular material & product flows in construction. *Energy Procedia*, 96, 301–311, <https://doi.org/10.1016/j.egypro.2016.09.153>
15. United Nations Environment Programme (2023) Building materials and the climate: constructing a new future. <https://wedocs.unep.org/handle/20.500.11822/43293>. Accessed 19 Mar 2026
16. Huang, M, Simonen, K, Ditto, J (2018) LCA for low carbon construction: tenant improvements in commercial office buildings, final report. <https://www.pankowfoundation.org/site/assets/files/2031/2lcaoftenantimprovementsincommercialofficebuildingsfinalreport.pdf>. Accessed 19 Mar 2026
17. Akinade OO, Oyedele LO, Ajayi SO, Bilal M, Alaka HA, Owolabi HA, Bello SA, Jaiyeoba BE, Kadiri KO (2017) Design for Deconstruction (DfD): critical success factors for diverting end-of-life waste from landfills. *Waste Manag* 60:3–13. <https://doi.org/10.1016/j.wasman.2016.08.017>

18. Kanters J (2018) Design for deconstruction in the design process: state of the art. *Buildings* 8. <https://doi.org/10.3390/buildings8110150>
19. ISO 20887 (2020) Sustainability in buildings and civil engineering works—design for disassembly and adaptability—principles, requirements and guidance. https://www.steelconstruct.com/wp-content/uploads/ISO-20887_2020_01.pdf. Accessed 19 Mar 2026
20. Crowther, P (2005) Design for disassembly—themes and principles. <https://eprints.qut.edu.au/2888/1/Crowther-RAIA-2005.PDF>. Accessed 19 Mar 2026
21. European Commission (2020) Circular economy—principles for building design. <https://ec.europa.eu/docsroom/documents/39984>. Accessed 19 Mar 2026
22. European Parliament (2011) REGULATION (EU) No 305/2011. <https://eur-lex.europa.eu/eli/reg/2011/305/oj/eng>. Accessed 19 Mar 2026
23. Flyvbjerg B (2006) Five misunderstandings about case-study research. *Qual Inq* 12:219–245. <https://doi.org/10.1177/1077800405284363>
24. Yin RK (2018) Case study research and applications: design and methods; 6th ed.; SAGE Publications, Inc. ISBN 9781506336169
25. Brand S (1995) How buildings learn: what happens after They're built; Penguin Books: New York. ISBN 978-0-14-013996-9
26. Cheshire D (2021) The handbook to building a circular economy; 1st ed.; RIBA Publishing: London. ISBN 978-1-003-21277-5
27. Prelikj K No time to die: how a market hall became a model for architecture that adapts. <https://architizer.com/blog/inspiration/stories/no-time-to-die-how-a-market-hall-became-a-model-for-architecture-that-adapts/>. Accessed 17 Mar 2026

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Embedding Circularity in Conceptual Building Design: A Functional Framework for Data-Driven Decisions during the Earliest Architectural Design Stages



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Abstract Circularity in the built environment is ultimately a design governance challenge rather than a purely technical one. While methodological support is increasingly available, its effectiveness depends on the capacity of project stakeholders to align early-stage decisions with long-term value retention, data continuity, and recovery infrastructures. In this context, the transition toward circular building design requires not only improved tools, but also institutional integration across design, procurement, and regulatory systems, enabling circular criteria to become embedded as standard design constraints rather than optional sustainability objectives. The coming convergence of digitalization, such as BIM and digital product passports, together with lifecycle regulation, and performance-based assessment frameworks will likely redefine the role of the conceptual design phase as a decision environment where circularity is operationalized, verified, and governed from the outset. Consequently,

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the advancement of circular architecture will depend less on the development of new isolated instruments and more on the systematic integration of existing knowledge into coherent, enforceable, and practice-oriented design processes, capable of bridging the gap between circular economy ambition and built reality.

Keywords Circular building · Regenerative design · Digital design tools · Circular architecture · Circular design criteria

1 Introduction

Architectural design is a critical process that defines not only the aesthetic and functional qualities of a building but also its environmental performance and long-term resource use. The conceptual design stage, during which fundamental decisions regarding spatial organisation, building form, orientation, structural systems and material selection are established, offers the greatest opportunity to influence a building's sustainability throughout its life cycle. Integrating circular economy principles into architectural design at its early stages steers the thinking towards circularity implementation and encourages a shift from conventional linear design toward regenerative and resource-efficient solutions.

However, embedding circularity in architectural design extends beyond the application of technical strategies and assessment methods. It is fundamentally a design governance challenge that requires project stakeholders to align early-stage design decisions with long-term value retention, information continuity, and material recovery pathways. Although a growing range of methodologies and decision-support tools is available, their effectiveness depends on their integration into design practice, procurement processes, and regulatory frameworks, enabling circularity to become an inherent design requirement rather than an optional sustainability objective.

To address these challenges, this chapter investigates how circularity can be systematically embedded within the conceptual architectural design process. In particular, it examines two core questions:

RQ1: What early-stage methodological approaches effectively embed Circular Economy (CE) principles in architectural design?

Circular Economy (CE) approaches in concept architectural design focus on systemic thinking, stakeholder collaboration, and frameworks that embed technical, cultural, business and governance aspects, shifting from mere material recycling to holistic lifecycle value retention and positive social and environmental impacts from planning through end-of-life. Key methodological approaches that were investigated included Systemic Design Strategies (e.g., Design for Future Climate Adaptability and Resilience); Collaborative and Iterative Frameworks that integrate technical design, local knowledge, business and governance through iterative activities to

embed circularity across all dimensions (e.g., Aim at Material Efficiency, Servitization); System Thinking; Stakeholder Engagement; and Early Stage Decision Making (e.g., Initiation and planning phases; Resource Stock Analysis).

RQ2: Which tools and frameworks can effectively support practitioners during circular conceptual architectural design?

The second RQ focused on how specific tools and frameworks can specifically support conceptual architectural design. Reference was made here to Early Integration, i.e., tools and frameworks that enable assessment of material sourcing, disassembly potential, and impact from the outset. Data-Driven Decision Making, i.e., tools and frameworks such as Building Information Modelling (BIM) and LCA that provide quantitative insights to compare options (e.g., primary vs recycled materials). Scenario Testing, i.e., tools and frameworks providing parametric modelling and computational plugins, thus helping to visualise and test different circular configurations. Holistic View, i.e., tools and frameworks that provide a structured approach to consider all lifecycle phases (extraction, design, use, EoL).

The underlying key assumption was that, although there have been notable advancements in sustainable design today, research indicates that design professionals still do not have comprehensive guidelines, frameworks and tools specifically supporting circularity, particularly during early-stage architectural design and decision-making, and the development of standardised circularity indicators for buildings is still evolving [1].

The aim was twofold: facilitating the adoption of CE strategies since the early stages of the design process at the building scale and ultimately mainstreaming the implementation of CE solutions in the built environment.

Together with Chap. 1 (best practices) and Chap. 3 (digital tools), this chapter constitutes a core knowledge base and guidance to design practitioners—particularly architects, as professionals ultimately responsible (“concert masters”) for shaping design outcomes across multiple scales.

2 Materials and Methods

The present study adopts a rigorous and structured methodological framework aimed at systematically identifying, analysing, and synthesising existing knowledge on frameworks, strategies, and tools that support the integration of Circular Economy (CE) principles during the early stages of architectural design. The methodology combines elements of Systematic Literature Review (SLR) with a Rapid Evidence Assessment (REA), ensuring both comprehensiveness and efficiency. This approach is rooted in the recognition of the early design phase as a critical leverage point for embedding circularity. The overall research workflow is articulated into a sequence of interrelated phases: (i) targeted literature search, (ii) screening and rapid evidence assessment, (iii) systematic review and critical synthesis, (iv) validation through cross-checking procedures, and (v) consolidation into a State-of-the-Art Report.

2.1 *Research Design and Methodological Approach*

The methodological design is grounded in established review protocols adapted to the interdisciplinary nature of circular design research, which spans architecture, engineering, environmental sciences, and sustainability studies. Given the heterogeneity of sources and the evolving character of the field, a hybrid approach was adopted. The Rapid Evidence Assessment enabled a timely yet structured appraisal of the literature, while the subsequent systematic review ensured analytical depth and critical interpretation.

The process was designed to maximise transparency and reproducibility through the use of predefined search strings, explicit inclusion and exclusion criteria, and a multi-reviewer validation procedure. Particular emphasis was placed on identifying contributions that explicitly address the operationalisation of CE principles within early design workflows, with a focus on actionable tools and frameworks rather than purely theoretical discussions.

2.2 *Literature Search Strategy*

The literature search was conducted using two major academic databases: Google Scholar and Scopus. The selection of these databases was made on the basis of their complementary strengths; Scopus provides access to high-quality, peer-reviewed publications, while Google Scholar ensures broader coverage, including grey literature and emerging contributions.

The search strategy was structured around two main keyword queries, formulated to capture the intersection between circular economy concepts and design-stage applications:

- Query 1: “*building AND circularity AND assessment AND tools*”;
- Query 2: “*circular AND building AND design AND frameworks AND tools*”.

In Scopus, the search was restricted to the Title, Abstract, and Keywords fields to ensure relevance and precision. In Google Scholar, the search was limited to document titles to reduce noise and increase specificity. The initial search yielded a total of 211 documents. Following the exclusion of irrelevant subject areas—such as those unrelated to the built environment or design processes—the dataset was refined to a more focused selection, comprising 75 documents from the first query stream and 84 and 95 documents from the second query stream.

2.3 Screening and Rapid Evidence Assessment

The second phase involved the application of a Rapid Evidence Assessment protocol, designed to streamline the review process while maintaining methodological robustness. This phase consisted of two main steps: dataset consolidation and preliminary screening.

Initially, documents retrieved from different databases were systematically compared to identify and remove duplicates. This process resulted in a consolidated dataset of 76 unique documents. A subsequent screening process was conducted, which entailed the examination of titles, abstracts and keywords. The purpose of this step was to evaluate the relevance of each document against a predetermined set of inclusion and exclusion criteria. The inclusion criteria focused on the following:

- Explicit reference to circular economy principles within the built environment;
- Relevance to the design phase, particularly early-stage decision-making;
- Presentation or discussion of tools, frameworks, strategies, or assessment methodologies.

The following criteria were used to determine exclusion from the study:

- Studies unrelated to the construction or architectural domain;
- Contributions lacking methodological or practical relevance;
- Purely conceptual or theoretical works without operational implications.

This phase ensured that only studies directly aligned with the research objectives were retained for in-depth analysis.

2.4 Systematic Review and Critical Analysis

Following the REA, a systematic literature review was conducted on the refined dataset. This phase involved full-text reading and detailed examination of the selected documents, with the aim of extracting relevant data and identifying recurring themes and methodological approaches.

A two-reviewer methodology was employed in order to enhance the reliability and validity of the analysis. Each document was subjected to independent review by two researchers, and any discrepancies in interpretation or classification were resolved through discussion and consensus. This methodological approach served to minimise subjective bias and ensure consistency in the evaluation process. The analysis focused on several key dimensions:

- The nature and scope of CE frameworks proposed;
- The types of tools and methodologies developed or applied;
- The stage of the design process addressed;
- The level of integration of CE principles;
- The practical applicability and scalability of the proposed solutions.

Through this process, the dataset was further refined to 38 documents, which were subjected to critical analysis and synthesis. This stage involved not only the extraction of descriptive information but also the interpretation and comparison of different approaches, highlighting strengths, limitations, and areas of convergence.

2.5 Tool Categorisation and Analytical Framework

A central component of the study was the systematic categorisation of the tools identified in the literature. Based on their functional characteristics and intended use within the design process, tools were classified into several categories, including:

- Toolkits, providing comprehensive sets of resources and methodologies;
- Assessment tools, enabling the evaluation of circularity performance;
- Digital design tools, supporting integration within computational workflows;
- Guidelines, offering procedural and strategic recommendations;
- Tool mapping approaches, facilitating the alignment of tools with design stages;
- Checklists and guidance documents, supporting decision-making processes.

This categorisation enabled a structured comparison of tools, allowing for the identification of gaps in current offerings and the assessment of their potential to support CE implementation in early design stages.

2.6 Cross-Checking and Secondary Search

To ensure the completeness and robustness of the review, a secondary search phase was conducted. This involved cross-checking references through backward and forward citation tracking of key publications identified during the primary review. The objective was to capture additional relevant studies that may not have been identified through keyword-based searches alone.

This iterative process resulted in the identification of 14 additional documents, which were evaluated against the same inclusion and exclusion criteria. Following this validation step, a final subset of 28 documents was selected for inclusion in the synthesis.

2.7 Synthesis and Development of the State-of-the-Art Report

The final phase of the methodology involved the integration and synthesis of findings into a comprehensive State-of-the-Art Report. This report represents the main outcome of the research and provides a critical overview of existing knowledge on CE implementation in early design stages. The synthesis process involved:

- Aggregating insights from the analysed documents;
- Identifying common themes and methodological trends;
- Evaluating the effectiveness and limitations of existing tools and frameworks;
- Highlighting research gaps and opportunities for future development.

The resulting State-of-the-Art Report not only maps the current landscape of CE-related design tools but also provides a foundation for the development of new methodologies and strategies aimed at enhancing the integration of circular principles within architectural workflows. The overall review process is shown in Fig. 1.

Overall, the adopted methodological framework ensures a high level of scientific rigor while remaining adaptable to the dynamic and interdisciplinary nature of circular economy research. By combining systematic and rapid review techniques, the study achieves a balance between comprehensiveness and analytical depth, supporting the generation of robust and actionable insights.

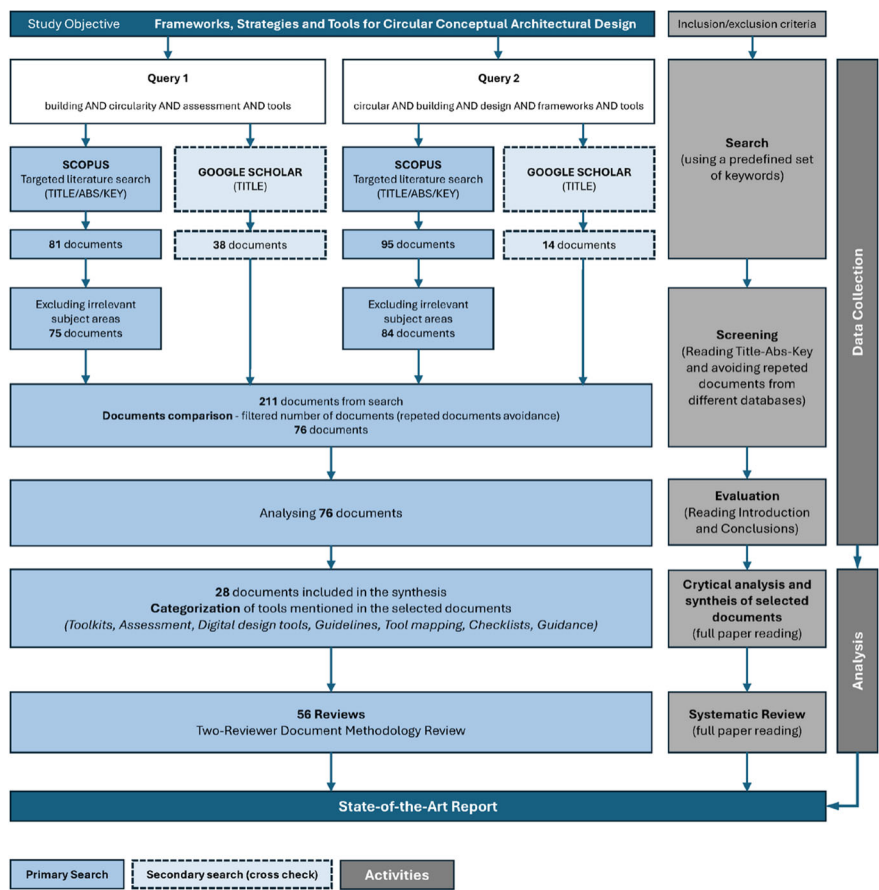


Fig. 1 The review process

3 Results

3.1 Circular Economy Principles in the Built Environment

Circular Economy is an economic model aimed at maintaining the value of products, materials, and resources within the economy for as long as possible while minimising waste generation and environmental impacts. In the context of the built environment, this approach seeks to optimise the use of resources throughout the entire life cycle of buildings, from design and construction to operation, adaptation, and end-of-life recovery processes [1]. While closely related to sustainability, circular economy approaches place a stronger emphasis on resource loops, value retention, and the continuous use of materials and components across multiple life cycles.

The *Circular Economy in the Built Environment* shifts from “take-make-dispose” to a regenerative model, designing buildings for durability, adaptability, reuse, and recycling to minimise waste and emissions, treating materials as valuable assets, and reducing reliance on virgin resources by keeping components in use longer through strategies like modular design, material passports, and prioritising bio-based materials to achieve net-zero goals. A circular building can be defined as a building that optimises resource use and minimises waste throughout its entire life cycle, while enabling the recovery, reuse, or recycling of materials and components at the end of their service life. This implies focusing on extending the life of buildings and materials, integrating with nature, and creating economic value while reducing environmental impact [1–5].

Core Principles & Goals of the Circular Economy in the Built Environment include but are not limited to: *Design Out Waste & Pollution*, creating buildings for disassembly, reuse, and repair from the start [1, 5–7]; *Keep Materials in Use*, maintaining components and materials at their highest value through continuous loops of use, reuse, repair, and recycling [3, 5, 8]; *Regenerate Natural Systems*, using bio-based materials, sustainably sourced, and designing buildings to integrate with ecosystems [1, 9, 10]; *Decouple Growth from Resource Use*, reducing the massive material footprint of the construction sector [2, 6, 9–14].

Key Strategies and Practice of the Circular Economy in the Built Environment encompass: *Material Focus*, prioritizing reclaimed wood, recycled steel, repurposed concrete, and bio-based materials [6, 11, 12, 14–16]; *Design for Adaptability*, creating flexible, multi-purpose buildings that can change function over time [4, 8–11, 13, 14, 16–19]; *End-of-Life Optimization*, developing methods for efficient deconstruction and material recovery [1–4, 14, 20, 21]; *Digital Tools*, using material passports to track materials for future reuse [1–3, 15, 17, 18, 22]; *New Business Models*, implementing sharing, leasing, and collaborative consumption [2–4, 14, 16].

Promoting Circular Economy in the Built Environment is crucial under several perspectives: *Environmental*, because it cuts carbon emissions, reduces landfill waste, and conserves virgin resources [11, 21]; *Economic*, as it unlocks significant economic benefits and new market opportunities [14]; *Resilience*, because it creates more resilient infrastructure less dependent on volatile raw material supply chains [4].

Currently, circular practices are still developing and are not yet widely implemented across the construction sector; focus remains on lower-order “reduce, reuse, recycle” rather than higher-value strategies. Circular Economy in design, building, and construction should be about viewing buildings as “banks of valuable materials” rather than just structures, shifting from a linear to a regenerative system towards a sustainable built environment [2, 5, 6, 8, 18, 23–27]. This perspective highlights the potential of buildings to act as temporary material reservoirs where materials and components can be recovered and reintegrated into future construction cycles [28].

Early-stage design decisions can significantly influence a building’s environmental and resource performance. Effects include and are not limited to: *Energy consumption*, as building orientation, massing, window placement, and insulation choices heavily influence operational energy demand (heating, cooling, lighting) [7, 20]; Impacts related to *material selection*, because early choices on structural systems, finishes, and envelope materials dictate embodied carbon (emissions from production and transport) and resource depletion [6, 11, 12, 14–16, 19]; Effects in *connection to resource use*, as design decisions affect water use, waste generation, and the potential for material reuse or recycling [6, 11, 12, 14–16, 19]; *Life Cycle Costs* (LCC), because early-stage choices significantly impact long-term operational costs (energy bills, maintenance) and potential end-of-life costs [5, 7, 15, 20, 22].

Early consideration of the circular economy principles in the design process consequently matters for several reasons. The ability to change fundamental aspects (e.g., building shape, orientation) is greatest and cheapest in the concept stages (*High Optimisation Potential*). Moreover, making sustainable changes later in design or construction becomes exponentially more expensive (*Reduced Costs*). Early LCA uses generic data for broad impact comparison (e.g., concrete vs. timber frame), becoming more precise as the design develops with specific product data (*Data Integration*) [5–7, 11, 12, 15, 20, 22].

Different tools and approaches can support the designer since the early-stage design phase. Life Cycle Assessment (LCA) is a science-based method for quantifying environmental impacts (such as global warming potential) across all stages. BIM integrates LCA tools with 3D models to provide real-time impact feedback during design iterations. Other decision-support tools, such as software, help planners simulate and compare scenarios for LCC and LCA in the early phases [5, 15, 20, 22].

3.2 The Importance of Early-Stage Architectural Design and Decision-Making

The concept stage is the initial phase of architectural design where core ideas regarding form, function, and site context are established, setting the foundation for sustainability, material durability, and user scenarios. It involves sketching, site analysis, and preliminary, non-binding decisions that define the project’s direction before detailed design phases. From a circular economy perspective, buildings are

increasingly understood as layered systems composed of elements with different service lives. Considering these layers during early design stages supports strategies such as adaptability, repair, and design for disassembly [1, 28].

Goals of the Concept Stage of architectural design include *Setting Direction*: establishing a clear, agreed-upon vision, often resulting in preliminary sketches, volume studies, and site plans. *Defining Scope*: identifying the core constraints and objectives (e.g., sustainability goals, structural systems). *Risk Mitigation*: addressing potential issues early through testing, modelling, and analysis of different scenarios. *Preparation for Design Development*: creating a framework for more detailed planning in subsequent, more defined design phases.

Key Activities and Focus Areas of the Early-Stage Architectural Design and Decision-making encompass: *Initial Ideas & Vision*: development of “Big Ideas,” aesthetic direction, and spatial organisation. *Suitability Assessment*: evaluating potential materials, construction techniques, and structural solutions for durability and performance. *Site & User Context*: analysing site constraints and defining how users will occupy the building, often involving user-centric research. *Preliminary Budgeting*: developing early, high-level cost estimates for feasibility.

All initial concepts and ideas from the concept stage of architectural design are refined and formalised during the subsequent design development phase. Abstract ideas are converted into detailed plans, including precise measurements, material selections, and integrated engineering systems (structural, mechanical, and electrical). Once the concept design is approved, the project brief is typically “frozen” to establish a controlled baseline for detailed technical design. Preliminary estimates from the concept stage are updated to reflect the more detailed specifications developed during the design phase.

Early-stage architectural design is recognised as the most critical phase for steering circular economy (CE) principles in the built environment. Decisions made during this phase determine a building’s entire lifecycle circularity while offering the highest flexibility at the lowest cost.

The influence of early-stage design decisions extends across the entire building lifecycle, affecting material selection, construction processes, operational performance, and end-of-life recovery potential. This lifecycle perspective, together with the integration of circular economy strategies, is illustrated in Fig. 2.

The Role of Building Information Modelling (BIM) in the Early Design Phase: Implications for Design Decision-Making and Circularity in Construction. The construction industry stands at a critical juncture, facing unprecedented pressure to reduce its environmental footprint whilst simultaneously delivering buildings that meet increasingly complex functional, aesthetic, and economic requirements. Buildings account for approximately 40% of global energy consumption and generate roughly one-third of worldwide waste streams, positioning the sector as both a significant contributor to environmental degradation and a crucial arena for sustainable transformation. Within this context, Building Information Modelling (BIM) has emerged as a potentially transformative methodology, particularly when deployed during the early design phases where decisions carry the greatest influence over a

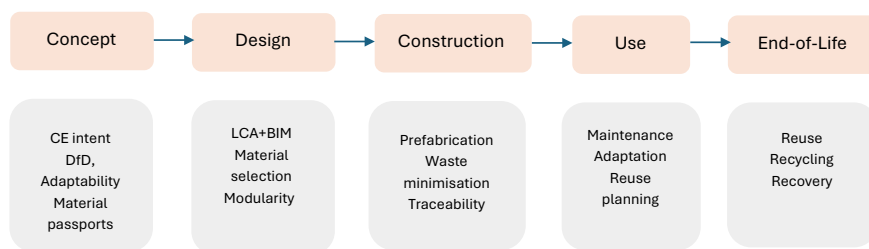


Fig. 2 Design process timeline illustrating key Circular Economy (CE) interventions across lifecycle stages

building's lifecycle performance. Chapter 3 provides thorough information on how BIM can support the integration of sustainability and circularity principles across all stages of building life cycle.

The conceptual design stage represents a unique window of opportunity in the project lifecycle. During this phase, fundamental decisions regarding building form, orientation, structural systems, and material selection are established—decisions that subsequently constrain or enable possibilities throughout construction, operation, and eventual end-of-life. Research consistently demonstrates that approximately 80% of a building's lifecycle costs and environmental impacts are determined during the first 20% of the design process. This asymmetry between early decision-making and long-term consequences underscores the strategic importance of deploying sophisticated analytical tools at the conceptual stage rather than reserving them for later phases when the capacity for meaningful change has substantially diminished.

Concurrently, the principles of circular economy (CE) have gained considerable traction within construction discourse, offering a systemic framework for rethinking how buildings are designed, constructed, operated, and ultimately decommissioned. Unlike traditional linear models—characterised by extraction, production, use, and disposal—circular approaches seek to maintain materials and components at their highest utility and value for as long as possible, minimising waste generation and virgin resource consumption. The integration of BIM with circular economy principles during early design phases presents substantial opportunities for enhancing both economic and environmental outcomes, yet this integration remains incompletely realised in practice.

This chapter examines the role of BIM in the early design phase, with particular attention to its implications for design decision-making and the advancement of circularity in construction. The discussion proceeds through an analysis of the conceptual design stage and its significance, the capabilities and limitations of BIM at this phase, the intersection of BIM with circular economy strategies, barriers to implementation, and emerging directions for research and practice.

Defining the Conceptual Design Stage. The Conceptual Design Phase, Sometimes Called the Schematic or Preliminary Design Stage, Constitutes the Initial Period of Design Development Following Project Inception and Briefing. During this Phase, Designers Translate Client Requirements and Project Constraints into Initial Spatial

Arrangements, Massing Studies, and Preliminary Technical Strategies. The Royal Institute of British Architects Plan of Work (RIBA, 2020) Identifies this As Stage 2—Concept Design, Characterised by the Preparation of the Initial Architectural Concept, Structural and Building Services Systems Strategies, and Preliminary Cost Information [29].

This phase is distinguished by several characteristics that differentiate it from subsequent design stages:

- First, the level of design certainty remains relatively low; many parameters exist as ranges rather than fixed values, and alternatives are actively explored rather than definitively selected.
- Second, the design team typically operates with incomplete information regarding site conditions, material availability, and regulatory requirements.
- Third, the potential for design modification remains high, as commitments to specific solutions have not yet been made.
- Fourth, interdisciplinary coordination is essential, as decisions in one domain—structural systems, for instance—directly influence possibilities in others, such as services routing and spatial flexibility.

The Strategic Importance of Early Design Decisions. The significance of the conceptual design phase derives from the enormous influence that early decisions exert over subsequent project outcomes. This phenomenon, sometimes termed the “design paradox,” reflects the inverse relationship between design freedom and design knowledge: at the point when designers possess maximum freedom to influence outcomes, they typically have minimum information upon which to base decisions; conversely, when detailed information becomes available, the capacity for meaningful change has substantially diminished.

Empirical research supports this theoretical understanding. Studies have demonstrated that fundamental design decisions—building orientation, envelope-to-floor-area ratio, structural grid dimensions, and principal material selections—establish performance parameters that subsequent phases can optimise but not fundamentally transform. A building oriented sub-optimally with respect to solar geometry, for instance, cannot subsequently achieve the energy performance of an optimally oriented alternative regardless of the sophistication of its mechanical systems or envelope detailing.

As illustrated in the “MacLeamy curve” [30], the ability to change design (and corresponding future costs and impacts) decreases with time, and, conversely, the cost of these changes (e.g. altering design, materials, orientation) increases with time. However, in a traditional design process, most decisions are made during construction documentation, a stage at which the cost of changes is already high. When using BIM, those decisions can be anticipated in early design stages when changes can be made at a minor cost and building performance can be optimised. Moreover, when using BIM, future performance (at different dimensions, e.g. economic, energetic, and cost) can be simulated and anticipated, and changes can be assessed before being implemented, so future performance can be optimised.

The implications for both economic and environmental performance are substantial. Life cycle cost analyses consistently demonstrate that decisions made during conceptual design regarding structural systems, facade configurations, and services strategies establish cost trajectories that persist throughout the building's operational life. Similarly, life cycle assessment studies indicate that embodied carbon—the emissions associated with material extraction, manufacturing, transportation, construction and maintenance—is largely determined by early decisions regarding structural efficiency, material selection, and design for longevity [31].

Decision-Making Challenges at the Conceptual Stage. Despite the strategic importance of early design decisions, several factors complicate effective decision-making during this phase. Information asymmetry presents a fundamental challenge: the decisions with the greatest long-term consequences must be made when project-specific data remains scarce and uncertain. Designers frequently rely on rules of thumb, precedent-based reasoning, and professional intuition rather than systematic analysis, introducing variability and potential suboptimality into the design process.

Time pressure represents an additional constraint. Commercial realities typically compress the conceptual design phase, limiting opportunities for iterative exploration of alternatives. Clients and project stakeholders often expect rapid progress from brief to concept, leaving insufficient time for comprehensive options analysis. The sequential nature of traditional design processes exacerbates this pressure, as conceptual decisions must be substantially complete before detailed design can commence.

Coordination complexity presents further difficulties. Effective conceptual design requires simultaneous consideration of architectural, structural, mechanical, electrical, and sustainability requirements—domains that traditionally operate within disciplinary silos with distinct professional cultures, analytical methods, and optimisation objectives. Achieving coherent whole-building solutions requires mechanisms for interdisciplinary communication and trade-off resolution that traditional practice often lacks.

BIM Capabilities at the Conceptual Stage. Building Information Modelling offers capabilities that address several of the decision-making challenges characteristic of early design phases. At its foundation, BIM provides a digital representation of physical and functional building characteristics, enabling visualisation, analysis, and coordination that would be substantially more difficult using traditional documentation methods. However, the specific capabilities most relevant to conceptual design differ from those emphasised in later phases [32].

During conceptual design, BIM's value derives less from detailed geometric modelling—which becomes appropriate as design certainty increases—than from rapid massing studies, performance simulation, and options comparison. Contemporary BIM platforms support the creation of simplified geometric models that capture essential building parameters without requiring the investment in detailed modelling characteristic of later phases. These conceptual models can interface with energy simulation engines, structural analysis tools, and cost estimation systems, enabling preliminary assessment of design alternatives against multiple performance criteria [33].

Parametric capabilities further enhance BIM's utility at the conceptual stage. By defining relationships between building elements rather than fixed geometries, parametric approaches enable rapid generation and evaluation of design variants. A parametric massing model might, for instance, allow manipulation of building footprint, height, and orientation whilst automatically maintaining relationships between floor area, structural grid, and envelope area—enabling systematic exploration of the solution space that would be prohibitively time-consuming using manual methods.

Interoperability capabilities allow BIM models to exchange information with specialist analysis tools, enabling multi-criteria assessment during conceptual design. A single conceptual model can, in principle, support energy simulation, structural analysis, quantity take-off, and cost estimation, providing integrated performance feedback that informs design decision-making. This integration addresses, at least partially, the coordination challenges that characterise traditional practice [34].

Building circularity assessment and its integration with BIM face several challenges but also present significant opportunities for improving early design decision-making. Existing circularity indicators, such as the Building Circularity Indicator (BCI), lack standardisation, often require uncertain future data (e.g., reuse rates), and fail to fully incorporate life cycle perspectives or component-level analysis. To address these limitations, recent research proposes enhanced models, such as the Predictive Whole Building Circularity Indicator (PWBCI), which integrates reusability potential, probabilistic assessment, and key factors like disassembly, transportability, and lifespan. BIM–BCA integration approaches can be grouped into three types: external platforms, linked databases, and fully embedded BIM solutions, each with advantages and limitations, particularly regarding real-time use and early design applicability. More advanced approaches embed circularity data directly within BIM through semantic enrichment and data dictionaries, enabling automated assessment of circularity, environmental (LCA), and economic (LCC) performance. Additionally, tools such as material passports and decision-support systems enhance traceability and support design optimization. Overall, the integration of BIM with circularity assessment—especially when combined with multi-criteria decision-making—provides a powerful framework for evaluating trade-offs and supporting sustainable, circular design decisions from the earliest project stages [35].

Research Evidence on BIM in Early Design. Empirical research has examined both the benefits and limitations of BIM application during conceptual design phases. Gerges et al. (2019), in a study of UK construction projects, found that BIM application during the conceptual design phase offered substantial benefits, including improved visualisation, enhanced stakeholder communication, and earlier identification of design conflicts [34]. However, the study also identified barriers including inadequate software interoperability, insufficient training in early-stage BIM applications, and organisational resistance to modifying established design processes. This research highlighted the importance of stakeholder engagement in effective early-stage BIM implementation. The study concluded that “an informed evaluation

of the application of BIM during any particular phase should take into consideration different stakeholders' roles and responsibilities," emphasising that technical capabilities alone are insufficient without appropriate organisational and procedural frameworks. The findings suggest that whilst BIM offers significant potential for enhancing early design decision-making, realising this potential requires attention to human and organisational factors alongside technical implementation [34].

Additional research has examined the specific application of BIM to life cycle cost analysis during conceptual design. McNeil-Ayuk and Jrade (2024) developed a methodology integrating BIM with Life Cycle Cost Analysis (LCCA) to enable comprehensive economic evaluation during early design stages [33]. Their approach combined initial construction costs with operational, maintenance, and end-of-life considerations, providing decision-makers with long-term financial perspectives typically unavailable during conceptual design. The research demonstrated that such integration "empowers designers to evaluate and justify their initial investments while designing and selecting potential construction methods for buildings and enabling stakeholders to make informed decisions by assessing different design alternatives based on long-term financial considerations during the early stages of design."

Limitations of Current BIM Practice in Early Design. Despite demonstrated capabilities, several limitations constrain effective BIM utilisation during conceptual design phases. Level of Development (LOD) specifications, which define the geometric and informational content appropriate to different project stages, often emphasise later phases where detailed modelling supports construction documentation and coordination. The relatively lower LOD specifications appropriate to conceptual design can create uncertainty regarding what information should be included in early-stage models and how that information should be structured.

Software tool development has historically prioritised capabilities supporting detailed design and construction documentation, with comparatively less attention to conceptual design requirements. Whilst contemporary platforms increasingly incorporate conceptual design features, workflows for early-stage exploration often remain less refined than those for later phases. Designers may find that available tools impose premature precision, requiring specification of details—exact dimensions, specific materials, fixed configurations—before such decisions are appropriately made.

Information management protocols present additional challenges. BIM implementation frameworks typically emphasise information consistency and change control—values appropriate to later phases where design stability enables coordination—but potentially constraining during conceptual design when productive exploration may require rapid iteration and tolerance for incompleteness. The overhead associated with maintaining information management protocols can discourage BIM adoption during phases where flexibility and speed are paramount.

BIM and Circular Economy in Construction.

Circular Economy Principles in the Built Environment. Circular Economy in the built environment can be understood through a six-dimensional framework comprising environmental, economic, technological, societal, governmental, and behavioural

aspects. This framework highlights the need for a holistic and interdisciplinary approach, where these dimensions are interconnected and must be addressed collaboratively to enable an effective transition towards circularity. While early research in the sector focused primarily on environmental and technological concerns, current discourse emphasises the growing importance of social behaviour, governance, and new economic models. Evidence from industry and policy discussions shows that technological solutions alone are insufficient; instead, challenges related to stakeholder behaviour, market structures, and regulatory support play a critical role. Furthermore, both top-down (policy-driven) and bottom-up (grassroots) approaches are essential in driving change. Overall, the framework provides a comprehensive basis for understanding the complexity of circularity in construction and supports more informed research and decision-making in the built environment [36].

The circular economy concept represents a systemic approach to economic activity that designs out waste and pollution, keeps products and materials in use, and regenerates natural systems. Within the built environment context, circular economy principles translate into design strategies that extend building and component lifespans, facilitate adaptation and reconfiguration, enable disassembly and component recovery, and maximise the value retained in materials throughout multiple use cycles [37].

AlJaber et al. (2023) identified several core circular economy design strategies applicable to buildings, including design for deconstruction, design for adaptability, and design for flexibility [31]. Design for deconstruction involves specifying connections, assemblies, and material combinations that enable non-destructive disassembly at the end of life, facilitating component reuse and material recycling. Design for adaptability addresses the capacity of buildings to accommodate changing functional requirements without substantial physical modification, extending useful life by enabling purpose evolution. Design for flexibility focuses on spatial and technical provisions that support reconfiguration, allowing buildings to respond to occupant needs without major intervention.

These strategies share a common characteristic: their effectiveness depends substantially upon decisions made during early design phases. A building designed with bolted rather than welded steel connections enables future disassembly; one with load-bearing walls in locations that constrain future spatial arrangements limits adaptability; one with services integrated into structural elements complicates future modification. The implications are clear: circular economy implementation requires consideration of end-of-life scenarios and lifecycle flexibility during conceptual design, not as an afterthought following completion of primary design development.

BIM as an Enabler of Circular Construction. Designing a building involves complex decision-making, often with conflicting objectives, particularly when aiming for sustainability and circularity, which makes decision support systems valuable for providing qualitative and quantitative insights to compare design alternatives. In the context of integrating BIM with circular economy principles, three main approaches have emerged: external circularity assessments using standardised exchange files,

internal assessments within the BIM environment using custom parameters, and automated links between BIM and external material databases through data platforms. For this research, the third approach is the most appropriate due to its high level of automation, scalability, and ability to generate interactive dashboards that help users understand complex information. This automated workflow reduces manual effort and accelerates circular assessments, making the decision support system more effective for guiding circular design choices in the early stages of a project [26]. BIM offers several capabilities relevant to circular economy implementation in construction.

First, the information management foundation of BIM supports the documentation and tracking essential to circular approaches.

Buildings designed for circularity require detailed information regarding material compositions, connection methods, component specifications, and maintenance histories—information that enables future decision-making regarding adaptation, reuse, and recycling. BIM provides a structured framework for creating, maintaining, and transmitting such information across extended timeframes.

Second, BIM's analytical capabilities support circular design evaluation during early phases.

Simulation and analysis tools can assess the implications of design alternatives for adaptability, disassembly potential, and lifecycle performance, providing quantitative feedback that informs circular design decision-making. Life cycle assessment tools interfacing with BIM models can evaluate the environmental implications of material selections and design configurations, supporting choices that minimise virgin resource consumption and waste generation.

Third, BIM's visualisation and communication capabilities support stakeholder engagement around circular economy concepts.

The complexity of circular approaches—which require consideration of extended timeframes, multiple use cycles, and systemic interactions—can challenge traditional communication methods. BIM's capacity to represent not merely current design intent but future scenarios—potential adaptations, disassembly sequences, component reuse opportunities—enhances understanding and buy-in among project stakeholders.

Research has begun examining the intersection of BIM and the circular economy specifically. AlJaber et al. (2023) observed that “applying core principles of circular economy could significantly help the environment by reducing waste and decreasing the life cycle cost of buildings,” whilst noting that BIM provides capabilities supporting this application [31]. Their review identified connections between BIM-enabled life cycle cost analysis and circular economy strategies, suggesting that economic analysis during early design phases can quantify the long-term benefits of circular approaches that might otherwise appear as additional first costs.

Material Passports and Digital Twins. Emerging concepts at the intersection of BIM and circular economy include material passports and digital twins.

Material passports comprise comprehensive documentation of building materials and components, including composition, origin, processing history, performance characteristics, and potential reuse or recycling pathways. When integrated with

BIM, material passports transform building models into dynamic repositories of information supporting circular decision-making throughout the building lifecycle.

Digital twin concepts extend BIM beyond static documentation to dynamic representations that maintain synchronisation with physical assets throughout their operational lives. For circular economy purposes, digital twins enable continuous updating of material and component information based on actual performance, maintenance interventions, and condition monitoring—information essential to informed decisions regarding adaptation timing, component reuse viability, and end-of-life management strategies.

The integration of these concepts with the early design phase of BIM presents both opportunities and challenges. Conceptual design decisions establish the framework within which material passports and digital twins subsequently operate; design for information management during early phases can enhance the effectiveness of these tools during operation and end-of-life. However, the informational richness required by material passports and digital twins may exceed what is practical to specify during conceptual design, creating tension between early-phase flexibility and lifecycle information continuity.

Barriers and benefits of BIM in early design phases. Research has identified numerous barriers to the effective integration of BIM with circular economy principles during early design phases. AlJaber et al. (2023) catalogued 22 barriers related to circular economy adoption in buildings as reported in the literature, divided into six categories: awareness, technical, economic and market, implementation, social and support/promotion, many of which intersect with BIM implementation [31].

Awareness barriers. They refer to limitations in knowledge, understanding, and information flow that hinder the adoption of circular economy principles in the built environment. These include a lack of skills in applying circular strategies, fragmented supply chains that reduce collaboration, and the absence of a holistic or global vision. Additionally, insufficient information during the design phase—such as missing data on existing structures, materials, and the availability of reclaimed components—further constrains decision-making and the effective integration of circular practices.

Technical barriers. Related to the inherent complexity of buildings and the lack of supporting systems and standards, these challenges include difficulties in managing and exchanging building data, the absence of common material classification systems, and limited traceability of components. Moreover, stakeholders often lack reliable information on the quality and quantity of reclaimed materials, face challenges in identifying reusable components, and must deal with insufficient standardisation and specifications for reused and recycled materials.

Economic and market barriers. They relate to financial uncertainties and the immaturity of markets for circular practices. These include difficulties in accurately estimating costs and benefits, a lack of established market mechanisms for material

recovery, and imbalances between supply and demand for reused materials. Furthermore, the absence of a comprehensive life cycle cost perspective limits the ability of stakeholders to recognise the long-term economic value of circular solutions.

Implementation barriers. They refer to organisational and operational challenges in applying circular economy principles in practice. A key issue is the limited understanding among management regarding circularity in construction projects, which can delay or prevent adoption. In addition, the lack of adequate storage facilities for reclaimed materials complicates logistics and reduces the feasibility of reuse strategies.

Social barriers. They stem from perceptions, attitudes, and levels of trust among stakeholders. Misconceptions about the performance, safety, or value of circular buildings can discourage adoption. At the same time, a lack of trust and interest in integrating circular practices further slows the transition, as stakeholders may be reluctant to deviate from conventional construction approaches.

Support and promotion barriers. These are linked to the absence of external drivers that encourage circularity. These include a lack of financial or regulatory incentives to adopt circular practices, as well as insufficient insurance frameworks for reclaimed materials, which increases perceived risk. Together, these factors reduce motivation and confidence among stakeholders to invest in circular solutions.

Barriers.

Technical barriers. Limitations in current BIM tools for representing circular design parameters, with technical barriers, include the fact that standard BIM object libraries often lack attributes relevant to circularity—disassembly time, connection type, material recyclability, component reuse potential—requiring custom development or manual documentation. Interoperability limitations constrain information exchange between BIM platforms and specialist circular economy assessment tools, fragmenting workflows and increasing manual intervention requirements.

Data availability presents additional technical challenges. Circular economy assessment requires information regarding material properties, environmental impacts, and end-of-life pathways that may not be readily accessible during early design phases. Embodied carbon databases, material recyclability indices, and component reuse networks are developing but remain incomplete, particularly for innovative or region-specific materials and systems.

Process and Organisational Barriers. Beyond technical limitations, process and organisational barriers significantly constrain implementation. Traditional design processes typically separate conceptual design from lifecycle considerations, with detailed sustainability analysis and end-of-life planning addressed (if at all) during later phases when fundamental design parameters have been established. Integrating circular economy principles and BIM-enabled lifecycle analysis into conceptual design requires process restructuring that challenges established professional practices.

Professional boundaries present related difficulties. Circular economy implementation requires collaboration across disciplinary boundaries—architects, structural engineers, building services engineers, cost consultants, sustainability specialists, demolition contractors—that traditional practice often separates. Whilst BIM provides technical infrastructure for such collaboration, realising collaborative potential requires complementary organisational and contractual arrangements that many project structures do not support.

Skills and training gaps compound these challenges. Effective early-stage BIM implementation requires competencies that differ from those emphasised in traditional professional education: parametric modelling, multi-criteria analysis, lifecycle thinking, and systems-level design integration. Similarly, circular economy design strategies require an understanding of materials science, building physics, and end-of-life logistics that may fall outside conventional architectural or engineering curricula. The intersection of BIM and circular economy in early design thus requires skill combinations that current professional development pathways incompletely address.

Economic and Market Barriers. Economic barriers significantly influence implementation prospects. First-cost focus in property development and construction procurement discourages investments in design time and analytical capability that yield lifecycle rather than immediate returns. Circular design approaches may involve additional upfront costs—for connection systems enabling disassembly, for example, or for design development time exploring adaptability scenarios—whose benefits accumulate over extended timeframes and potentially to future owners rather than initial developers.

Market mechanisms for circular material flows remain underdeveloped. The economic viability of design for disassembly depends upon the existence of markets for recovered components and materials; without such markets, the additional costs of designing for disassembly yield no countervailing benefits. Similarly, lifecycle cost analyses during conceptual design must incorporate assumptions regarding future material and energy prices, adaptation costs, and end-of-life values that involve substantial uncertainty, potentially undermining confidence in analytical conclusions.

Regulatory frameworks provide mixed signals. Building regulations increasingly address operational energy performance, creating requirements and incentives that BIM-enabled analysis can support. However, regulatory treatment of embodied carbon, material circularity, and end-of-life management remains less developed, reducing external pressure for circular design implementation. The absence of consistent metrics and reporting requirements for circular economy performance complicates comparison across projects and organisations, limiting market recognition for circular approaches.

Benefits. Azhar 2011 demonstrates that Building Information Modelling (BIM) provides significant benefits across different project phases, particularly in terms of cost and time savings, improved decision-making, and enhanced coordination [38]. For example, BIM-enabled clash detection can identify hundreds of conflicts before construction, resulting in substantial cost avoidance and time savings. In

early design and planning stages, BIM supported rapid evaluation of multiple design options, leading to major cost reductions and more informed decisions. Similarly, in fast-track projects, BIM improved coordination, reduced risks associated with incomplete designs and ensured timely project delivery. In sustainable design contexts, BIM facilitated environmental analyses (e.g., daylight and orientation studies), allowing design optimisation early in the process and avoiding costly changes later. Overall, these case studies highlight BIM's strong return on investment and its critical role in enhancing efficiency, collaboration, and decision-making throughout the building lifecycle.

Emerging Directions and Future Prospects.

Technological Developments. Several technological developments offer potential for enhanced integration of BIM with circular economy principles during early design phases. Advances in parametric and generative design enable more systematic exploration of design alternatives against multiple criteria simultaneously. Machine learning approaches show promise for supporting multi-criteria optimisation, potentially identifying design configurations that achieve superior performance across lifecycle cost, environmental impact, and circularity metrics.

Improved interoperability standards and protocols may reduce barriers to information exchange between BIM platforms and specialist analysis tools. Ongoing development of Industry Foundation Classes (IFC) and related standards increasingly addresses sustainability-related information requirements, whilst application programming interfaces (APIs) enable tighter integration between modelling and analysis environments.

Cloud-based platforms and collaborative technologies offer the potential to enhance stakeholder engagement during early design phases. By reducing access barriers and enabling asynchronous participation, such platforms may facilitate the interdisciplinary collaboration essential to effective circular design whilst accommodating the distributed nature of contemporary project teams.

Policy and Market Evolution. Policy developments in several jurisdictions signal increasing attention to lifecycle and circular economy considerations in construction. The European Union's Circular Economy Action Plan (EC 2020) and associated initiatives establish frameworks for addressing material flows, waste reduction, and resource efficiency across economic sectors, including construction [39]. National and local governments are increasingly incorporating embodied carbon and material circularity into planning requirements and public procurement criteria, creating market incentives for circular approaches.

Voluntary standards and certification systems complement regulatory developments. BREEAM, LEED, and similar sustainability assessment methods increasingly incorporate lifecycle and circular economy criteria, creating market recognition and potential competitive advantage for projects demonstrating circular performance. Material certification schemes and supply chain transparency initiatives support the information availability essential to informed circular design decision-making.

Financial mechanisms are evolving to address lifecycle value creation. Green finance initiatives, sustainability-linked loans, and ESG investment criteria increasingly consider building lifecycle performance, potentially improving access to capital for projects demonstrating circular approaches. Insurance and risk management frameworks are beginning to address climate adaptation and material supply risks, creating additional incentives for design strategies that enhance resilience and reduce resource dependencies.

Research Priorities. Several research priorities emerge from analysis of current practice and barriers. Methodological development is needed for early-stage circular economy assessment, including metrics and indicators appropriate to the uncertainty and information constraints characteristic of conceptual design. Such methods must balance analytical rigour with practical applicability, providing decision-relevant insights without requiring informational precision that early design phases cannot support.

Empirical research is needed to document circular design implementation in practice, identifying success factors, common challenges, and effective response strategies. Case study research examining projects that have successfully integrated BIM with circular economy principles during early design would provide valuable learning for the broader industry, whilst longitudinal studies tracking buildings through construction, operation, and end-of-life would generate evidence regarding the actual outcomes of circular design approaches.

Integration research should examine how BIM-enabled circular design intersects with other early-phase considerations, including cost, programme, aesthetics, and regulatory compliance. Understanding these interactions would support the development of practical guidance for design teams seeking to incorporate circular principles alongside conventional project requirements.

Final Remarks on BIM integration in early design phases. The early design phase represents a critical opportunity for influencing building lifecycle performance, yet realising this opportunity requires analytical capabilities and decision-making support that traditional practice often lacks. Building Information Modelling offers substantial potential for enhancing early-phase decision-making through visualisation, simulation, and multi-criteria analysis capabilities, whilst the principles of the circular economy provide a framework for design approaches that reduce environmental impacts and enhance long-term value.

The integration of BIM with circular economy principles during conceptual design remains incompletely achieved. Technical barriers, including tool limitations and data availability; process barriers, including traditional phase separation and professional boundaries; and economic barriers, including first-cost focus and underdeveloped markets for circular material flows, all constrain current implementation. Addressing these barriers requires coordinated advancement across technology development, professional practice, regulatory frameworks, and market mechanisms.

Evidence from research and practice demonstrates both the potential benefits and the practical challenges of early-stage BIM application. Studies consistently find that effective implementation requires attention to organisational and human factors

alongside technical capabilities, suggesting that technology alone is insufficient without complementary process and skills development. The emerging intersection of BIM with circular economy concepts amplifies these requirements, demanding integration of lifecycle thinking into design workflows traditionally focused on immediate project delivery.

Future developments in technology, policy, and market mechanisms offer promise for enhanced implementation. Advances in parametric design, interoperability, and analytical capabilities may reduce technical barriers, whilst evolving regulatory requirements and market incentives may strengthen the business case for circular approaches. Realising this promise will require sustained engagement from researchers, practitioners, policymakers, and industry stakeholders committed to transforming how buildings are conceived, designed, and delivered.

The construction industry's transition toward circularity represents a generational challenge requiring fundamental reconsideration of design assumptions, professional practices, and value frameworks. BIM, deployed effectively during early design phases, can serve as both a technical enabler and a catalyst for this transformation—supporting the informed decision-making essential to creating buildings that serve their intended functions whilst contributing to rather than detracting from environmental sustainability and resource stewardship.

3.3 Roles and Responsibilities of Design Practitioners in a Circular Built Environment

Design practitioners in a circular built environment act as “orchestrators” of a restorative industrial economy, moving beyond traditional aesthetics to manage complex resource loops. Their primary responsibility is to “design out” waste by viewing buildings and building components as resources with multiple future lifecycles. Core roles and responsibilities of design practitioners to steer CE in the built environment include Strategic Resource Management, through which practitioners prioritise “leanness” by reducing initial material volume and specifying non-toxic, sustainable materials that allow for future reuse. *Design for Disassembly (DfD) & Adaptability (DfA)*, when architects and engineers are responsible for creating buildings that can be easily taken apart, repaired, or repurposed. This involves using non-permanent connections and modular components to prevent future demolition waste. *Digital Data Custodianship*, when designers utilise Building Information Modelling (BIM) and Material Passports to track components. Creating digital building information models and material inventories is increasingly considered an important responsibility to provide future stakeholders with data for disassembly and high-quality material recovery. Digital information systems, including material passports and building databases, play an important role in supporting circular construction by enabling traceability of materials and facilitating their recovery and reuse in future building cycles [1]. *Lifecycle Orchestration*, on the basis of which professionals perform Life

Cycle Assessments (LCA) to evaluate embodied carbon and environmental impacts across all future cycles, not just the initial construction. *Collaborative Leadership*, thanks to which practitioners co-create solutions with the entire supply chain—including investors, demolition experts, and material suppliers—to align technical designs with circular business models like “product-as-a-service”.

The concept stage marks the beginning of architectural design, establishing essential ideas about form, function, and how the project fits within its context. This phase lays the groundwork for elements such as sustainability, material longevity, and potential user experiences. Activities include sketching and analysing the site, as well as making early non-final choices that help guide the project before moving on to detailed design work.

To mainstream Circular Economy in the built environment, it is important to identify and implement circular strategies at the early stages of architectural design, leveraging the support of specific frameworks and tools.

3.4 *Circular Strategies for Early-Stage Architectural Design*

Circular design strategies can also be interpreted through the management of resource flows within the built environment. These flows typically include materials, energy, water, and mobility, and their management influences broader environmental and social values such as ecosystem protection, health, and cultural value [25]. Circular design strategies for early-stage architectural design focus on pre-emptive measures and systems thinking to minimise resource depletion and waste before a project is designed in detail, engineered, and realised. Research highlights that up to 80% of a building’s environmental impact is determined during the initial concept phase.

Circular frameworks also emphasise a sequence of strategies that prioritise the preservation of existing assets, the reduction of resource demand, the integration of circular material inflows, the securing of future reuse, and the responsible management of material outflows [25].

Developing guidelines for early design phases to embed circularity involves integrating systemic thinking, engaging stakeholders, and using iterative processes and specific strategies. Key strategies for circularity pertaining to the early-stage architectural design that emerged from the conducted study are summarised below.

Design for future climate adaptation and resilience. This strategy aligns with the core objective of Design for Longevity, which is to maximise the enduring value of buildings and their individual components by enhancing both value retention and recovery over time. At the building level, the approach focuses on safeguarding architectural qualities that retain lasting appeal by prioritising the selection and design of resilient products that can withstand prolonged use. At the component level, it advocates for materials and products engineered for durability, ideally exceeding the required service life to enable future adaptation and reuse. The longevity of these components is intrinsically connected to their design, as it determines essential

aspects such as quality, maintenance requirements, repair needs, adaptability, and residual value upon removal. Incorporating resilience to evolving climate conditions into the early-stage design process is essential to ensuring the long-term performance and value of buildings, particularly for layers and systems with extended lifespans [10, 13, 20, 25].

While futureproofing often results in designs that require increased material consumption to meet rigorous performance criteria, adopting a staged approach that emphasises incremental adaptability over planning for distant worst-case scenarios is advisable [2, 12, 16, 20].

Investigate Product-as-a-Service schemes for components expected to have a short or medium service life in the project. This strategy supports Design for Longevity by maximising the value of buildings and components over time through enhanced retention and recovery. It emphasises durable, resilient architectural choices and advocates for materials that exceed required service lives, allowing for future adaptation and reuse. Longevity depends on thoughtful design that addresses quality, maintenance, repair, adaptability, and end-of-life value. Factoring in resilience to climate change is also key to maintaining long-term performance, especially for elements with long lifespans [1, 8, 9, 13–15, 17].

Certain building components are frequently replaced before the end of their initial functional lifespan. For instance, facades, building services, or interior design elements may be substituted due to tenant turnover or for aesthetic updates [1, 2, 8, 9, 13–15, 17]. Product-as-a-service and leasing models enable payment based on actual utilisation—measured by time, cycles, or performance—instead of full ownership of the asset. These approaches significantly enhance the value retention of serviced products, optimising proactive maintenance and increasing opportunities for reuse and recycling [3, 13, 16, 22].

Design for Adaptability. This approach is intended to enable and enhance the adaptability of buildings during their operational phase. Given the typically short functional lifespan of buildings, it is essential that they be capable of accommodating new uses to maintain their value. The strategy incorporates two key design principles for adaptability: versatility and convertibility, each associated with specific requirements for system modifications. This strategy is particularly suitable for sites and building types where changes in use are anticipated [2, 4, 5, 8–11, 13, 15, 17–19, 22–24].

Refuse Unnecessary Components. This strategy aims to meet the project requirements with minimal material consumption. At all levels, it fosters simple design approaches and thoughtful consideration of the real needs of components and materials. It aims to question whether certain components can be refused without compromising the project's ability to function at the desired performance level [4–6, 10–12, 14].

Increase material efficiency. This approach focuses on fulfilling project requirements while using as little material as possible. It emphasises making the most efficient use of materials to achieve top performance at every level. The strategy seeks to avoid inefficient building elements, such as tall structures, long spans, cantilevers,

or deep underground spaces, and instead prioritises effective systems and designs. Additionally, it encourages the selection of high-performance materials and advanced engineering methods [1, 2, 4–6, 8, 10, 16, 20, 28].

System Thinking. Systems thinking offers a holistic approach, enabling designers to view products as interconnected parts of larger ecological and economic systems. When combined with Circular Economy practices, systems thinking facilitates strategies to extend product life and maximise resource efficiency. Systems thinking offers a pathway to resilient, regenerative design that aligns with Circular Economy principles. Designing with long-term thinking shifts the focus from immediate utility to sustainable longevity. This fosters a mindset where buildings are valued, maintained, and shared. Adaptability becomes key, encouraging designers to develop since the early-stage projects that can be updated to suit evolving user needs and societal shifts [2–4, 7, 13, 14, 20, 25].

Stakeholder Engagement. Early-stage stakeholder engagement is crucial for early-stage circular architectural design to align diverse interests, foster collaboration, and establish a shared vision for sustainability. By involving key actors—clients, designers, contractors, and policymakers—from the inception, projects can effectively adopt, for example, circular principles such as design for adaptability, material traceability, and resource management. A primary barrier remains the lack of CE-specialist integration at the start of projects, often leading to missed opportunities for a radical shift in design-thinking [1, 8, 20, 26, 27].

Early-Stage Decision Making. In early-stage architectural design (schematic and concept phases), decision-making has the highest impact on a building’s final circularity while implementation costs remain lowest. The ongoing shift in practice emphasises integrating qualitative ambitions with automated digital tools to guide these initial choices [13, 21, 26].

3.5 Frameworks and Tools Supporting Conceptual Circular Building Design

The second research question—*RQ2: “Which tools and frameworks can effectively support practitioners during conceptual circular building design?”*—focuses on the operational mechanisms that enable the implementation of Circular Economy during architectural concept development. In early-stage design, key decisions on morphology, structural system, spatial grid, and principal material families are made with limited information, exerting substantial influence on lifecycle impacts and circular potential. As already highlighted, the conceptual phase is the highest-leverage stage, offering low-cost opportunities to steer long-term resource and emissions outcomes before design lock-in.

Drawing on the conducted literature review, tools and frameworks supporting circular early-stage architectural design can be structured into four analytically distinct but interrelated categories:

1. *Early Integration*: tools that embed circular criteria from the project outset.
2. *Data-Driven Decision Making*: tools that quantify performance and trade-offs (e.g., circularity indicators, LCA integration).
3. *Scenario Testing*: tools enabling exploration of alternative circular configurations (e.g., reuse, transformation, deconstruction).
4. *Holistic View*: tools that structure lifecycle coherence and connect building decisions to broader CE systems (e.g., traceability, governance, value chains).

The development of reliable circularity indicators for buildings remains an important research topic. Existing studies highlight the need for transparent metrics that enable comparison of design alternatives and support decision-making throughout the building life cycle [1].

Following the identification and screening of relevant publications addressing Circular Economy tools and frameworks in the built environment, the selected studies were subjected to thematic coding. Rather than classifying tools by technological typology (e.g., digital vs non-digital) or scale (component vs building), the analysis focused on their *functional role within the conceptual design process*. This function-oriented approach is consistent with the role of architects as “concert masters” coordinating circular outcomes across stakeholders and lifecycle stages.

An open coding phase first identified recurring operational function attributed to tools in early-stage design contexts, including impact benchmarking, disassembly assessment, lifecycle structuring, and configurational exploration. These preliminary codes were then clustered through axial coding into higher-order categories reflecting distinct knowledge-based functions in architectural decision-making. The resulting four categories capture complementary dimensions of methodological support: (i) tools embedding circular criteria at the design outset; (ii) tools enabling quantitative comparison of alternatives; (iii) systems facilitating iterative scenario exploration; and (iv) frameworks ensuring lifecycle coherence across stages.

This function-oriented categorisation provides a process-based analytical lens aligned with the dynamics of conceptual architectural design, thereby enabling a structured comparison of heterogeneous tools within a coherent decision-making framework. By grounding the classification in the design process rather than in technological taxonomy, the framework enhances transferability across different regulatory, geographic, and practice contexts.

1. **Early Integration: Embedding circular criteria in early-stage design configuration.** Early Integration tools intervene at the point where architectural decisions most strongly define future circular performance: selection of building typology and massing, structural logic, spatial modularity, and high-level material strategies. Their principal contribution is to ensure that circularity is treated as a front-end design requirement, rather than a downstream evaluation exercise.

A first cluster consists of stage-based guidance frameworks that embed CE criteria into briefing and conceptual design workflows. The *Circular Building Design Toolkit* [9] and the *Circular Economy Design Guide* [17] provide structured pathways that translate CE principles into design-stage actions, supporting early alignment between client ambition, spatial concept, and material strategy. Similarly, the *DGNB framework* [18] and broader systemic guidance documents such as *Building a Circular Economy* [23] and *Circular Building Design: Strategies and Tools* [22] normalise Circular Economy principles by embedding them within established design-stage structures, certification logic, and structured project guidance. Through checklists, lifecycle alignment mechanisms, and stage-based integration, these tools reposition circular criteria as standard decision parameters within early architectural development rather than optional sustainability enhancements. Client-facing instruments [4] and commitment-setting tools [14, 16] further operationalise early integration by stabilising expectations, responsibilities, and circular performance intent before design development.

A second cluster comprises low-detail steering and circularity index approaches that enable comparative screening at the schematic stage. Tools focused on early design evaluation [26] and building-level circularity indicators [7] allow concept teams to compare alternative schemes using simplified inputs (e.g., structural typology assumptions, material families, separability heuristics). Their strength lies in supporting relative decision-making when detailed datasets are not yet available, enabling early prioritisation of higher-value retention strategies rather than “end-of-pipe” mitigation.

A third cluster integrates Design for Disassembly (DfD) and reversibility logic into conceptual configuration. The *Circular Toolbox* [6]—including components such as material passport thinking, circular demolition approaches, digitalisation, and reuse-oriented supply chain strategies—strengthens early integration by connecting design decisions to future recovery pathways. Scenario-oriented tools, such as the Conceptual Digital Deconstruction Model [24], also support early DfD thinking by making disassembly and recovery consequences visible before technical detailing is finalised.

Across these subclusters, *Early Integration* tools reinforce the report’s emphasis on leveraging early-stage decisions and the architect’s responsibility to coordinate circular intent among stakeholders, including clients, engineers, contractors, and future recovery actors.

2. **Data-Driven Decision Making: Quantitative evaluation of environmental and circular performance trade-offs.** Data-driven tools provide measurable evidence for comparing alternatives during concept design. Their primary contribution is to shift circular decision-making from intuitive sustainability claims toward transparent, auditable evaluation—particularly important under emerging regulatory and market expectations for demonstrable performance and traceability.

This category is dominated by indicator frameworks, circularity metrics, and assessment methodologies. Tools such as the *Framework for Circular Buildings Indicators* [10], *Circular Economy Metrics for Buildings* [11], and *Methodology to Assess Circularity in Buildings* [12] formalise what “circular performance” means at the building scale. Complementary works [1, 21] provide conceptual clarification and classification of indicator families, supporting comparability and reducing conceptual ambiguity across studies and applications. This is consistent with the broader literature identifying fragmentation and a lack of harmonisation as core obstacles to effective circularity assessment.

A key methodological subset concerns integration with life cycle assessment (LCA). *Applying Circularity in the LCA Framework* [15] and *Assessing Prospective Environmental Impact* [5] demonstrate how circularity assessment can be embedded within environmental evaluation, including forward-looking framing. This integration is critical because circular design decisions often involve trade-offs (e.g., more robust assemblies enabling reuse may increase initial embodied impacts; reuse strategies may lower carbon but increase logistics). The literature increasingly underlines that digital tools and indicators only generate environmental benefit when embedded in coherent circular strategies such as DfD and value-chain alignment.

Data-Driven methodologies also include building-type-specific indices [7] and approaches focused on existing building contexts [25]. Their relevance to concept design is twofold: (i) they inform whether adaptive reuse or transformation is preferable to demolition and rebuilding, and (ii) they help evaluate circular potential under constraints typical of retrofit and reuse projects.

Finally, methodological critiques such as *Obstacles and Barriers for Measuring Building Circularity* [28] are not intended as “tools” in the operational sense but rather function as essential decision-quality safeguards. They support proper tool selection by highlighting pitfalls such as data gaps, inconsistent boundaries, and indicator misuse—issues that are explicitly echoed in the broader assessment literature.

In conceptual design practice, Data-Driven tools are most effective when used iteratively and comparatively—testing multiple massing options, structural solutions, and material families—rather than being applied once as a late-stage validation. This aligns with the assumption that early-stage decision-making is the primary lever for reducing lifecycle impact.

3. **Scenario Testing: Exploring alternative circular futures under uncertainty.**

Scenario Testing tools enable conceptual teams to explore multiple plausible futures—changes of use, refurbishment cycles, component replacement, and end-of-life strategies—before committing to detailed design pathways. This is particularly relevant because circular outcomes depend not only on present design choices but also on future governance, market infrastructure, recovery technologies, and regulatory conditions. The literature emphasises that uncertainty about future circular systems is a real barrier, making scenario-based design support especially valuable.

Among the scenario-testing tools identified in the systematic review, the *Conceptual Digital Deconstruction Model* [24] clearly supports exploration of disassembly

sequencing and recovery outcomes. Rather than functioning only as an end-of-life tool, its conceptual-stage value lies in revealing how structural layouts, access strategies, and connection logics constrain future reversibility.

Tools such as the *Developing Regenerate: Circular Economy Engagement Tool* [13] expand scenario testing beyond technical simulation to structured stakeholder exploration, supporting collaborative evaluation of circular options, value propositions, and feasibility under alternative conditions. Meta-level mapping and evaluation works [19, 27] further support scenario testing by helping practitioners identify which digital/analytical tools are suitable for a given design intent and context.

In conceptual design, scenario tools are particularly important for operationalising the report's strategic approaches, such as Design for Adaptability and System Thinking, transforming them into explicit, testable design choices rather than mere aspirations.

4. **Holistic View: Structuring lifecycle coherence and connecting design to CE systems.** Holistic tools provide frameworks that ensure concept design decisions remain coherent across lifecycle stages and across the value network required for circularity (procurement, maintenance, recovery, and secondary markets). The literature repeatedly notes that circularity in the built environment is multi-level and stakeholder-dependent; therefore, tools that structure whole-of-life alignment are essential.

The *Circular Built Environment Playbook* [8] provides integrated lifecycle guidance that supports strategic coherence across project stages, while the *Circular Toolbox* [6] embeds traceability and recovery logic through digitalisation and material passport thinking. Cross-cutting indicator methodologies such as *Circular Transition Indicators* [3] and the *BCM Methodology* [20] further strengthen holistic framing by connecting building-level choices to broader governance and performance monitoring systems.

Holistic tools are crucial for addressing a recurring gap highlighted in the literature: digitalisation and traceability systems (BIM, digital twins, passports) do not automatically deliver circular outcomes unless circular requirements and value-creation models are embedded from the outset.

In practical terms, holistic tools support architects and teams in ensuring that early design integrates the enabling conditions for circularity: traceable information, compatible procurement logic, and future recovery pathways. This directly reflects the report's framing of practitioner responsibilities and the need for early stakeholder coordination.

5. **Synthesis: How the four categories function together in conceptual design.** The four categories describe complementary functions, not alternative approaches. A consistent pattern across the tools and frameworks identified in the literature review is that circular concept design is most robust when it integrates:

- Steering (Early Integration: define constraints and intent early),
- Evidence (Data-Driven: quantify trade-offs and compare options),

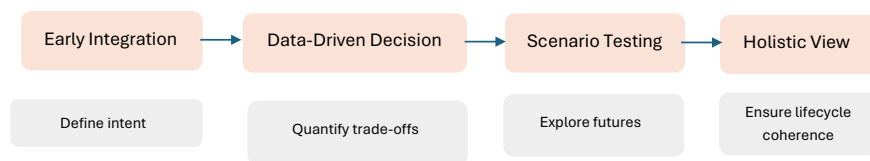


Fig. 3 Function-oriented framework for circular design supports early-stage architectural decision-making, integrating four complementary domains

- Exploration (Scenario Testing: test alternative futures and trajectories),
- Coherence (Holistic: align lifecycle stages and value networks).

This layered use reflects the aim of this research work, emphasising that circular design is not a single technical action but a coordinated design-and-governance process.

The analysis of tools and frameworks supporting conceptual circular building design highlights the existence of four complementary functional domains: Early Integration, Data-Driven Decision Making, Scenario Testing, and Holistic View. These domains do not operate independently but form an integrated decision-support structure for circular architectural design. This functional relationship is illustrated in Fig. 3.

4 Discussion

The Circular Economy in the Built Environment transitions from a “take-make-dispose” approach to a regenerative framework that emphasises designing buildings for longevity, adaptability, reuse, and recyclability. This model seeks to minimise waste and emissions by treating materials as valuable assets and reducing dependence on virgin resources. Strategies such as modular design, implementation of material passports, and the prioritisation of bio-based materials are employed to extend the useful life of building components and support net-zero objectives. Overall, this approach aims to lengthen the lifespan of both structures and materials, harmonise with natural systems and generate economic value while mitigating environmental impact.

4.1 From Tool Inventory to Functional Design Logic

This study adopts a function-oriented analytical approach to examine how circular design support tools operate within the conceptual phase of architectural decision-making. Rather than organising instruments according to their technological format

or disciplinary origin, the analysis classifies them based on their functional contribution to early-stage design processes. Existing literature often presents Circular Economy tools as discrete instruments, such as indices, guidelines, digital platforms, or lifecycle assessment extensions, without systematically clarifying how they influence spatial configuration, structural choices, or lifecycle reasoning at the conceptual stage. As a result, the relationship between tool typology and architectural decision logic remains under-theorised. By structuring the analysis around functional roles in conceptual design, this study provides a clearer methodological lens for assessing the operational relevance of circular support instruments.

By classifying the identified tools and frameworks into four functional domains—Early Integration, Data-Driven Decision Making, Scenario Testing, and Holistic View—this research proposes a new interpretative structure grounded explicitly in the logic of conceptual design. The novelty does not reside in the individual tools themselves but in demonstrating that their effectiveness depends on their position within a coordinated decision-support ecosystem.

This functional categorisation moves beyond technological classification (e.g., digital vs analogue tools) and instead foregrounds decision influence as the key analytical variable. The central methodological insight is that circular design tools must be evaluated according to how they shape early-stage architectural reasoning, not merely by their technical sophistication or indicator complexity.

4.2 Relevance of Early-Stage Framing

A second contribution concerns the explicit positioning of the conceptual phase as the critical leverage point for circular economy implementation. While numerous studies emphasise lifecycle thinking, relatively few systematically connect tool typologies to early spatial and structural decisions.

The present framework demonstrates that circularity becomes structurally embedded—or structurally constrained—at the moment when massing logic, structural systems, and material families are defined. This finding reinforces the argument that circular economy strategies must be integrated upstream, before technical detailing and procurement logic stabilise the project trajectory.

The relevance of this framing lies in its capacity to redirect research and professional focus toward the design moment of strongest influence rather than toward end-of-life mitigation strategies.

4.3 Integrating Quantification and Systemic Alignment

Another methodological contribution of this study is clarifying the relationship between quantitative evaluation and systemic coherence. The circularity assessment literature often emphasises measurement challenges, indicator proliferation,

boundary inconsistencies, and data fragmentation. However, the present analysis demonstrates that these challenges are not purely technical; they stem from insufficient integration between measurement tools and lifecycle structuring frameworks.

Measuring circularity in buildings remains methodologically challenging due to the inherent complexity of building systems and the absence of universally standardised circularity indicators. Buildings consist of multiple components with different service lives and replacement cycles, which complicates the definition of system boundaries and the interpretation of circularity performance. Furthermore, the overlap between sustainability and circularity indicators, along with potential subjectivity in indicator selection, may lead to inconsistent or biased assessments. These challenges highlight the importance of transparent methodologies and harmonised measurement approaches when evaluating circular building performance [28].

The distinction between Data-Driven and Holistic domains highlights that quantification must be embedded within clearly defined lifecycle boundaries and governance structures. Without this alignment, circular metrics risk producing partial or misleading performance representations.

This insight contributes to ongoing debates in Circular Economy research concerning the reliability and comparability of circularity indicators. The study suggests that measurement robustness is inseparable from systemic integration.

4.4 Addressing Uncertainty through Scenario Logic

The identification of Scenario Testing as a distinct functional domain reflects a methodological advancement in the conceptualisation of circular design. Circular transitions are inherently uncertain: future reuse markets, regulatory standards, and technological infrastructures cannot be assumed to be static. By elevating scenario exploration to a structural component of conceptual design support, the study introduces adaptability as a testable design variable rather than a rhetorical objective. This contribution aligns circular design with broader resilience and foresight research, positioning architectural conceptualisation as an anticipatory practice.

4.5 Theoretical Implications

At a theoretical level, the framework contributes to bridging Circular Economy theory and architectural methodology. Circular Economy discourse often operates at macroeconomic or industrial scales, while architectural research focuses on building-scale interventions. By structuring tool functions according to early-stage decision processes, this study creates an analytical bridge between systemic resource logic and spatial configuration.

By adopting this approach, the concept of circularity is refined, expanding its role beyond mere sustainability enhancement to become a fundamental aspect of architectural reasoning itself.

5 Final Remarks

This chapter aimed to identify how circularity principles can be implemented during the conceptual phase of architectural design and to examine the methodological support needed for architects and other stakeholders to make informed circular design decisions from the outset, by addressing two central questions. The first referred to “What early-stage methodological approaches effectively embed CE principles in building design?” Key findings included the confirmation that early CE strategies for building design emphasize systemic frameworks (like Design for Climate Adaptability and Resilience, and Servitization), and comprehensive frameworks that address technical (like Design for Adaptability and Increase Material Efficiency), cultural, business and governance factors, all supported by collaboration among stakeholders and the use of integrated digital tools (such as BIM, AI, and LCA).

The focus shifts from simple material recycling to a holistic approach that aims to retain lifecycle value and achieve positive social and environmental outcomes across all project stages, starting from the concept and architectural design phase.

The second research question aimed to explore: “Which tools and frameworks can effectively support practitioners during conceptual circular building design?” By answering this question, this research advances Circular Economy implementation in the built environment by clarifying how conceptual architectural design can be methodologically supported through the deployment of structured tools. Rather than reiterating the inventory of instruments identified, the study provides a functional interpretation of circular design support grounded in four interrelated domains:

- “Early Integration”: Instruments that assess material origins, ease of disassembly, and projected impacts from the initial design stages;
- “Data-Driven Decision Making”: Solutions like BIM and LCA offer quantitative data for comparing alternatives (e.g., primary vs. recycled materials);
- “Scenario Testing”: Parametric modelling and computational plugins facilitate visualisation and experimentation with various circular design scenarios;
- “Holistic View”: Tools and frameworks that structure consideration of all lifecycle stages—extraction, design, usage, and end-of-life.

In this field, the primary contribution of this work lies in demonstrating that circularity at the conceptual stage is not achieved through the isolated application of indicators, digital platforms, or guidance documents. Instead, effective circular design requires a coordinated alignment of steering mechanisms, quantitative evaluation frameworks, exploratory modelling tools, and lifecycle structuring instruments. The four-category framework provides a coherent analytical structure that organises this alignment and

clarifies the distinct yet complementary roles that tools play in shaping early-stage architectural decisions.

A central finding of the study is that circular performance is fundamentally determined at the moment when spatial and structural systems are defined. *Early Integration tools* are therefore not merely supportive instruments; they establish the conditions under which adaptability, reversibility, and value retention remain feasible. Without early embedding of circular criteria, subsequent evaluation and optimisation efforts operate within already constrained design logics. The research thus reinforces the strategic importance of the conceptual phase as the most influential arena for circular transition in the built environment.

At the same time, the analysis confirms that normative steering alone is insufficient. *Data-Driven Decision-Making tools* are necessary to substantiate design choices using measurable and comparable criteria. In an increasingly performance-based regulatory and procurement environment, circular ambition must be translated into quantifiable evidence. However, measurement frameworks derive their effectiveness from clear boundary definition and coherent lifecycle logic. The study, therefore, underscores the importance of structured, transparent indicator systems that support informed trade-off analysis without oversimplifying the complexity of circularity.

Scenario Testing tools introduce an additional dimension that is often underemphasized in architectural discourse: the management of uncertainty. Circular economy transitions unfold within evolving regulatory, technological, and market contexts. Buildings are long-lived entities, and conceptual design must anticipate potential transformation, reuse, and recovery pathways. By enabling structured exploration of alternative futures, scenario-based instruments increase design resilience and operationalise adaptability as a measurable attribute rather than an abstract principle.

Finally, *Holistic tools* ensure that conceptual decisions remain aligned with broader lifecycle systems, including governance frameworks, traceability infrastructures, and value chain coordination. Circular architecture does not end at the design studio; it requires compatibility with material passport systems, digital information flows, and recovery networks. The study highlights that lifecycle coherence must be structurally embedded from the outset if circular intent is to be realised beyond project boundaries.

Collectively, the four functional domains identified in this research form a coherent decision-support architecture for conceptual circular building design. Their integration reflects a shift from viewing circularity as a discrete sustainability measure toward understanding it as a systemic design condition. This reframing has significant implications for both research and practice.

From a scientific perspective, the framework advances circular design research by providing a function-oriented taxonomy grounded in early-stage architectural processes. It moves beyond descriptive tool catalogues toward a structured understanding of how different methodological families interact within the design workflow. This structure supports comparability across contexts and provides a stable analytical lens for future studies examining emerging digital tools or regulatory instruments.

From a professional standpoint, the findings highlight the expanding scope of architectural responsibility. Circular conceptual design requires the integration of spatial reasoning, lifecycle analysis, performance quantification, and systemic coordination. Architects and design teams are increasingly positioned not only as form-makers, but also as orchestrators of material flows, information systems, and long-term value retention strategies. The functional architecture presented here offers a structured basis for operationalising these responsibilities.

The study also clarifies that circularity cannot be reduced to material substitution or enhanced recycling rates. Upstream design decisions regarding structural rationalisation, modularity, and separability determine whether downstream recovery strategies remain technically and economically viable. Consequently, circular transition in the built environment depends less on isolated technological breakthroughs and more on the systematic integration of decision-support instruments within the conceptual phase.

Future research should therefore focus on empirical validation of the four-category framework across real-world projects, assessing how different tool combinations influence design outcomes. Additional investigation is required to evaluate interoperability between digital platforms, lifecycle assessment systems, and emerging regulatory mechanisms such as digital product passports. Furthermore, research into organisational and procurement structures will be critical to understanding how circular design support can be effectively institutionalised.

In conclusion, the transition toward a circular built environment requires a methodological infrastructure capable of shaping decisions at the point of greatest leverage. The four functional domains identified in this study provide a scientifically grounded foundation for such an infrastructure. By structuring how circular criteria are embedded, quantified, tested, and aligned across lifecycle stages, this framework contributes to transforming circular economy principles from aspirational discourse into operational design logic.

While this research provides a structured and function-oriented framework for categorising tools and frameworks supporting circular conceptual building design, some limitations should be acknowledged.

Scope and Dataset Boundaries. Firstly, the study is based on a defined corpus of selected tools and frameworks identified through systematic review procedures. Although the selection process followed transparent criteria, the circular economy tool stack is rapidly evolving. New digital platforms, assessment methodologies, and regulatory instruments continue to emerge, particularly regarding digital product passports, BIM-integrated lifecycle tools, and AI-assisted material tracking. Consequently, the proposed framework reflects the state of knowledge at the time of analysis and may require periodic updating to remain comprehensive.

Conceptual-Phase Focus. Secondly, the analysis deliberately focuses on the conceptual architectural design phase. While this focus is justified by the high leverage of early-stage decisions, it also limits the scope of investigation. Some tools included in the dataset demonstrate greater operational precision at later design stages (e.g., detailed LCA calculations, advanced material passport documentation).

Their classification within conceptual support functions necessarily abstracts from their full technical capacity.

Additionally, conceptual design operates under conditions of uncertainty and incomplete data. Many tools rely on generic datasets or simplified assumptions at this stage. While comparative benchmarking remains meaningful under such conditions, absolute performance accuracy cannot be guaranteed. The findings should therefore be interpreted as addressing decision-support robustness rather than predictive precision.

Functional Categorisation Assumptions. The categorisation into four functional domains reflects an analytical abstraction. Although grounded in systematic thematic coding aligned with the aim of this research work, functional boundaries between Early Integration, Data-Driven Decision Making, Scenario Testing, and Holistic View are not rigid in practice. Many tools operate across multiple design stages and organisational levels. The framework emphasises dominant functional roles, but it does not capture all contextual variations in tool deployment.

Moreover, the study does not empirically measure the performance effectiveness of individual tools. Instead, it evaluates their methodological potential and states design support functions based on documented characteristics. The actual impact of these tools depends on practitioner competence, organisational culture, procurement models, and stakeholder coordination, which were beyond the scope of this review.

Interoperability and Data Quality Constraints. The increasing reliance on digital tools (e.g., BIM-integrated LCA, material passports) introduces further limitations related to data quality, interoperability, and standardisation. Circular performance metrics are highly sensitive to system boundaries, data granularity, and modelling assumptions. Inconsistent datasets or incompatible digital platforms may reduce comparability across projects. While the study identifies these issues conceptually, it does not empirically evaluate technical interoperability between platforms.

These limitations do not diminish the relevance of the findings but rather delineate their scope. The proposed framework should be understood as:

- A structured analytical lens for organising circular design support tools;
- A decision-support framework applicable to early-stage design contexts;
- A basis for further empirical validation and methodological refinement.

By explicitly acknowledging contextual, technological, and organisational constraints, the study situates its contribution within the broader and evolving landscape of circular transition research.

Advancing Circular Economy within the Built Environment is essential from multiple perspectives. From an environmental standpoint, this approach reduces carbon emissions, minimises landfill waste, and preserves natural resources. Economically, it presents significant opportunities for value creation and market expansion. In terms of resilience, it supports the development of infrastructure that is less vulnerable to fluctuations in raw material supply chains.

Early-stage circular building design is critical for determining lifecycle impacts because decisions made in the concept and planning phases lock in major environmental consequences for energy, resources, and costs, with huge potential for

low-cost optimisation before detailed design commits to materials and systems. Integrating Life Cycle Assessment (LCA) early allows architects to test different options (such as materials, site layout, and energy systems) to minimise impacts across a building's entire life cycle, from material extraction through construction, operation, and end-of-life.

At present, circular practices remain limited in adoption, with predominant emphasis placed on lower-order principles such as “reduce, reuse, recycle,” rather than on more strategic, higher-value interventions. Integrating Circular Economy principles into conceptual architectural design requires a shift towards designing for disassembly, modularity, and material reuse from the outset. It necessitates selecting sustainable materials, employing life cycle systemic thinking, utilising material passports, and adopting collaborative, regenerative, and adaptive design strategies to ensure buildings can be adapted, dismantled, and repurposed, facilitating a transition from linear models to a sustainable built environment.

Opportunity windows for integrating circular economy principles in early-stage design are emerging, moving from theoretical frameworks to mandatory operational requirements. Driven by landmark legislation and technological breakthroughs, early-stage design is now recognised as the critical phase where up to 80% of a product's environmental impact is determined. Significant policy shifts soon expected will be forcing designers to prioritise circularity at the ideation stage to ensure market access. Those include *EU Circular Economy Act*: expected in late 2026, this act will establish horizontal standards for design, focusing on durability, reparability, and recyclability to create a unified market for secondary raw materials. *Ecodesign for Sustainable Products Regulation* (ESPR): effective July 2026, it will mandate sustainability requirements for nearly all physical goods in the EU. *Digital Product Passports* (DPPs): by July 2026, the first wave of DPPs will be activated, requiring designers to embed data traceability into products to facilitate future repair and recycling. By July 31st, 2026, EU member states must ensure citizens have a material right to repair, compelling manufacturers to design goods for longer lifespans and easier disassembly.

Achieving circularity in the built environment, therefore, requires integrating circular design principles from the earliest stages of architectural design and developing reliable assessment tools and indicators that capture the complexity of building life cycles [1, 28].

Beyond the identification of strategies, tools, and frameworks, a critical implication of this work lies in the recognition that circularity in the built environment is ultimately a design governance challenge rather than a purely technical one. While methodological support is increasingly available, its effectiveness depends on the capacity of project stakeholders to align early-stage decisions with long-term value retention, data continuity, and recovery infrastructures.

In this context, the transition toward circular building design requires not only improved tools, but also institutional integration across design, procurement, and regulatory systems, enabling circular criteria to become embedded as standard

design constraints rather than optional sustainability objectives. The coming convergence of digitalisation (e.g., BIM and digital product passports), life cycle regulation, and performance-based assessment frameworks will likely redefine the role of the conceptual design phase as a decision environment where circularity is operationalised, verified, and governed from the outset.

Consequently, the advancement of circular architecture will depend less on the development of new isolated instruments and more on the systematic integration of existing knowledge into coherent, enforceable, and practice-oriented design processes, capable of bridging the gap between circular economy ambition and built reality.

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References

1. World Business Council for Sustainable Development (2023) Circular transition indicators v4.0. WBCSD. <https://www.wbcd.org/resources/measuring-circular-buildings/>. Last accessed 12 Feb 2026
2. Beurskens P (2021) The development of an evaluation method to support circular building design. PhD Thesis, University of Twente
3. World Business Council for Sustainable Development (2022) Measuring circular buildings. WBCSD. <https://www.wbcd.org/resources/circular-transition-indicators-v4/>. Last accessed 10 Feb 2026
4. UK Green Building Council (2019) Circular economy guidance for construction clients. How to practically apply circular economy principles at the project brief stage. UKGBC
5. Alaux N, Schwark B, Hörmann M, Saade MRM, Passer A (2024) Assessing the prospective environmental impacts and circularity potentials of building stocks: an open-source model from Austria (PULSE-AT). *J Ind Ecol* 28:1435–1448. <https://doi.org/10.1111/jiec.13558>
6. Metabolic, City of Amsterdam, Copper, The Circular Toolbox delivers resources on sustainability in the built environment. <https://www.metabolic.nl/news/the-circular-toolbox-delivers-resources-on-sustainability-in-the-built-environment/>. Last accessed 18 Feb 2026
7. Cottafava D, Ritzen M (2021) Circularity indicators for residential buildings. *Resour Conserv Recycl* 164:105120. <https://doi.org/10.1016/j.resconrec.2020.105120>
8. World Green Building Council (2023) The circular built environment playbook. WorldGBC
9. ARUP, Circular Building Design Toolkit. <https://ce-toolkit.dhub.arup.com/>. Last accessed 28 Jan 2026
10. Kubbinga B et al (2018) A framework for circular building. Indicators for possible inclusion in BREEAM. Circle Economy

11. Wilde C et al (2023) Circular economy metrics for buildings. UKGBC
12. Gonzalez A, Sendra C, Herena A, Rosquillas M, Vaza D (2021) Methodology to assess the circularity in building construction and refurbishment activities, 2021. *Resour, Conserv Recycl Adv* 12:200051. <https://doi.org/10.1016/j.rcradv.2021.200051>
13. Gillott C, Mikhelson W, Lanau M, Cheshire D, Tingley DD (2023) Developing regenerate: a circular economy engagement tool for the assessment of new and existing buildings. *J Ind Ecol* 27. <https://doi.org/10.1111/jiec.13377>
14. Platform CB'23, Guide to Circular Design 2.0: Working agreements for circular construction. https://platformcb23.nl/wp-content/uploads/PlatformCB23_Guide_Circular-Design.pdf. Last accessed 19 Feb 2026
15. Leopold Wambersie et al. (ARUP), applying circularity in the life cycle assessment of buildings. <https://www.arup.com/insights/applying-circularity-in-the-life-cycle-assessment-of-buildings/>. Last accessed 19 Feb 2026
16. Greater London Authority, Circular Economy Statements (2023) Mayor of London. <https://www.london.gov.uk/programmes-strategies/planning/implementing-london-plan/london-plan-guidance/circular-economy-statement-guidance>. Last accessed 12 Feb 2026
17. Architects Climate Action Network, Circular Economy in Built Environment (2024) ACAN!. <https://architectscan.org/>. Last accessed 25 Feb 2026
18. DGNB, Toolbox “Circular Building” (2024) DGNB, circular building | DGNB. <https://www.dgnb.de/en/sustainable-building/circular-building>. Last accessed 20 Feb 2026
19. Cambier C, Galle W, Vandervaeren C, Tavernier I, De Temmerman N (2020) An analysis of design support tools for circular building practice. In: Littlewood J, Howlett RJ, Jain LC (eds) *Sustainability in energy and buildings 2020, smart innovation, systems and technologies*, vol 203. Springer, Singapore. https://doi.org/10.1007/978-981-15-8783-2_4
20. Arnau González A et al (2017) Conceptualizing the circular economy. *Resour Conserv Recycl*
21. Segara S, Li Q, Gallotta A, Wang Y, Gosling J, Rezgui Y (2024) Taxonomy of circularity indicators for the built environment: integrating circularity through the Royal Institute of British architects (RIBA) plan of work. *J Clean Prod* 446:141429. <https://www.sciencedirect.com/science/article/pii/S0959652624008771>
22. Pešta J, Vlasatá B, Trubina N, Pavlu T (2023) Circular building design: strategies and tools, CirCon4Climate project
23. Cambier C et al. (2019) Circular building design, VUB, architectural engineering—circular building design. <https://vubwevjv405.405.axc.nl/arch/>. Last accessed 28 Jan 2026
24. Durmisevic E, Guerriero A, Boje C, Domange B, Bosch G (2021) Development of a conceptual digital deconstruction platform with integrated reversible BIM to aid decision making and facilitate a circular economy. In: *CIB W78 2021*, 11–15 October 2021, Luxembourg. ISSN 0921-3449
25. DGBC, A framework for circular existing buildings (2021). <https://www.dgbc.nl/publicaties/framework-voor-circulaire-bestaande-gebouwen-42>. Last accessed 27 Jan 2026
26. van der Zwaag M, Wang T, Bakker H, van Nederveen S, Schuurman A, Bosma D (2023) Evaluating building circularity in the early design phase. *Autom Constr* 152:104941. <https://www.sciencedirect.com/science/article/pii/S0926580523002017>
27. Rexfelt O, Selvefors A (2024) Mapping the landscape of circular design tools. *Resour Conserv Recycl* 209:107783. <https://www.sciencedirect.com/science/article/pii/S092134492400377X>
28. Rahla KM, Bragança L, Mateus R (2019) Obstacles and barriers for measuring building's circularity. In: *SBE19 Brussels BAMB-CIRCPATH*
29. Royal Institute of British Architects (2020) RIBA plan of work 2020. RIBA
30. The American Institute of Architects (2007) Integrated project delivery: a guide. https://assets.aiacontracts.com/ctrzdweb02/zdpdfs/ipd_guide.pdf. Last accessed 21 Jul 2026
31. AlJaber A, Alasmari E, Martínez-Vázquez P, Baniotopoulos C (2023) Life cycle cost in circular economy of buildings by applying building information modeling (BIM): a state of the art. *Buildings* 13(7):1858
32. Eastman C, Teicholz P, Sacks R, Liston K (2011) *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors*, 2nd edn. Wiley

33. McNeil-Ayuk N, Jrade A (2024) A building information modeling–life cycle cost analysis integrated model to enhance decisions related to the selection of construction methods at the conceptual design stage of buildings. *Open J Civ Eng* 14(3)
34. Gerges M, Mayouf M, Watson P, John G, Ahmed E, Selim O, Wenman B (2019) BIM role within the conceptual design phase: a case study of a UK construction project. *Int J Arch, Eng Constr* 8(1):54–62
35. Al-Qazzaz I, Osorio-Sandoval CA, Tokbolat S, Thermou G (2025) A BIM-based decision support system for circularity and sustainability assessment in the early design stages. *Archit Eng Des Manag*
36. Pomponi F, Moncaster A (2017) Circular economy for the built environment: a research framework. *J Clean Prod* 143:710–718
37. Akanbi LA, Oyedele LO, Akinade OO, Ajayi AO, Davila Delgado M, Bilal M, Bello SA (2018) Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. *Resour Conserv Recycl* 129:175–186
38. Azhar S (2011) Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadersh Manag Eng* 11(3):241–252
39. European Commission (2020) Circular economy action plan: for a cleaner and more competitive Europe. European Commission

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BIM for Circular Built Environments: Data, Indicators, and Implementation Frameworks



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Abstract This study explores how Circular Economy (CE) indicators can be effectively integrated into Building Information Modelling (BIM) to support sustainability in the built environment. Given the construction sector's significant contribution to resource use and carbon emissions, there is an urgent need for improved lifecycle data and circularity assessment methods. While BIM offers strong potential for managing building data across all lifecycle stages, its use for CE purposes remains limited due to

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fragmented data structures and lack of standardised indicators. The research is based on a multi-language survey of stakeholders across the architecture, engineering, construction, and operations (AECO) sector in several European countries. The findings show that although awareness of BIM-CE integration is high, its practical implementation is still low and mostly restricted to early design phases. Many organisations rely on manual data handling, and BIM systems are often not prepared to support structured circularity data. Key barriers include lack of standardised metrics, insufficient regulatory frameworks, limited product-level data, and low digital maturity. The study highlights the importance of tools such as material passports and digital logbooks to improve data traceability. A policy framework is proposed focusing on interoperability, standardisation, capacity building, and regulatory support to enable scalable BIM-CE integration.

Keywords Building information modelling (BIM) · Built environment · Circular economy · Circularity indicators · Data interoperability · Lifecycle assessment

1 Introduction

The transition toward a Circular Economy (CE) in the built environment is essential to reduce resource depletion, waste generation, and lifecycle carbon emissions, particularly given the construction sector's significant environmental footprint [1, 2]. Recent EU-wide assessments further emphasise this urgency, showing that buildings account for around 36% of total greenhouse gas emissions in the European Union and highlighting the need for robust, harmonised lifecycle data to support decarbonisation strategies [3].

Achieving circularity requires harmonised methods to define, collect, and operationalise CE indicators throughout the building lifecycle, supported by reliable and

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interoperable digital information systems. Building Information Modelling (BIM) has emerged as a key enabling technology for lifecycle data management, offering opportunities to integrate circularity considerations into design, construction, operation, and end-of-life phases. However, despite its potential, the integration of CE indicators into BIM remains limited due to fragmented data structures, a lack of standardised circularity metrics, and insufficient availability of product-level environmental and circularity data, including Environmental Product Declarations (EPDs), Digital Product Passports (DPP), the construction Products Regulation (CPR) and Digital Building Logbooks (DBLs) [4, 5]. The DBL functions as a centralised repository containing technical, legal, and administrative data of a building throughout its life cycle [6]. The European Commission has promoted the building renovation passport (BRP) as a structured roadmap to support renovation and long-term decarbonization [2]. The integration of these tools with BIM enables dynamic data exchange improves decision-making for renovation and maintenance, ensuring traceability of all material and component data throughout the building lifespan.

This report aims to investigate how CE indicators can be effectively integrated into BIM environments by analysing stakeholder data needs, workflows, and implementation barriers, and by developing policy-oriented recommendations to support harmonised CE data practices. The scope focuses on identifying technical, organisational, and regulatory challenges affecting BIM-CE integration, particularly in the context of evolving regulatory frameworks such as the revised Energy Performance of Buildings Directive (EPBD) and the transition toward Zero-Emission Buildings (ZEB), which require more comprehensive lifecycle data and improved digital transparency [7]. From a practical perspective, this research addresses critical market gaps related to the lack of interoperable circularity data, incomplete product information, and the absence of consistently implemented digital tools such as material passports and renovation logbooks. Based on a structured stakeholder survey across the construction value chain, this report proposes a policy framework to enable scalable CE indicator integration within BIM, supporting public authorities, industry stakeholders, and standardisation bodies in accelerating the transition toward a circular, data-driven, and climate-neutral built environment.

2 Background and Literature Review

2.1 Circular Economy Indicators in the Built Environment

Circular Economy indicators represent measurement tools designed to assess how effectively products, materials, components, and systems retain value over time and remain in productive use instead of following a linear “take–make–dispose” model. Rather than constituting a single standardised family of metrics, CE indicators encompass a heterogeneous set of quantitative and semi-quantitative measures

aimed at evaluating different circular strategies, system boundaries, and scales of application.

The recent EU-wide assessment framework on whole-life carbon emissions highlights persistent gaps in harmonised lifecycle data, particularly concerning material flows, renovation cycles, and demolition patterns, which continue to hinder effective policy implementation and circularity assessment practices. These limitations reinforce the importance of digital environments such as BIM and DBLs for enabling structured, interoperable, and traceable lifecycle data management.

Saidani et al. [8] conducted one of the most comprehensive reviews of CE indicators, identifying 55 indicator sets developed for purposes such as benchmarking, target setting, decision support, communication, and performance monitoring. Their analysis demonstrates that indicator selection strongly depends on the intended application context, system scale, and circularity strategy under evaluation.

A further important contribution is provided by Moraga et al. [9], who proposed a classification framework distinguishing CE indicators according to what they preserve (functions, products, components, materials, or embodied energy) and how they measure preservation. Their analysis shows that most existing indicators remain strongly focused on material recovery and recycling, while comparatively limited attention is dedicated to higher-order circular strategies such as adaptability, shared use, functional preservation, and product-service systems.

This distinction is particularly relevant in the built environment, where building circularity depends not only on recycled content but also on durability, flexibility, reparability, reusability, adaptability, and design for disassembly over long temporal horizons. In the broader CE literature, indicators are commonly discussed across micro-, meso-, and macro-level scales. Within the construction sector, building-scale and component-scale indicators are especially important because they allow circularity to be operationalised directly within design and construction decision-making processes.

Pomponi and Moncaster [10] argue that the built environment occupies an intermediate scale between products and cities, requiring dedicated circularity frameworks rather than direct adaptation of industrial or manufacturing-oriented models. More recent reviews confirm that construction circularity assessment still suffers from fragmented definitions, inconsistent system boundaries, and uneven treatment of lifecycle stages.

Within the construction sector, CE indicators are mainly applied to assess resource efficiency, waste prevention, reuse potential, recyclability, recoverability, design for disassembly, and service-life extension. Akhimien et al. [11] demonstrate that the most common CE applications in buildings focus on design for disassembly, material reuse, design flexibility, and waste minimisation, reflecting a shift from end-of-life waste management toward upstream design strategies capable of influencing future recovery and adaptability.

Similarly, Antonini et al. [12] identify reversibility and durability as critical dimensions for assessing circular building technologies, since they directly influence whether systems and components can be maintained, upgraded, separated, and

reused without significant loss of value. Consequently, a building may appear materially efficient while still exhibiting low circularity if its systems are difficult to access, adapt, or repurpose.

Recent reviews specifically dedicated to building circularity indicators reveal both methodological progress and persistent fragmentation. Khadim et al. [13], for example, critically reviewed 35 circularity assessment tools and observed that most indicators remain predominantly quantitative and heavily focused on reuse and recycling, while often neglecting dimensions related to energy, emissions, and water consumption. Similarly, Segara et al. [14] identified 32 building-specific circularity indicators and proposed a taxonomy linked to the RIBA Plan of Work, demonstrating that no single indicator currently captures all dimensions of building circularity. Effective assessment, therefore, requires the use of combinations of complementary indicators aligned with specific project phases and decision contexts.

2.2 Building Information Modelling for Lifecycle Data Management

Building Information Modelling (BIM) is a collaborative digital methodology for the integrated planning, design, construction, and management of buildings and infrastructure, based on the creation and use of intelligent three-dimensional models enriched with structured information throughout the asset lifecycle. Beyond geometric representation, BIM enables the coordination of multidisciplinary data, supports informed decision-making, enhances interoperability, and improves efficiency, cost control, and sustainability performance across all project phases. BIM therefore represents a paradigm shift in the Architecture, Engineering, and Construction (AEC) sector by enabling integrated information management and reducing fragmentation in project delivery processes [15].

More specifically, BIM can be understood as a set of interacting policies, processes, and technologies that generate and manage structured digital representations of built assets [15], providing significant benefits in terms of error reduction, interdisciplinary collaboration, traceability, and improved project outcomes. Recent studies further emphasise the growing role of BIM and other Building Digital Technologies (BDTs) in supporting lifecycle-based environmental assessment and decarbonisation strategies within the construction sector [16].

The International Organization for Standardization (ISO 19650 series) defines BIM as the “use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions” [17]. Within this context, the concept of *Open BIM* relies on non-proprietary and interoperable data standards, particularly the Industry Foundation Classes (IFC) schema developed by buildingSMART International [18]. Open BIM facilitates information exchange among heterogeneous software platforms and supports long-term data accessibility and interoperability. Alongside IFC, additional buildingSMART

standards and services - such as the Information Delivery Specification (IDS) and the buildingSMART Data Dictionary (bSDD) - contribute to semantic consistency and structured information exchange across the building lifecycle. IDS enables the formal specification of information requirements in a machine- and human-readable format, allowing automated validation of IFC-based models against project-specific data requirements, and can be directly linked to bSDD for enhanced semantic interoperability.

These developments are increasingly relevant in the context of Circular Economy (CE) implementation within the built environment, where digital information continuity is essential to support lifecycle-oriented decision-making. In this context, the Digital Building Logbook (DBL) has emerged as a centralised repository of technical, administrative, legal, and environmental information associated with a building throughout its lifecycle. Gómez-Gil et al. (2018) [6] describe the DBL as a key enabling instrument for integrating heterogeneous building data streams and improving traceability across design, operation, renovation, and end-of-life phases. The integration of BIM with DBL frameworks can therefore facilitate dynamic information management, improve transparency, and support circularity-oriented building governance.

Similarly, the Building Renovation Passport (BRP) has been promoted by the European Commission as a structured and tailored roadmap supporting staged deep renovation strategies and long-term decarbonisation objectives at building level [2]. Earlier research highlighted the strategic role of BRPs in reducing information asymmetry among stakeholders, increasing transparency, and improving access to reliable building data for owners, investors, and public authorities [19]. The BRP concept is closely linked to lifecycle data continuity and can act as a complementary instrument to BIM-enabled digital information systems. Recent European research also underlines the growing need for harmonised and interoperable building performance indicators to strengthen data quality, comparability, and usability across Member States [20].

The integration of BIM, DBLs, and BRPs enables the continuous exchange and updating of information related to materials, components, maintenance interventions, environmental impacts, and operational performance throughout the building lifecycle. Such integration supports renovation planning, lifecycle assessment, circularity monitoring, and end-of-life decision-making, while simultaneously improving data traceability and reliability. Furthermore, recent literature highlights how the convergence between BIM and lifecycle assessment methodologies can accelerate the transition toward zero-emission and circular buildings through improved digitalisation of environmental assessment processes [16].

Another significant research stream links CE indicators with material passports and digital information systems. Atta et al. [21] proposed a BIM-integrated material passport framework incorporating deconstructability, recovery, and environmental performance scores, demonstrating how digitalised material information can support sustainable design decisions and improve end-of-life traceability. Material passports are increasingly recognised as structured repositories containing information on

material composition, quantities, disassembly procedures, recovery potential, and future value retention.

This relationship is particularly important because the reliability and usefulness of CE indicators depend directly on the quality, granularity, and interoperability of building data. Consequently, CE indicators become substantially more operational when integrated into BIM objects, product data templates, Digital Building Logbooks, and material passport systems, rather than being calculated as isolated post-occupancy metrics.

The BIM-related literature further reinforces this operational perspective. Akanbi et al. [22] developed a BIM-based whole-life performance estimator capable of evaluating the salvage performance of structural components during the design phase, demonstrating how circularity-related performance assessment can be embedded into digital workflows rather than performed only after demolition. Similarly, Ganiyu et al. [23] show that achieving waste-efficient and circular construction through BIM requires not only digital technologies themselves, but also dedicated competencies in data management, lifecycle thinking, interoperability, and interdisciplinary coordination.

Overall, the literature suggests that CE indicators achieve their greatest effectiveness when integrated within digital design and information management ecosystems. In this sense, BIM, DBLs, BRPs, and material passports collectively provide the digital infrastructure necessary to support circularity assessment, lifecycle optimisation, decarbonisation strategies, and long-term value retention in the built environment.

2.3 Circular Economy–BIM Integration Approach

Circular economy (CE) indicators provide measurable benchmarks for evaluating resource efficiency, material recovery, and waste reduction in the built environment. Honic et al. [24] and Saidani et al. [8] note that the growing policy and industrial interest in CE has created a strong need for indicators that can monitor transition progress, noting that indicator choice depends on the intended use, scale of application, and the specific circularity strategy being evaluated. Moraga et al. [9] further show that most existing indicators are biased toward material preservation, particularly recycling, while higher-order strategies such as adaptability, shared use, and design for disassembly receive less attention - dimensions that are especially critical in the built environment.

BIM has been increasingly recognised as a key enabler for tracking CE indicators, given its capacity to store rich geometric and semantic data throughout the building lifecycle. Honic et al. [24] demonstrated that BIM-based material passports can facilitate the quantification of CE indicators by mapping material flows at the component level. Atta et al. [21] further showed that digitised material information within BIM can support more sustainable design choices and improve material traceability at the

end of life. Despite growing interest, CE indicators are rarely embedded systematically into BIM workflows in real projects, and their operationalisation remains constrained by fragmented data structures, inconsistent assessment boundaries, and limited product-level information [23].

Research emphasizes the need to identify these BIM applications and assess their maturity at various project stages. BIM has the potential to significantly reduce waste during both the construction phase and the asset's end-of-life stage; however, the specific applications for waste reduction remain relatively unclear. The growing interest in using BIM for waste minimization aligns with Circular Economy principles, indicating that lifecycle data, from construction to demolition, can support improved decision-making. Despite these advancements, a substantial research gap exists regarding specialized BIM applications that integrate Circular Economy principles throughout asset lifecycles. This underscores the need for further inquiry into how BIM can enhance sustainable practices and bolster resource efficiency in asset management [25].

2.4 BIM-Building Circularity Assessment (BCA) Integration Approaches

BIM workflows can be implemented throughout the entire life cycle of a building, including the end-of-life stage. As such, BIM could be used to overcome barriers to achieving a circular economy by, for example, supporting circularity assessment or embedding material passports [25]. Charef and Emmitt [25] identified seven new uses of BIM for a circular built environment: (1) digital model for sustainable end-of-life, (2) material passport development, (3) project database, (4) data checking, (5) circularity assessment, (6) material recovery processes and (7) material banks.

Three integration approaches for BIM and BCA were identified: external platforms, external databases, and assessment within the BIM environment [26]. The first approach involves performing the assessment on an external platform, typically online such as Madaster. The second approach relies on linking BIM to an external database. The third approach conducts the assessment directly within the BIM environment, using its embedded geometric and semantic information. The assessment is conducted using embedded geometric and semantic information within the BIM environment. One of the main challenges for BCA within BIM is that the current IFC schema does not include all the necessary properties required to assess circularity. Moreover, most existing tools are developed using Autodesk Revit as the BIM software [26]. Notably, no tool currently enriches BIM models while simultaneously aligning data schemas with both IFC and the buildingSMART Data Dictionary (bSDD) [27].

However, there are emerging open developments that have established common information requirements for circularity assessment. These are available as datasets within the buildingSMART Data Dictionary (bSDD), such as the Decommissioning

and Reuse (DOR) dataset by Akbarieh and the Circularity dataset by Guntermann et al. [28]. Tomczak et al. [29] used the IDS for semi-automated compliance checking of BIM content against circularity data. Their study found that some circularity information beyond the IDS and BIM scope, and information regarding disassembly, end-of-life predictions, and component connections are relatively difficult to represent in BIM. They also concluded that circularity terms are not standardised and highlighted the need to unify definitions within a standardised data dictionary.

2.5 Case Studies Regarding the Use of BIM and Circularity

In Portugal, within the framework of the Circular EcoBIM project, Fernandes et al. [30] developed a plugin based on the Building Circularity Indicator (BCI), Portuguese building archetypes, and a Product Data Template (PDT) to support circularity assessment in alignment with the Level(s) framework.

In Romania, Marin et al. [31] revealed that the country significantly underperforms relative to the EU average in circular economy implementation, particularly in construction and demolition waste recovery. Regarding BIM, Mysak and Mysak [32] confirmed that its adoption in Romania remains limited to individual projects, impeded by the lack of national standards, insufficient skilled personnel, and low market awareness, with no formal BIM mandate yet established.

In Serbia, the literature suggests that BIM-supported circularity assessment is still at an early stage, but important enabling developments are rising [33]. A recent case study from Belgrade shows the potential of integrating GIS and BIM to map urban building stocks for circular economy purposes, showing that Serbian research is moving toward data-driven approaches for identifying material stocks, demolition potential, and recovery opportunities at the district scale [32].

This is a relevant step for future BIM-BCA implementation because stock mapping and material identification are foundational for circularity assessment, urban mining, and decision support. At the same time, broader Serbian literature on circular economy in construction indicates that implementation is still constrained by weak recovery practices for construction and demolition waste, insufficiently established recycling systems, and the need for stronger operationalization of the existing policy framework. Taken together, these studies suggest that Serbia has a growing research basis and a supportive policy direction, but still needs stronger standardisation, data availability, market uptake, and institutional support before BIM-integrated BCA can be implemented at scale.

In the United Kingdom, Al-Qazzaz et al. [34] developed a plugin based on a new version of the Building Circularity Indicator (BCI) and the bSDD service to support circularity assessment in alignment with the EU Level(s) framework. The tool also enables the prediction of future scenarios and supports identifying trade-offs between circularity and sustainability.

3 Materials and Methods

This research has aimed to investigate how CE indicators can be integrated into BIM environments by analysing stakeholder data needs, workflows, and implementation barriers. In order to fulfil its aim, the research followed a survey methodology. The survey was prepared in multiple languages, including Portuguese, Italian, English, Turkish, Serbian, and Romanian, to be conducted internationally and map BIM-CE integration across various countries. Hence, different ecosystem needs were analysed to demonstrate which approaches countries are adopting for CE indicators in BIM environments.

The survey was created using an online tool and distributed via email and online participation to those who have relevant experience in the circular economy and BIM. The survey consisted of five sections and 31 questions, following the survey introduction. Firstly, the research aim, the main institution beyond the research, information about the participation, and data security were introduced. Following this, the sections included different contents as defined below:

- The first section included six questions about respondents' profiles, such as age, gender, education, years of experience in AECO, and country of origin, followed by consent to participate in the survey.
- The second section, presenting six questions, aimed to analyse the characterisation of stakeholders' groups, including organisation type and role within the organisation, BIM and CE levels, experience with CE across life-cycle stages, and experience within the buildingSMART standards.
- The third section included eight questions about needs, expectations, and constraints, such as the organisational needs to implement CE, expectations for BIM support for CE goals, the potential of BIM-CE integration, constraints on adopting CE indicators, data format needs for CE implementation, reporting requirements that the organisation has to fulfil, and decision-support tools used within the organisation.
- The fourth section included seven questions about integration of CE indicators into BIM, such as the level of use of CE indicators and the relevance of indicators to the organization, the construction stages that CE indicators can be accessed via BIM, the level of maturity of the BIM environment of the organization to host CE data, the functions required to link CE indicators to BIM models, the expectation between BIM and CE monitoring systems, and existing monitoring systems to obtain CE-related data.
- The fifth and last section included two questions on final remarks, presented as open-ended questions.

To indicate the BIM-CE integration in the AECO industry, quantitative results were collected using a 5-point Likert scale, ranging from very low to very high, developed by Rensis Likert in 1932 [35], as well as multiple-choice and open-ended questions.

3.1 *Sampling Strategy*

The survey targeted professionals operating across the AECO value chain with direct or applied experience in BIM, CE practices, or both. Three primary groups were identified as the intended participant population: (i) academic researchers working in fields related to sustainable construction, lifecycle assessment, digital building technologies, or CE in the built environment; (ii) industry professionals, including architects, structural and services engineers, contractors, project managers, facility managers, and clients; and (iii) providers of digital solutions, encompassing BIM software developers, platform vendors, and technology consultants active in the construction sector. No minimum threshold of prior experience with BIM or CE was set as a formal inclusion criterion, allowing the survey to capture a broad spectrum of perspectives, from professionals at early stages of adoption to those with consolidated expertise.

Given the specialised nature of the topic, a purposive sampling strategy was adopted as the primary recruitment approach, ensuring that participants were substantively relevant to the research questions. This was supplemented by a snowball sampling technique, through which initial participants were invited to refer the survey to further qualified contacts within their professional networks and project consortia, extending reach within specialist communities that are typically difficult to access through generalised recruitment methods.

The survey was distributed electronically via institutional email networks and professional channels over a 2-week data collection window. A minimum target of approximately 20 respondents per participating country was established as a benchmark to enable meaningful country-level comparative analysis. Although the survey was prepared in six languages and distributed across multiple national contexts, only the samples from Portugal, Romania, and Serbia met this threshold and were therefore retained for individual analysis, and then the whole aggregated group of respondents was analysed for this report. The final sample characteristics and response distributions are reported in the Results section.

3.2 *Data Analysis*

Quantitative data were analysed using descriptive statistics to identify trends in BIM-CE maturity, data needs, and perceived barriers. Cross-tabulation techniques supported the exploration of differences across stakeholder groups. Qualitative responses to open-ended questions were analysed thematically to identify recurring themes related to interoperability, data governance, organisational readiness, and policy needs.

The combined findings informed the development of a policy-oriented framework aimed at supporting harmonised CE indicator integration within BIM environments across projects and governance levels.

4 Results and Discussion

A total of 74 valid responses were collected from across six country groups: Portugal ($n = 21$), Romania ($n = 34$), Serbia ($n = 19$), the UK and wider international ($n = 30$), Italy ($n = 8$), and Türkiye ($n = 14$). As established in the sampling strategy, only the Portuguese, Romanian, and Serbian sub-samples met the minimum threshold of approximately 20 respondents per country required for country-level comparative analysis; results from the remaining groups are therefore presented at the combined level and used to contextualise overall trends.

4.1 Section 1: Respondents' Profile

Regarding age distribution, most respondents belonged to the 35–44 age group (46%), followed by the 45–54 group (27%), and the 25–34 group (16%), with minimal representation from age groups below 25 or above 55 (see Fig. 1). This age profile reflects the career-stage consolidation typical of specialist surveys in the AECO sector, where participation tends to be concentrated among mid-career and senior professionals with direct practice experience in BIM or CE.

The gender distribution showed that 62% of respondents identified as male and 38% as female (Fig. 2), which, although uneven, is broadly consistent with the documented gender distribution within AECO professional communities across Southern and Eastern Europe (European Commission data on STEM workforce composition). In terms of educational attainment, 54% held a university degree and 46% a post-graduate qualification, with no respondents reporting only secondary or vocational

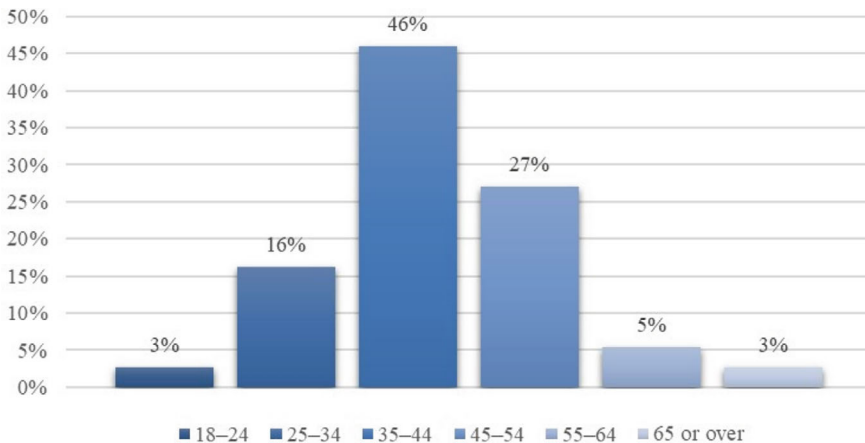


Fig. 1 Age group

education (see Fig. 3). This indicates a highly educated sample, appropriate to the technical and policy-oriented nature of the survey topics.

Professional experience was predominantly at the senior end of the spectrum: 74% of respondents reported more than 10 years of experience in the AECO sector, and a further 19% reported between 6 and 10 years (Fig. 4). Only a small minority (7%) had fewer than 5 years of experience. This seniority profile lends weight to responses regarding practice-level constraints and implementation expectations, as most participants are established professionals with direct exposure to project delivery cycles.

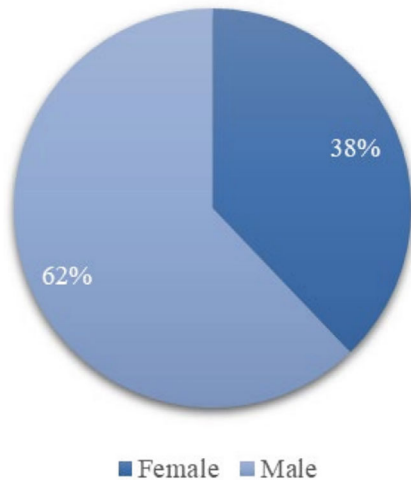


Fig. 2 Gender balance

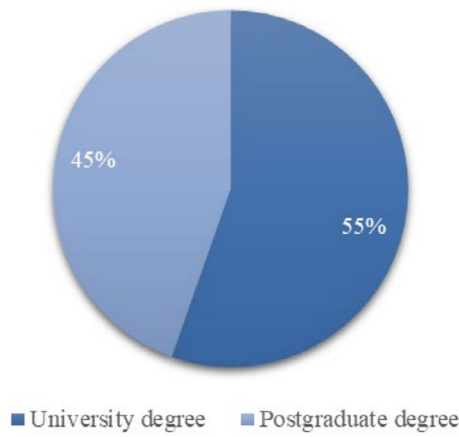


Fig. 3 Education level

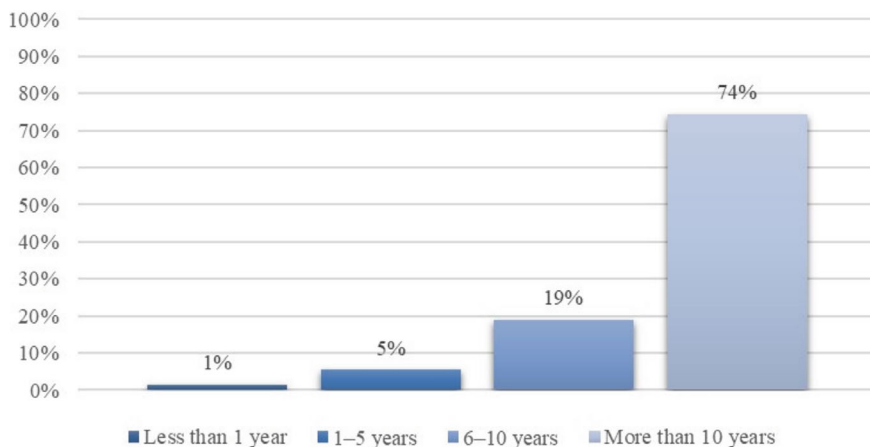


Fig. 4 AECO sector experience

4.2 Section 2: Stakeholders' Group Characterisation

The sample encompassed a range of organisation types across the AECO value chain (Fig. 5). Architectural design firms represented the largest group (36%, $n = 30$), followed by engineering consultancies (31%, $n = 26$), and research and innovation organisations (12%, $n = 10$). Contractors and construction companies accounted for 7% ($n = 6$), while manufacturers, suppliers, public entities, facility managers, and digital technology providers each contributed marginal proportions. This distribution reflects both the purposive sampling strategy, which targeted practitioners with direct experience of BIM and CE, and broader structural characteristics of the sector in the three focus countries, where design and consultancy firms tend to be more deeply engaged with digital tools and sustainability frameworks than contractors or clients. The relative underrepresentation of clients, facility managers, and demolition service providers is noteworthy, as these actors play critical roles in the operational and end-of-life phases of the building lifecycle where CE data continuity is particularly challenging. This gap may point to a structural asymmetry in BIM-CE knowledge distribution across the value chain, with upstream design actors more engaged than downstream operators.

Respondents' self-reported BIM use levels indicate a sector that is still in a transitional phase (Fig. 6). The largest proportion described their use as Intermediate, encompassing modelling and coordination functions (36%, $n = 27$), followed by Basic use, limited to model viewing and simple applications (34%, $n = 25$). Advanced BIM use, defined as encompassing integrations, automation, and data management, was reported by only 20% of the sample ($n = 15$), while 9% ($n = 7$) reported no BIM engagement.

CE strategy use levels showed a broadly lower maturity profile than BIM, suggesting that even where BIM competency exists, its application to CE objectives

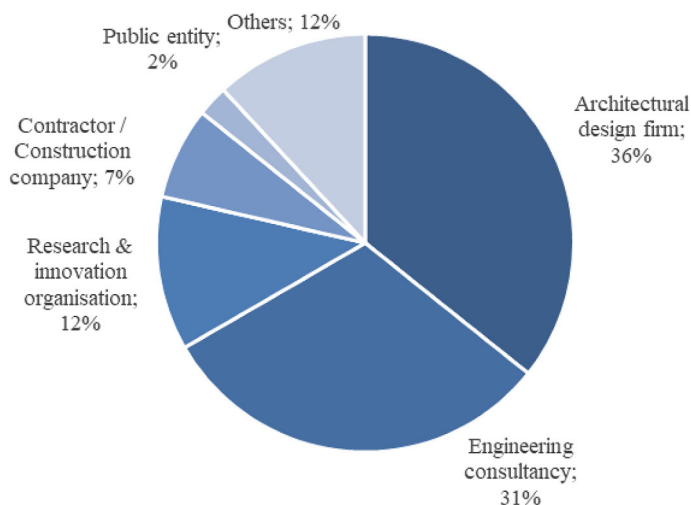


Fig. 5 Organisation type

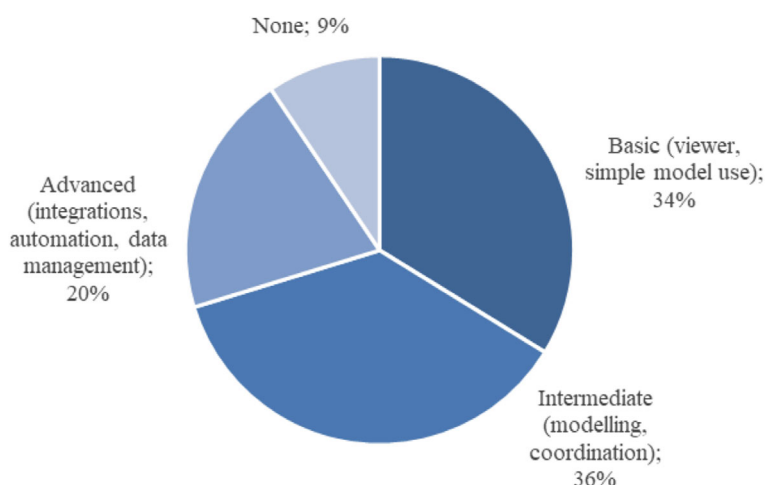


Fig. 6 BIM use level

remains limited (Fig. 7). The largest group reported Intermediate CE engagement (46%, $n = 34$), defined as occasional use of CE strategies, while 24% ($n = 18$) reported only Basic or rare use, and 15% ($n = 11$) reported no CE engagement at all. Advanced or frequent CE strategy use was recorded for only 15% of the sample ($n = 11$). These figures support a central argument in the literature: BIM maturity and CE maturity are not co-evolving at the same pace within the sector, and the majority of professionals with BIM skills have not yet translated them into systematic CE-oriented workflows [23, 25].

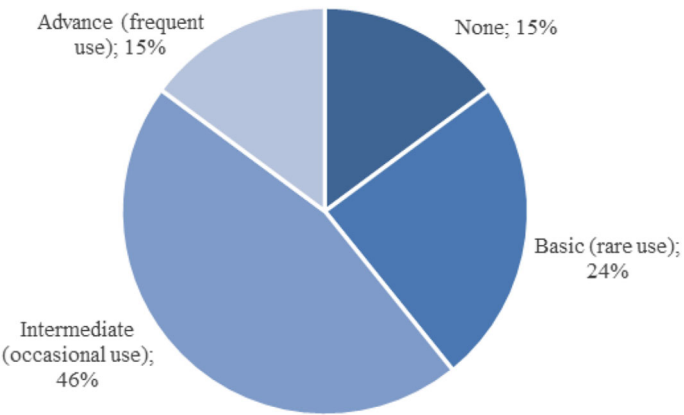


Fig. 7 CE strategies use level

The graphic presented in Fig. 8 shows the distribution of CE experience levels across the five principal building lifecycle stages, aggregated for the full combined sample. The data reveal a consistent pattern in which CE knowledge concentrates in the earlier phases of the project lifecycle and diminishes substantially as buildings move through operation, end-of-life, and beyond-system-boundary processes. Concept and Early Design showed the most balanced distribution of experience levels, with 46% of respondents reporting at least Intermediate experience in this stage, and 19% reporting Advanced experience. This is consistent with literature emphasising that design-stage interventions, including design for disassembly, modular construction, and material selection, remain the most prevalent entry point for CE thinking in the built environment [2, 28].

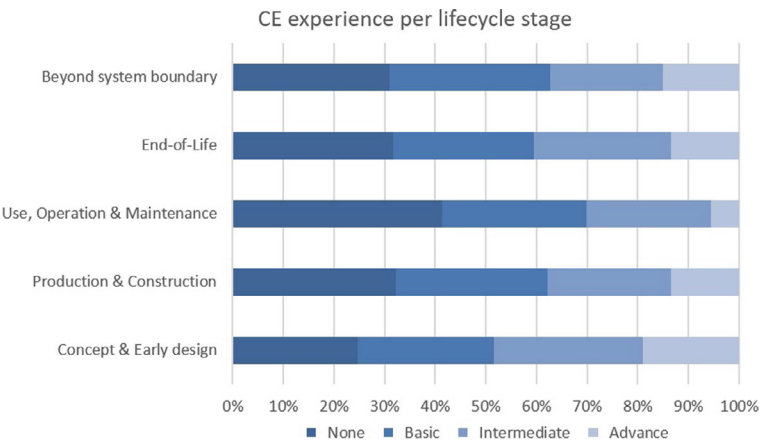


Fig. 8 CE experience per lifecycle stage

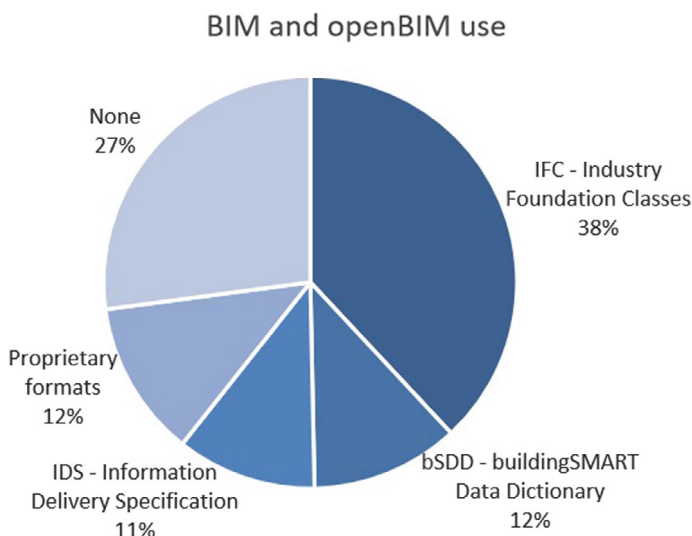


Fig. 9 BIM and openBIM experience

Experience in Production and Construction was more limited, with 55% of respondents reporting None or Basic experience (Fig. 8). The Use, Operation and Maintenance stage showed the weakest profile of all five stages: 70% of respondents indicated no CE experience at this phase, and only 9% described their engagement as Advanced.

This finding is particularly significant given that the operational phase constitutes the longest portion of a building's lifecycle and represents the phase at which monitoring, maintenance planning, and life extension decisions are made, all of which are directly relevant to CE performance. End of Life and Beyond System Boundary stages showed moderate but still predominantly low experience levels, with approximately 54% and 53% of respondents, respectively, reporting None or Basic engagement. Together, these findings confirm a structural front-loading of CE knowledge within the sector that closely mirrors patterns identified in systematic reviews of CE tools and indicators [24] the field invests heavily in upstream design thinking while leaving the downstream stages, where most material recovery value resides, comparatively underdeveloped.

Among the buildingSMART standards, the Industry Foundation Classes (IFC) schema was by far the most widely recognised, with 59 respondents reporting experience with it across all country groups (Fig. 9). In contrast, the buildingSMART Data Dictionary (bSDD) and the Information Delivery Specification (IDS) were each known to fewer than 20 respondents ($n = 18$ and $n = 17$, respectively), and 42 respondents reported no engagement with any open standard, relying exclusively on proprietary formats.

This distribution highlights a significant readiness gap for the implementation of open, interoperable data workflows. IFC experience, while widespread, does not

necessarily translate into the kind of schema-level mastery needed for CE-oriented data exchange; bSDD and IDS, which are the standards most directly relevant to defining and validating CE-relevant property sets within BIM environments, remain poorly adopted. This finding aligns with the arguments presented by Honic et al. [24] and Atta et al. [21], who note that the operationalisation of CE indicators in BIM requires not merely the existence of BIM models but the structured semantic enrichment of those models through open standards.

4.3 Section 3: Needs, Expectations and Constraints

Respondents were asked to identify the principal drivers behind their organisation’s engagement with CE implementation (Fig. 10).

National building regulations emerged as the most widely cited need, selected by 63 respondents (85% of the combined sample), confirming the central role of regulatory compliance as a motivating force across all three focus countries. This finding resonates with the European Commission’s (2020, 2024) [2, 7] emphasis on legislative instruments, particularly the revised EPBD and the Construction Products Regulation, as key levers for transforming practice. Training and capacity building were the second most frequently cited need ($n = 49$, 66%), followed closely by client requirements ($n = 48$, 65%), national sustainability strategies ($n = 40$), project implementation guidance including LCA integration ($n = 41$), and private and public procurement requirements ($n = 45$).

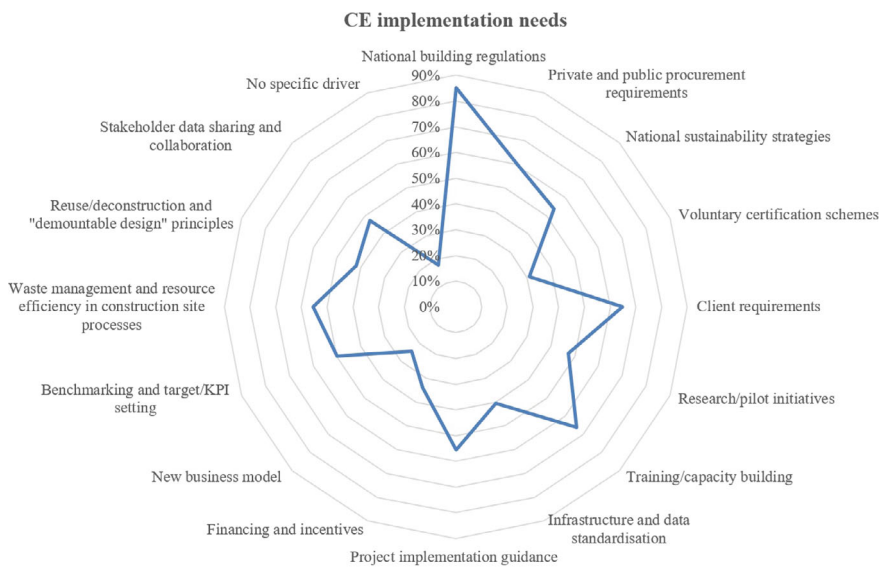


Fig. 10 CE implementation needs

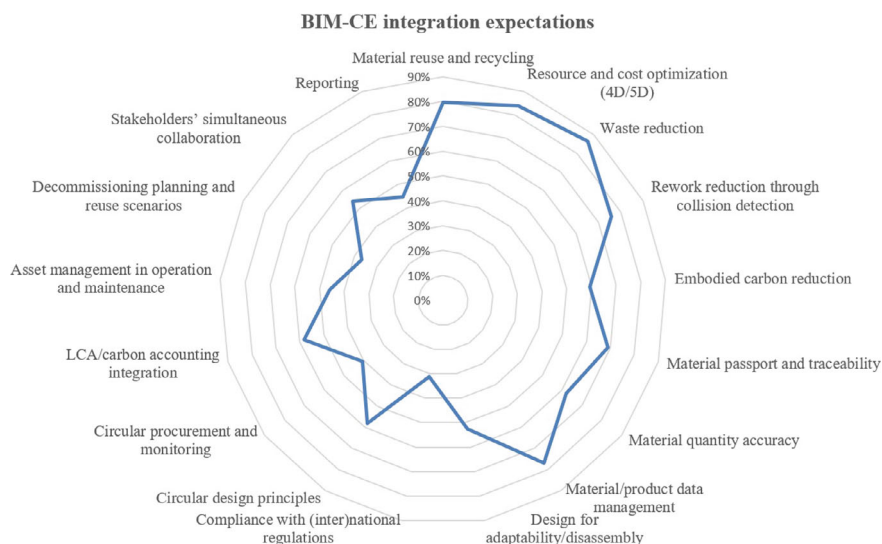


Fig. 11 BIM-CE integration expectations

Taken together, these responses suggest that CE adoption is being driven by a combination of regulatory pressure, market demand, and skills deficits, rather than by organic professional interest alone. The prominence of training needs is particularly notable, as it implies that even organisations with motivations to adopt CE are not yet equipped with the human capital to do so effectively. This echoes findings from Ganiyu et al. [23], who argue that achieving waste-efficient and circular building delivery requires not only digital tools but also specific competencies in data handling, lifecycle thinking, and cross-disciplinary coordination.

Respondents were asked what they expected BIM to contribute to CE goals within their work (Fig. 11).

Resource and cost optimisation through 4D and 5D planning was the most frequently cited expectation ($n = 54$), followed by waste reduction ($n = 55$), material passport development and traceability ($n = 45$), reduction of rework through clash detection ($n = 49$), and embodied carbon reduction ($n = 39$). Material and product data management, including EPDs and certifications, was cited by 48 respondents, and LCA and carbon accounting integration by 37. These responses reflect a predominantly operational and design-phase framing of BIM's CE role, with a strong emphasis on quantitative material efficiency gains and data-quality improvements rather than on the more complex, systemic aspects of circularity such as design for disassembly, life extension, or circular procurement. Notably, however, material passport and traceability expectations were prominent, indicating growing awareness of the relevance of BIM as a data infrastructure for longer-term material-flow governance, consistent with the policy trajectory of Digital Building Logbooks and Digital Product Passports under the European Green Deal [5].

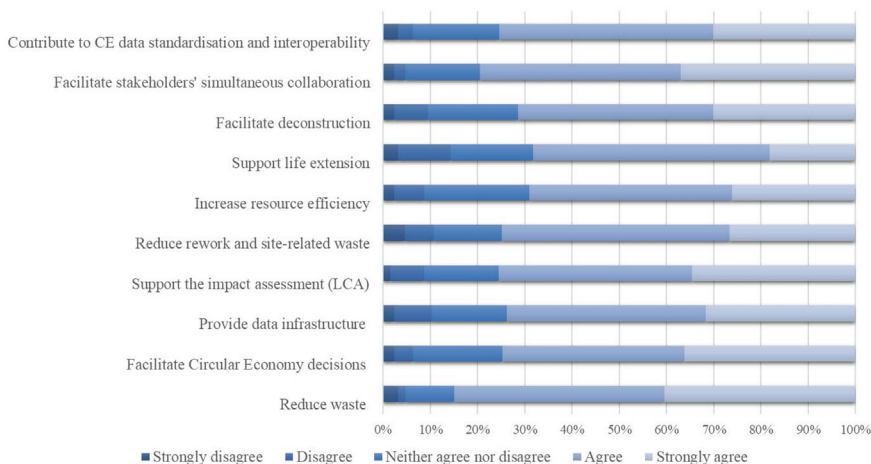


Fig. 12 BIM-CE integration capabilities

To assess the perceived potential of BIM-CE integration, respondents rated ten specific integration propositions using a five-point Likert scale. The Portuguese subsample, for which fully disaggregated country data were available, showed strong positive agreement across all ten propositions (Fig. 12).

The capacity of BIM-CE integration to reduce waste through more accurate material quantity estimations attracted the highest consensus, with 95% of Portuguese respondents agreeing or strongly agreeing. Supporting the evaluation of LCA and carbon impacts through alternative scenario comparison was endorsed by 81%, while providing data infrastructure for material passports and traceability received 90% agreement. Facilitating stakeholders' simultaneous collaboration along the building lifecycle was endorsed by 86% of Portuguese respondents.

The propositions attracting the most neutral or ambiguous responses concerned 4D/5D resource planning (62% agree or strongly agree, with 33% neither agreeing nor disagreeing) and data standardisation and interoperability (67% agree or strongly agree, with one respondent strongly disagreeing), suggesting that while professionals broadly support the concept of BIM-CE integration, they hold more cautious views regarding the practical operability of specific functionalities that require deep interoperability with external data sources or advanced digital workflows. This pattern of broad conceptual endorsement combined with more qualified operational expectations has been documented in previous BIM adoption research [36, 37] and supports the view that the sector's readiness gap is not primarily attitudinal but technical and infrastructural.

The primary barriers to CE indicator adoption identified across the combined sample were: lack of skills ($n = 64$, cited by 86% of respondents), lack of data ($n = 60$, 81%), unclear regulatory guidance ($n = 57$, 77%), lack of standardised BIM data structures ($n = 52$, 70%), cost constraints ($n = 54$, 73%), lack of standardised

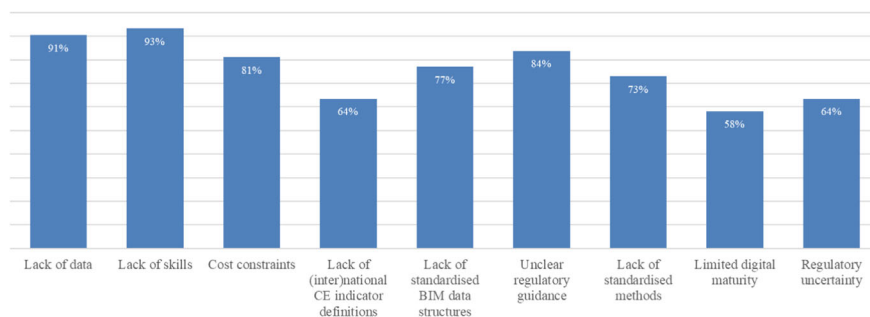


Fig. 13 Constraints for CE indicators adoption

methods ($n = 48$, 65%), limited digital maturity ($n = 37$, 50%), and regulatory uncertainty ($n = 43$, 58%) (Fig. 13).

These findings paint a picture of multi-layered, interconnected barriers in which technical, human capital, data governance, and regulatory dimensions reinforce each other. The dominance of skills-related and data-related barriers over cost constraints is significant, suggesting that investment in human capacity and in accessible, standardised data infrastructure would likely yield greater impact than financial instruments alone. The high proportion of respondents citing lack of standardised methods and absence of internationally accepted CE indicator definitions ($n = 44$, 59%) directly supports the need for coordinated standardisation efforts at the European level, particularly through the work of technical bodies such as CEN and buildingSMART International.

The most sought-after data formats for CE implementation were material databases and BIM object libraries ($n = 67$, 91%), LCA datasets ($n = 59$, 80%), and IFC ($n = 59$, 80%) (Fig. 14). COBie was cited by 23 respondents (31%), ERP and asset management system formats by 22 (30%), and proprietary BIM formats by 51 (69%). The high demand for LCA datasets and material databases confirms that CE indicator operationalisation within BIM is primarily constrained by data availability at the product and material level, rather than by the absence of modelling environments per se. This observation is consistent with the argument of Atta et al. [21] that CE indicator outputs depend directly on the quality, completeness, and granularity of embedded material information.

Nearly half of all respondents ($n = 46$, 62%) reported having no CE-related reporting obligations at the time of the survey (Fig. 15). Among those who did report obligations, project-based reporting upon client or employer request was the most common ($n = 31$), followed by reporting for green building certification schemes such as LEED or BREEAM ($n = 25$), LCA results reporting ($n = 25$), and corporate sustainability or ESG reporting ($n = 27$). In terms of the mandatory character of such obligations (Fig. 16), voluntary or corporate policy was the most prevalent basis ($n = 78$ instances across countries), followed by contractual obligation ($n = 49$) and legal or regulatory obligation ($n = 28$).

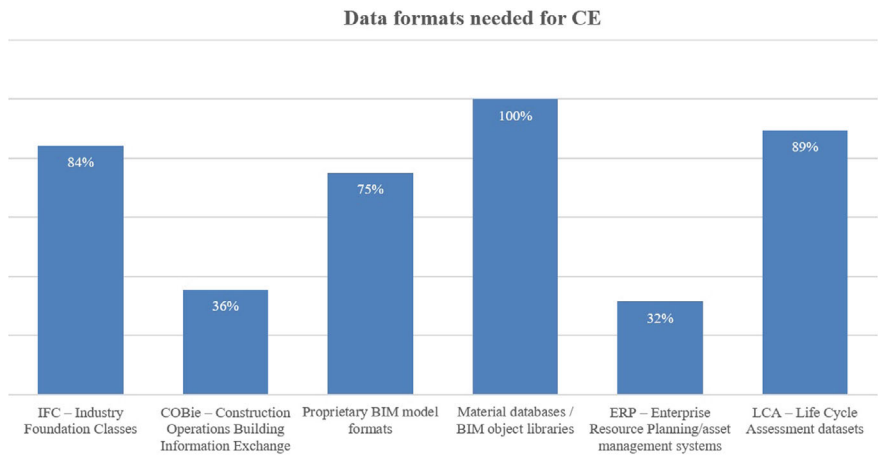


Fig. 14 Data formats needed for CE adoption

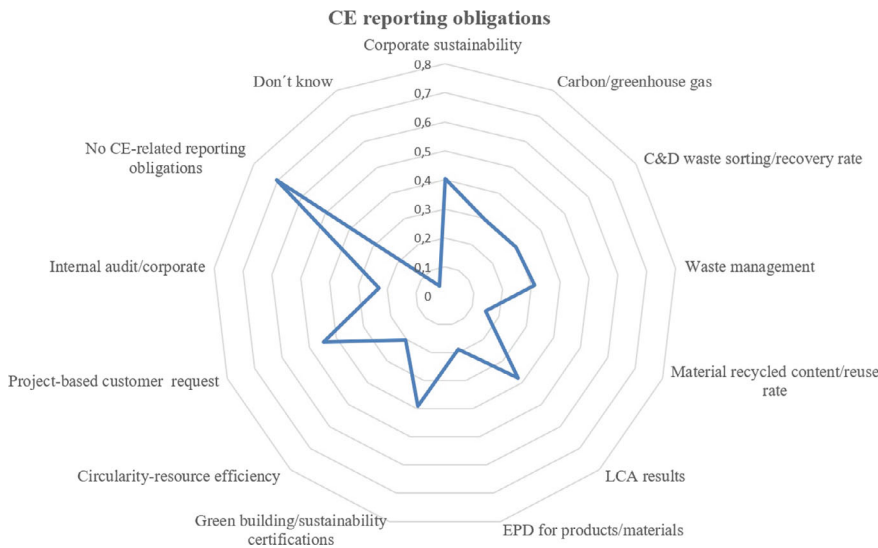


Fig. 15 CE reporting obligations

The low prevalence of legally mandated CE reporting is consistent with the current state of regulatory transposition across the three focus countries, where EU-level directives promoting lifecycle data transparency are still being translated into national instruments. This underscores the importance of regulatory certainty as a precondition for scalable CE adoption, as identified in the broader literature [3].

LCA tools, including One Click LCA, SimaPro, and OpenLCA, were the most widely used decision-support tools for material and lifecycle optimisation, cited by



Fig. 16 Mandatory extent of reports

50 respondents (68%) (Fig. 17). Cost estimation tools were reported by 34 respondents (46%), and project management tools by 37 (50%). Material tracking tools ($n = 18$), asset management systems ($n = 18$), custom plugins ($n = 12$), and visual programming environments such as Dynamo and Grasshopper ($n = 15$) were used by smaller minorities. Notably, 23 respondents (31%) reported using no decision-support tool at all. The dominance of LCA software reflects the current regulatory and certification framework, in which carbon and environmental impact reporting is more firmly established than CE-specific indicator reporting. The limited uptake of material tracking and asset management tools is consistent with the previously identified weakness in operational phase CE engagement.

4.4 Section 4: Integration of CE Indicators into BIM

Most respondents indicated that CE indicators are used only intermittently in their projects (Fig. 18). When required by a client or regulatory obligation was the most frequent response ($n = 47$, 64%), followed by occasional use ($n = 32$, 43%) and no use at all ($n = 34$, 46%). Only 13 respondents (18%) reported systematic use of CE indicators. Country-level analysis reveals that Portugal had the highest rate of systematic use ($n = 3$ systematic, $n = 6$ occasional), Romania the highest rate of non-use ($n = 14$ reporting no CE indicator use), and Serbia a profile dominated by occasional and required use. These findings confirm that the integration of CE indicators into project workflows remains largely reactive, triggered by external demands rather than embedded in standard professional practice. This is consistent with Khadim

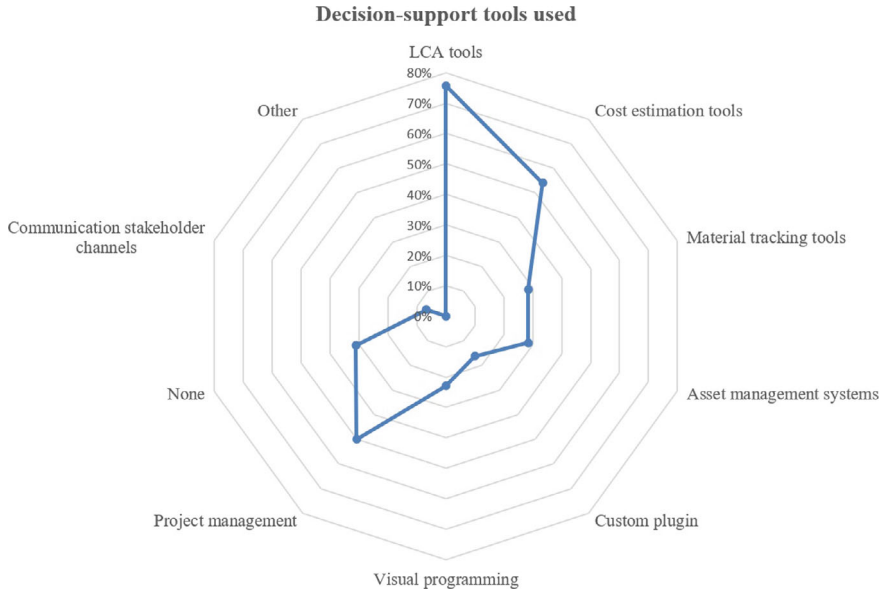


Fig. 17 Decision-support tools used

et al.’s (2022) [13] observation that most building circularity tools are still in a developmental phase and have not achieved routine uptake.

Figure 19 presents the relevance of nine CE indicators as assessed by respondents across the combined sample, expressed as a percentage distribution across six relevance levels. Durability and service life, encompassing maintenance and

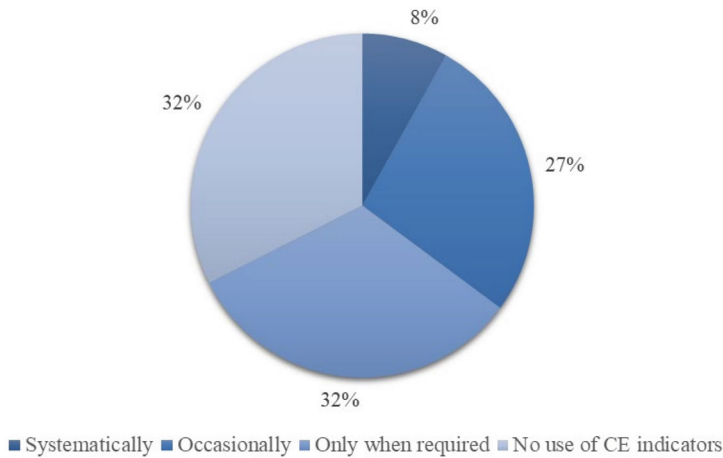


Fig. 18 Use of CE indicator in projects

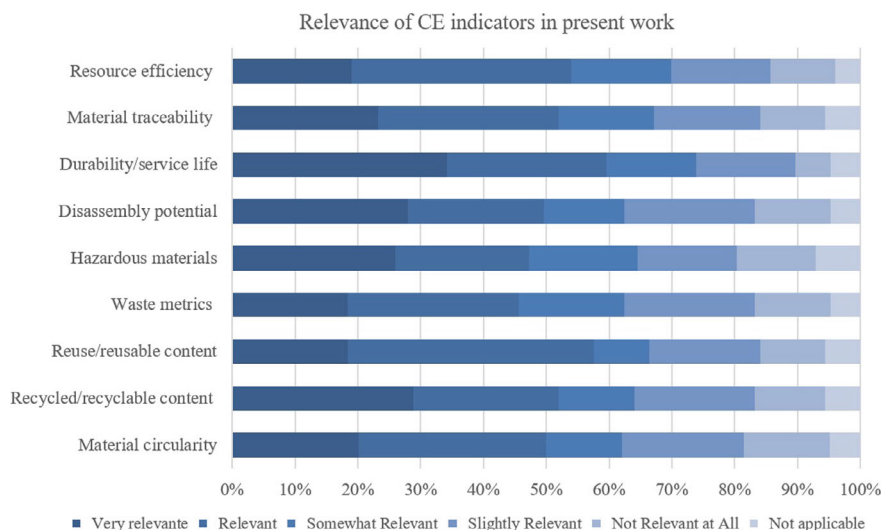


Fig. 19 Relevance of CE indicators in work

repairability considerations, was the indicator rated as most consistently relevant, with a high proportion of respondents across all three focus countries categorising it as Very Relevant or Relevant. This finding is significant because durability-related indicators bridge design intentions and long-term performance, connecting directly to lifecycle data management functions within BIM and to regulatory objectives related to building renovation and life extension under the revised EPBD [7].

Disassembly potential and design for disassembly was the second highest-ranked indicator overall, particularly prominent in the Portuguese and Serbian sub-samples, reflecting growing awareness of the importance of upstream design decisions for end-of-life material recovery. Reuse and reusable content followed closely, while material circularity as captured by composite metrics such as the Material Circularity Indicator (MCI) showed a more dispersed distribution, with notable proportions of respondents selecting Slightly Relevant or Not Relevant. This pattern suggests that composite circularity scores, despite their conceptual appeal as summary measures, are perceived as less operationally relevant by practitioners than more disaggregated, stage-specific metrics, possibly because composite indicators require data inputs that are rarely available in standard project documentation. Resource efficiency and material traceability showed moderate relevance ratings overall, while hazardous materials and toxicity-related metrics attracted divergent responses across country groups, being rated as highly relevant in Romania, potentially reflecting differences in regulatory context and construction practice related to legacy building stock. Waste metrics showed moderate relevance, somewhat surprisingly given the prominence of waste management reporting obligations, but this may reflect a disconnect between reporting obligations and indicator-level practice.

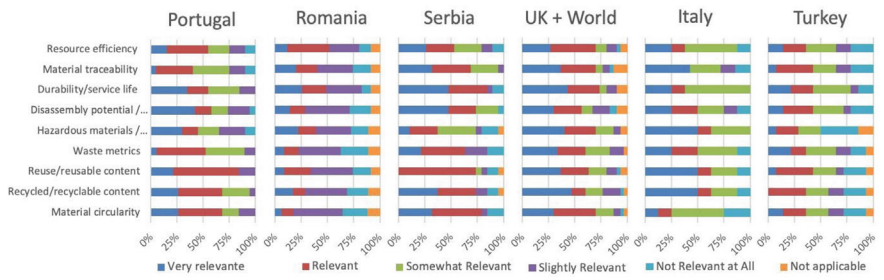


Fig. 20 Relevance of CE indicators in work per country

The country-level pattern revealed by the heatmap reinforces the conclusion that CE indicator relevance is context-dependent and that a uniform set of indicators is unlikely to serve all national contexts equally (Fig. 20). This observation directly supports the recommendation in the literature for flexible, modular frameworks that allow practitioners to select and combine indicators based on project phase, client requirements, and regulatory context [8, 14].

Figure 21 presents the distribution of responses indicating at which lifecycle stages CE indicators are currently assessed using BIM, organised by indicator type. The dominant pattern across nearly all indicator categories is a strong concentration in the Concept and Early Design stage, which was the most frequently cited stage for seven of the nine indicators. Production and Construction was the second most cited stage across most indicators, confirming that BIM-enabled CE assessment is primarily limited to the early phases of project delivery.

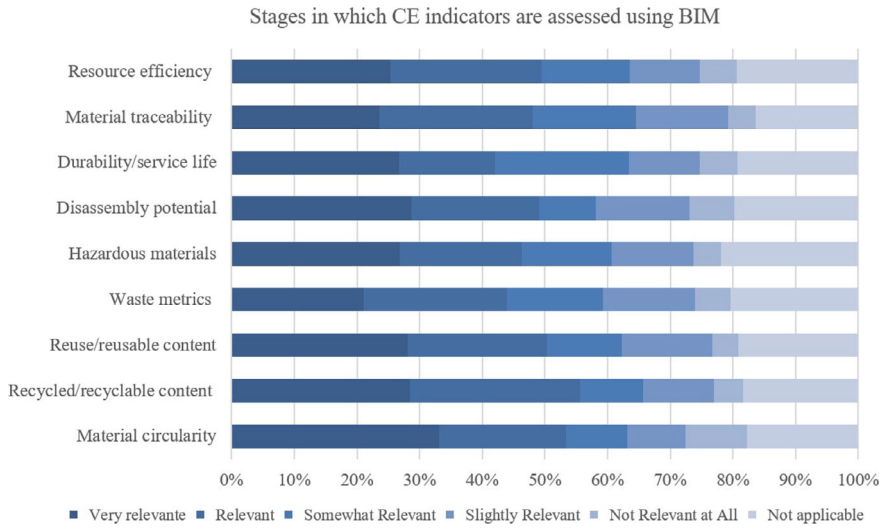


Fig. 21 Stages in which CE indicators are assessed using BIM

Use, Operation and Maintenance was cited with appreciable frequency only for durability and service life indicators, which is conceptually consistent: this is the phase at which lifecycle performance is observable, and durability metrics are most directly assessable through monitoring data. For all other indicators, the operational phase was largely absent from respondents' current BIM workflows. End of Life and Beyond System Boundary stages were cited by small proportions of respondents, predominantly in connection with disassembly potential and waste metrics, reflecting a nascent awareness that these stages require specific data structures and design decisions to be operationalised. The Not Applicable response was selected by a significant proportion of respondents across all indicators, particularly in the Romanian sub-sample, reinforcing the finding from Q4.1 that CE indicator assessment in BIM is not yet a mainstream activity.

The stage-by-indicator pattern revealed by this analysis has direct implications for the design of a BIM-CE integration framework. The current concentration of BIM-enabled CE assessment at early design stages reflects both a genuine alignment with where CE decisions are most impactful, notably in terms of material selection, design for disassembly, and passive design strategies, and a structural limitation in the availability of BIM environments capable of supporting CE data throughout the full asset lifecycle (see Fig. 22). The European Commission [3] analysis of whole-life carbon emissions explicitly identifies gaps in operational and end-of-life data availability as a key impediment to effective policy design, a finding that resonates strongly with the stage-by-stage gaps revealed here.

Respondents assessed the current suitability of their BIM environments for hosting CE-relevant data (Fig. 23). The combined results showed that the largest group described their environment as Poorly Suitable ($n = 35, 47\%$), followed by Moderately Suitable ($n = 32, 43\%$) and Suitable ($n = 22, 30\%$). Only nine respondents (12%) considered their environment Highly Suitable, while 12 (16%) described it as Not Suitable, and 16 (22%) indicated that no BIM environment was in use. Portugal showed a bimodal distribution, with respondents clustering at both Not Suitable and Highly Suitable ends, reflecting the coexistence within the Portuguese sample of

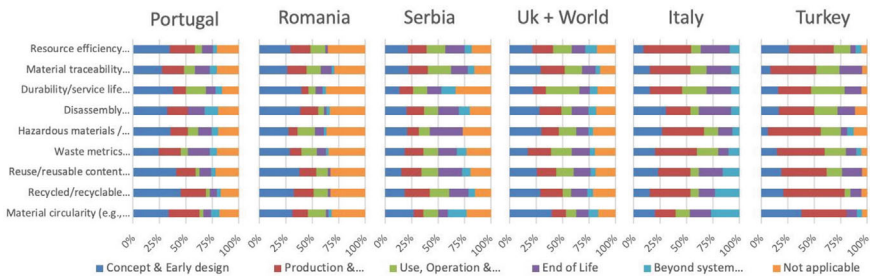


Fig. 22 Stages in which CE indicators are assessed using BIM per country

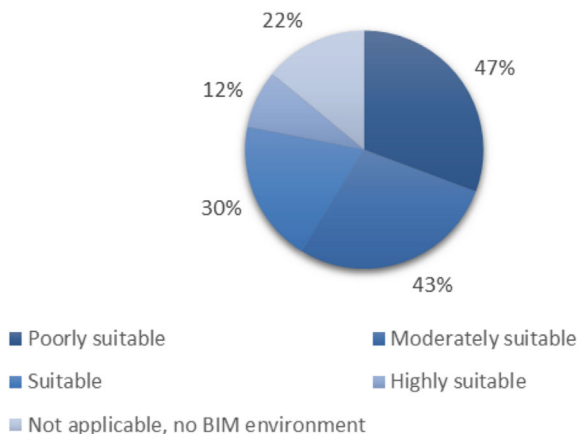


Fig. 23 BIM environment suitability for CE data

organisations with mature BIM practices alongside those with minimal digital infrastructure. Romania's distribution was skewed toward Poorly Suitable and Moderately Suitable, and Serbia showed a concentration at Moderately Suitable.

These findings suggest that even among BIM-experienced respondents, the current generation of BIM environments is perceived as insufficiently equipped for the structured hosting of CE data, reinforcing the case for the development of dedicated CE data templates, property sets, and validation mechanisms within open BIM standards.

The functionalities considered most necessary for linking CE indicators with BIM models were: automated data extraction ($n = 76$, 100% of respondents across all groups), interoperability with LCA and CE-specific tools ($n = 65$, 88%), interoperability between BIM and CE monitoring platforms ($n = 64$, 86%), metadata tagging for material properties ($n = 52$, 70%), interoperability with Building Energy Models ($n = 55$, 74%), dynamic dashboards for CE performance visualisation ($n = 40$, 54%), reuse and recycling potential evaluation tools ($n = 33$, 45%), and versioning and traceability functions for CE data ($n = 29$, 39%) (Fig. 24).

The overwhelming consensus around automated data extraction reflects frustration with current manual workflows and a clear professional expectation that CE data should flow between BIM environments and external calculation or reporting tools without requiring repeated manual re-entry. The strong demand for interoperability with LCA tools is consistent with the dominance of LCA software in current decision-support practice and points to the need for standardised data exchange mechanisms, such as IFC-based property sets aligned with EPD and LCA data formats, to enable seamless calculation workflows. The interest in dynamic dashboards and visualisation suggests that CE indicator reporting is expected to become a real-time or near-real-time function embedded in design and construction workflows, rather than a retrospective calculation exercise.

The majority of respondents ($n = 68$, 92%) expected a Moderate level of integration, encompassing partial automation and semi-structured data exchange, as the

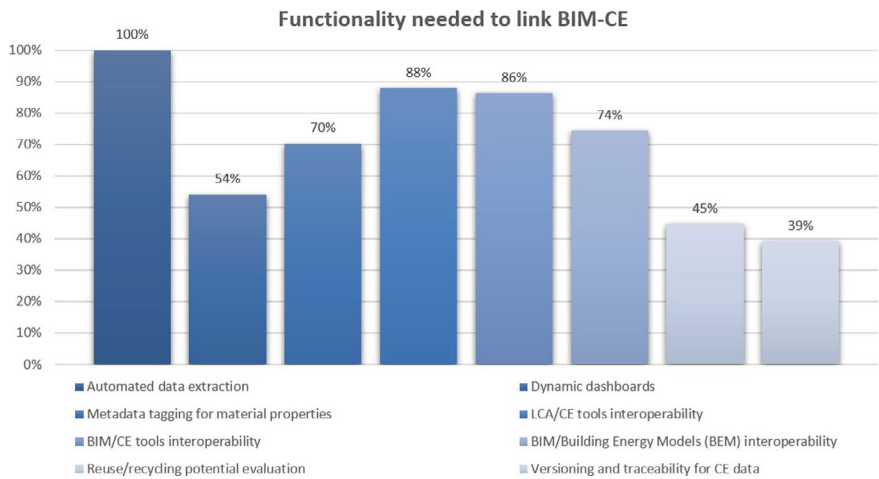


Fig. 24 Functionality needed to link BIM-CE

most realistic near-term configuration for BIM-CE monitoring systems (Fig. 25). Full automation and high interoperability were the aspiration of 43 respondents (58%), and only 15 (20%) were prepared to accept Minimal, manually driven integration. Portugal showed the strongest preference for High integration, with seven of its respondents selecting this option, while Romania and Serbia were more concentrated around Moderate integration. This calibration of expectations is important for framework development: a policy approach that mandates full automation in the short term would encounter severe implementation barriers given current BIM and CE maturity levels, while a framework oriented around incremental, modular progress toward partial automation is more likely to secure uptake across the heterogeneous landscape of AECO organisations.

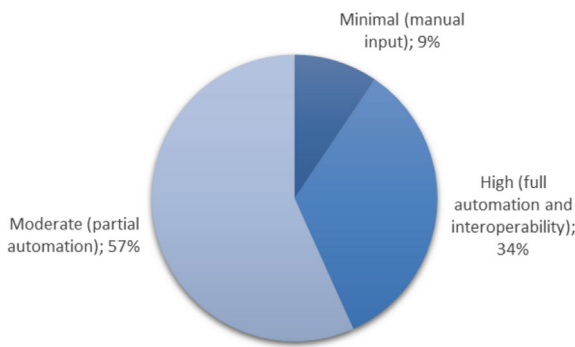


Fig. 25 Functionality Expected BIM-CE integration level

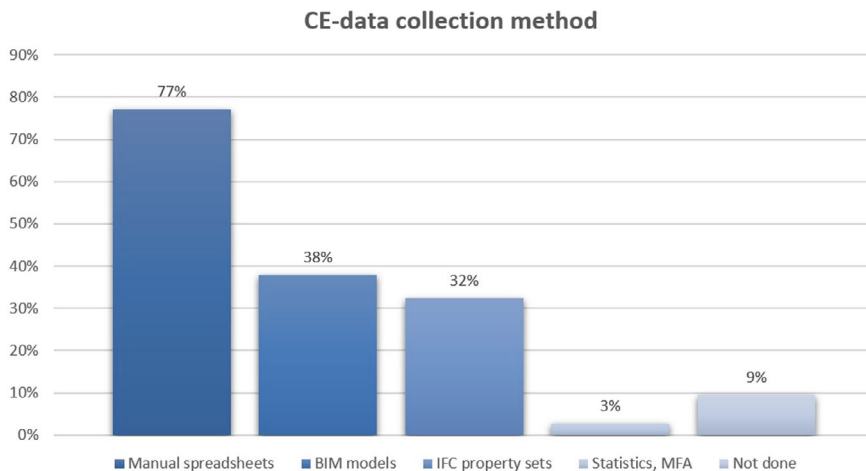


Fig. 26 CE-data collection method

Manual spreadsheets remained the dominant method for CE-related data collection, cited by 57 respondents (77%) across the combined sample (Fig. 26). BIM native models were used by 28 respondents (38%), IFC property sets by 24 (32%), and statistical or material flow approaches by only two respondents. Seven respondents (9%) reported not conducting CE data collection at all.

The persistence of manual spreadsheet workflows even among respondents with intermediate or advanced BIM capabilities confirms a well-documented implementation gap: BIM tools are adopted for geometric and coordination purposes, while the data exchange workflows needed to feed CE indicators remain outside the standard BIM environment. This gap is not merely a technical limitation but also a governance and skills issue, in which the absence of standardised data templates, validated property sets, and interoperable export formats means that professionals fall back on familiar, if inefficient, manual approaches. Overcoming this gap requires not only better tooling but also the development of structured data specifications, such as IDS-compliant property sets for CE indicators, that can be embedded in BIM authoring workflows and validated at export.

5 Towards a Conceptual BIM-Enabled Circularity Simulation Workflow

Although the present study primarily investigates the current maturity of BIM-CE integration rather than implementing a fully operational simulation model, the survey findings allow the formulation of a conceptual workflow.

The proposed workflow integrates the main data requirements identified by stakeholders with the early-stage decision framework presented in Chapter 2 and the

validated circular design strategies identified through international case studies in Chapter 1.

The workflow consists of five sequential steps:

1. Definition of circularity objectives, where designers establish project priorities such as adaptability, design for disassembly, material reuse, embodied carbon reduction, or service-life extension.
2. Development of BIM alternatives, in which several design scenarios are modelled using BIM objects enriched with circularity-related attributes, including Environmental Product Declarations (EPDs), Digital Product Passports (DPPs), material passports, recyclability, reuse potential, and deconstructability information.
3. Indicator-based assessment, where BIM-linked circularity indicators evaluate alternative scenarios through lifecycle-based metrics combining environmental, technical, and resource-efficiency criteria.
4. Trade-off analysis, allowing comparison of alternative solutions according to multiple objectives such as embodied carbon, material circularity, adaptability, lifecycle costs, and future recovery potential.
5. Decision support, where the preferred scenario is selected based on transparent multi-criteria evaluation while preserving traceability of design decisions throughout the building lifecycle.

Although this workflow remains conceptual, it illustrates how BIM can evolve from a digital documentation platform into a decision-support environment capable of evaluating circularity scenarios during the earliest design stages. Such an approach directly addresses the long-term objective of integrating simulation-based circular decision support into BIM-enabled workflows.

6 Conclusion and Final Remarks

The findings of this chapter complement the evidence generated in the previous chapters of Deliverable D4 and complete the implementation pathway proposed within COST Action CA21103. While Chapter 1 demonstrated, through international case studies, how BIM-enabled material passports and digital information management can support circular design strategies, and Chapter 2 established methodological frameworks for integrating circularity into early design decision-making, the present chapter (Chapter 3) identifies the digital, organisational, and regulatory conditions required to implement these approaches in professional practice. Together, the three chapters provide a coherent progression from validated circular design strategies, through conceptual decision-support methods, to the digital infrastructure required for their large-scale adoption.

This chapter investigated the integration of Circular Economy (CE) indicators within Building Information Modelling (BIM) through an international stakeholder survey involving professionals from across the AECO sector. The results demonstrate that, although awareness of BIM-CE integration is relatively high and its potential

is widely recognised, practical implementation remains limited and is concentrated primarily in the early design stages. Manual spreadsheet-based workflows continue to dominate CE data management, while fragmented data structures, inconsistent indicator definitions, limited interoperability, and insufficient digital maturity restrict BIM from functioning as a true lifecycle management platform for circular buildings.

The study confirms that BIM alone cannot enable circularity unless it is supported by harmonised information requirements, interoperable data standards, and reliable product-level information. Material Passports, Digital Product Passports, Digital Building Logbooks, and structured product data templates emerge as complementary elements of an integrated digital ecosystem capable of ensuring lifecycle traceability and supporting evidence-based decision-making. Furthermore, the survey highlights that practitioners increasingly require BIM environments capable not only of storing project information but also of evaluating alternative circular design scenarios. The conceptual BIM-enabled circularity simulation workflow proposed in this chapter illustrates how lifecycle-based indicators can support the comparison of alternative design solutions by assessing trade-offs between environmental performance, resource efficiency, adaptability, reuse potential, and future recoverability from the earliest design stages.

The survey further reveals that the barriers to BIM-CE implementation are systemic rather than isolated. Limited digital maturity, insufficient skills, fragmented data structures, lack of standardised circularity indicators, and inconsistent regulatory requirements reinforce one another and collectively hinder implementation. Consequently, successful BIM-CE integration requires coordinated progress across four complementary domains: (1) interoperable data infrastructures based on open standards; (2) harmonised and modular CE indicator methodologies; (3) capacity building and digital maturity; and (4) coherent regulatory and governance frameworks.

From a technical perspective, the findings emphasise the importance of IFC-compatible property sets, Information Delivery Specification (IDS) validation workflows, buildingSMART Data Dictionary (bSDD) integration, and structured information exchange capable of supporting Digital Building Logbooks, Digital Product Passports, material passports, and lifecycle assessment systems. Equally important is the development of practical implementation guidance, including reusable BIM templates, Exchange Information Requirements (EIRs), validated case studies, and training programmes that enable organisations with basic and intermediate BIM maturity to progressively adopt circular workflows. At the policy level, the results indicate that stronger alignment between CE reporting requirements and emerging European initiatives, including the revised Energy Performance of Buildings Directive (EPBD), the Construction Products Regulation (CPR), the Renovation Wave, and Digital Building Logbooks, will be essential to provide the long-term regulatory certainty needed for widespread implementation.

Based on the survey findings and literature review, this chapter proposes a progressive implementation roadmap. In the short term, priority should be given to developing harmonised CE property sets, structured BIM templates, and interoperable data validation workflows. Medium-term efforts should focus on integrating BIM environments with lifecycle assessment databases, material passports, and Digital

Building Logbooks through common European information frameworks. In the longer term, the convergence of BIM, digital twins, CE indicators, and automated lifecycle monitoring systems has the potential to enable continuously updated circularity assessments throughout the entire building lifecycle, transforming BIM into a comprehensive decision-support platform for circular construction.

This study has several limitations. Although the survey was distributed in six languages, only Portugal, Romania, and Serbia achieved sufficient response rates to support country-level analysis, while responses from the United Kingdom, Italy, and Türkiye contributed only to the aggregated dataset. Furthermore, the survey provides a snapshot of current practice at a particular point in time. Future studies should therefore expand the geographical scope, include countries with more mature BIM implementation, and monitor the evolution of BIM-CE maturity through longitudinal investigations.

Despite these limitations, this work provides one of the first multi-country, practice-oriented assessments of CE indicator integration within BIM environments across Southern and Eastern Europe. Rather than proposing technology-driven solutions in isolation, it identifies the organisational, technical, and regulatory conditions necessary for effective implementation and translates stakeholder evidence into a practical policy framework. Overall, the study demonstrates that the transition towards circular built environments depends not only on innovative design strategies but also on integrated, interoperable, lifecycle-oriented information ecosystems capable of connecting design, construction, operation, renovation, reuse, and end-of-life decision-making. BIM, when combined with harmonised CE indicators, open standards, and robust governance frameworks, can become a key enabling infrastructure supporting the transition towards a more circular, transparent, and climate-neutral built environment.

Future research should move beyond identifying implementation barriers towards developing and validating operational BIM-based decision-support systems capable of automatically evaluating multiple circularity scenarios using standardised lifecycle indicators. Such developments would represent a natural continuation of the work initiated within COST Action CA21103 and would further accelerate the practical implementation of circular economy principles throughout the built environment.

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References

1. Ellen MacArthur Foundation (2019). Circular economy in the built environment
2. European Commission (2020) A renovation wave for Europe: greening our buildings, creating jobs, improving lives, Brussels

3. European Commission (2025) Analysis of life cycle greenhouse gas emissions of EU buildings and construction: analysis of results and implications. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2873/2247112>
4. CEN (2022). Relevant standards related to the construction products regulation and digital building logbook
5. European Commission (2023). Construction products regulation; digital product passport; digital building logbook
6. Gómez-Gil M, Espinosa-Fernández A, López-Mesa B (2022) Contribution of new digital technologies to the digital building logbook. *Buildings* 12(12):2129. <https://doi.org/10.3390/buildings12122129>
7. European Commission (2024) Revised energy performance of buildings directive (EPBD) proposal, Brussels
8. Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A (2019) A taxonomy of circular economy indicators. *J Clean Prod* 207:542–559. <https://doi.org/10.1016/j.jclepro.2018.10.014>
9. Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, Van Acker K, De Meester S, Dewulf J (2019) Circular economy indicators: what do they measure? *Resour Conserv Recycl* 146:452–461. <https://doi.org/10.1016/j.resconrec.2019.03.045>
10. Pomponi F, Moncaster A (2017) Circular economy for the built environment: a research framework. *J Clean Prod* 143:710–718. <https://doi.org/10.1016/j.jclepro.2016.12.055>
11. Akhimien NG, Latif E, Hou SS (2021) Application of circular economy principles in buildings: a systematic review. *J Build Eng* 38:102041. <https://doi.org/10.1016/j.jobe.2021.102041>
12. Antonini E, Boeri A, Lauria M, Giglio F (2020) Reversibility and durability as potential indicators for circular building technologies. *Sustainability* 12:7659. <https://doi.org/10.3390/su12187659>
13. Khadim N, Agliata R, Marino A, Thaheem MJ, Mollo L (2022) Critical review of nano and micro-level building circularity indicators. *J Clean Prod* 357:131859. <https://doi.org/10.1016/j.jclepro.2022.131859>
14. Segara S, Li QJ, Gallotta A, Wang Y, Gosling J, Rezgui Y (2024) Taxonomy of circularity indicators for the built environment. *J Clean Prod* 446:141429. <https://doi.org/10.1016/j.jclepro.2022.141429>
15. Eastman C, Teicholz P, Sacks R, Liston K (2011) BIM handbook: a guide to building information modeling for owners. Wiley, Managers, Designers, Engineers and Contractors
16. Sesana MM, Dell’Oro P, Salvalai G, Gervasio H (2026) Building life cycle assessment and digital technologies. *Energy Build* 352. <https://doi.org/10.1016/j.enbuild.2025.116833>
17. International Organization for Standardization (ISO) (2018b). ISO 19650-1—organization and digitization of information about buildings and civil engineering works
18. International Organization for Standardization (ISO) (2018a). ISO 16739-1—industry foundation classes (IFC)
19. Sesana MM, Salvalai G (2018) A review on building renovation passport: potentialities and barriers on current initiatives. *Energy Build* 173:195–205. <https://doi.org/10.1016/j.enbuild.2018.05.027>
20. Sesana MM, Salvalai G, Della Valle N, Melica G, Bertoldi P (2024) Towards harmonising energy performance certificate indicators in Europe. *J Build Eng* 95. <https://doi.org/10.1016/j.jobe.2024.110323>
21. Atta I, Bakhoun ES, Marzouk MM (2021) Digitizing material passport for sustainable construction projects using BIM. *J Build Eng* 43:103233. <https://doi.org/10.1016/j.jobe.2021.103233>
22. Akanbi LA, Oyedele LO, Akinade OO, Ajayi AO, Delgado MD, Bilal M, Bello SA (2018) Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. *Resour Conserv Recycl* 129:175–186. <https://doi.org/10.1016/j.resconrec.2017.10.004>
23. Ganiyu SA, Oyedele LO, Akinade O, Owolabi H, Akanbi L, Gbadamosi A (2020) BIM competencies for delivering waste-efficient building projects in a circular economy. *Dev Built Environ* 4:100036. <https://doi.org/10.1016/j.dibe.2020.100036>

24. Honic M, Kovacic I, Aschenbrenner P, Ragossnig A (2021) Material passports for the end-of-life stage of buildings. *J Clean Prod* 319:128702. <https://doi.org/10.1016/j.jclepro.2021.128702>
25. Charef R, Emmitt S (2021) Uses of building information modelling for overcoming barriers to a circular economy. *J Clean Prod* 285:124854. <https://doi.org/10.1016/j.jclepro.2020.124854>
26. Al-Qazzaz I, Osorio-Sandoval CA, Tokbolat S, Thermou G (2024) Integration of building information modeling into building circularity assessment: a systematic review. *Built Environ Project Asset Manage*. <https://doi.org/10.1108/BEPAM-12-2023-0229>
27. Dervishaj A, Gudmundsson K (2024) From LCA to circular design: a comparative study of digital tools for the built environment. *Resour Conserv Recycl* 200. <https://doi.org/10.1016/j.resconrec.2023.107291>
28. Guntermann L, Hagedorn P, König M (2025) Enhancing IFC models for circular design: validation of required information through an IDS framework. In: *Proceedings of ISARC 2025*, Montreal
29. Tomczak A, Benghi C, van Berlo L, Hjelseth E (2024) Requiring circularity data in BIM with information delivery specification. *Circ Econ* 1(2). <https://doi.org/10.55845/REJY5239>
30. Fernandes JB, Ferrão PC, Silvestre JD, Costa AA, Göswein V (2022) Advancing circular economy in the existing building stock. *Acta Polytech CTU Proc* 38:599–605. <https://doi.org/10.14311/APP.2022.38.0599>
31. Marin G, Marin E, Stroe R, Zaharia MF (2023) Analysis regarding the implementation of the circular economy in Romania. *Sustainability* 15(1):333. <https://doi.org/10.3390/su15010333>
32. Mysak I, Mysak P (2024) BIM technologies adoption and implementation challenges in eastern European countries. *Arch Stud* 10(2):124–135. <https://doi.org/10.56318/as/2.2024.124>
33. Milović T, Laban M, Bulatović V, Starčev-Čurčin A, Draganić S, Bukvić O (2024) Circular economy as a new concept for sustainable building development in Serbia, Lecture notes in civil engineering, vol 489. Springer. https://doi.org/10.1007/978-3-031-57800-7_46
34. Al-Qazzaz I, Osorio-Sandoval C, Tokbolat S, Thermou G (2025) A BIM-based decision support system for circularity and sustainability assessment in the early design stages. *Archit Eng Des Manag*. <https://doi.org/10.1080/17452007.2025.2566094>
35. Likert R (1932) A technique for the measurement of attitudes. *Arch Psychol* 140:1–55
36. Azhar S (2011) Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadersh Manag Eng* 11(3):241–252. [https://doi.org/10.1061/\(ASCE\)LM.1943-5630.0000127](https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127)
37. Succar B (2009) Building information modelling framework: a research and delivery foundation for industry stakeholders. *Autom Constr* 18(3):357–375. <https://doi.org/10.1016/j.autcon.2008.10.003>

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