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Review

Urban Metabolism-Based Approaches for Promoting Circular Economy in Buildings Refurbishment

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Abstract: The systemic transformation towards climate neutral cities depends on a dramatic reduction in the use of natural resources, whose use are directly or indirectly associated with greenhouse gas emissions. This means improving Urban Metabolism (UM) and one of the most promising pathways is to promote Circular Economy (CE) practices in the existing building stock, as this approach could reduce global CO_2e emissions from building materials by 38% in 2050. However, although resource efficiency is at core of CE, there are still only a few established connections between CE and UM. This paper aims to fill this gap by adopting a three-tier approach based on the dimensions and the spatial implementation of CE (building, neighbourhood and UM scales), with the aim of discussing strategies for CE implementation. Although this not a one-size-fits-all process and cities must adapt these strategies to their local contexts, the strategic actions offered by this paper will facilitate the future development of a dedicated framework for buildings refurbishment using the principles of CE and the definition of multisectoral policy-based actions, in line with the decarbonization goals for cities, which will contribute to improving UM.

Keywords: circular economy; circular design; circular refurbishment; circular urban metabolism; urban mining

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1. Introduction

Although urban areas occupy 4% of land surface, they are responsible for 80% of carbon emissions and 60% of water consumption [1]. Moreover, 57% of global population live in cities [2] and it is estimated that, following current urbanization trends, global urban population will grow 78% from 2010 to 2050 [3]. However, global urban material consumption is expected to grow even faster: 116% from 2010 to 2050, which will result in approximately 14 tons per capita by 2050 [3]. This is the result of a linear economy model, based on resources consumption and waste generation, where material production accounts for 45% of global Greenhouse Gas (GHG) emissions [4]. To tackle climate change and resources depletion, cities must adapt to a more sustainable and holistic approach.

Studying and mapping cities' resources use is at the core of Urban Metabolism (UM). UM approaches cities as living organisms [5] and analyses their flows (inputs, stocks and outputs) by studying production, distribution and consumption-related processes and their corresponding outputs: growth, energy production and waste [6]. By providing resource use mapping data, UM is a valuable tool for policy making, urban planning and urban management.

Aimed at carbon neutrality, public authorities are being challenged to implement alternative strategies to a more sustainable management of resources. This requires a shift from a linear economy to a Circular Economy (CE) model and closing materials loops, minimizing resource extraction, waste production and maximizing products' utility [7]. According to [4], a CE approach to the built environment could reduce global CO_2e emissions from building materials by 38% or 2.0 billion tons CO_2e in 2050. In fact, applying CE principles to the existing building stock might contribute significantly to achieving decarbonization targets, not only by extending buildings' lifespan but also by using buildings as material stocks for refurbishment or new construction.

However, the application of CE has been concentrated in the industrial sector, through industrial symbiosis [8]. Only a few studies relate CE application to the improvement of UM, with a special focus on the built environment. To tackle this issue, this paper surveys the state-of-the-art on integrating CE in the existing building stock. The main barriers to CE adoption are identified and categorized and possible solutions are acknowledged and linked to the territory within a multi-level approach: from building to neighbourhood and city. This research aims to contribute with strategies to promote cities' potential to becoming carbon neutral, by enabling innovative systemic solutions within CE in the existing building stock, in line with European goals towards decarbonization [9] and refurbishment of existing building stock [10]. Public authorities can lead this process by engaging stakeholders, implementing guidelines, incentives and dedicated facilities, so that UM studies can be received and give the inputs to facilitate CE adoption for the existing building stock.

This paper is organized as follows: Section 2 describes the methodology; Section 3 explores the connection between UM and CE and identifies the multiple dimensions of CE in the built environment; Section 4 analyses and categorizes the existing literature on CE in the construction, identifies the main barriers to CE integration and provides strategic solutions to mitigate the identified challenges. Discussion and conclusions are presented in Section 5.

2. Methods

The formulation of the research questions to guide the literature review process constituted the first step of this research. The keywords "adaptive reuse", "anthropogenic stock", "buildings refurbishments", "circular economy", "circular economy in construction", "circular economy regulation", "construction recycling", "design for disassembly", "design methodology for CE", "material flows", "construction reuse", "circular design", "construction and demolition waste", "industrial ecology" and "urban metabolism" were selected and combined for the search of relevant literature.

The search comprised scientific papers, reports, and other grey literature, as the objective was to obtain state-of-the-art scientific, policy and practice approaches. From the initial sample of 251 papers, 84 were found to be directly related to the scope of the research, using the PRISMA methodology [11]. Their analysis resulted in identifying 64 papers addressing the challenges to adopt CE in construction, which were linked to six dimensions of CE in construction: economic, social, organizational, technical and policy. As circular design principles are related to Eco-design, it was decided to include them in this stream. The challenges identified in the literature review, and the corresponding solutions to adopt CE in buildings refurbishment were categorized into three scales of application: building, neighbourhood and city, as represented in Figure 1, which illustrates the overall methodology adopted.

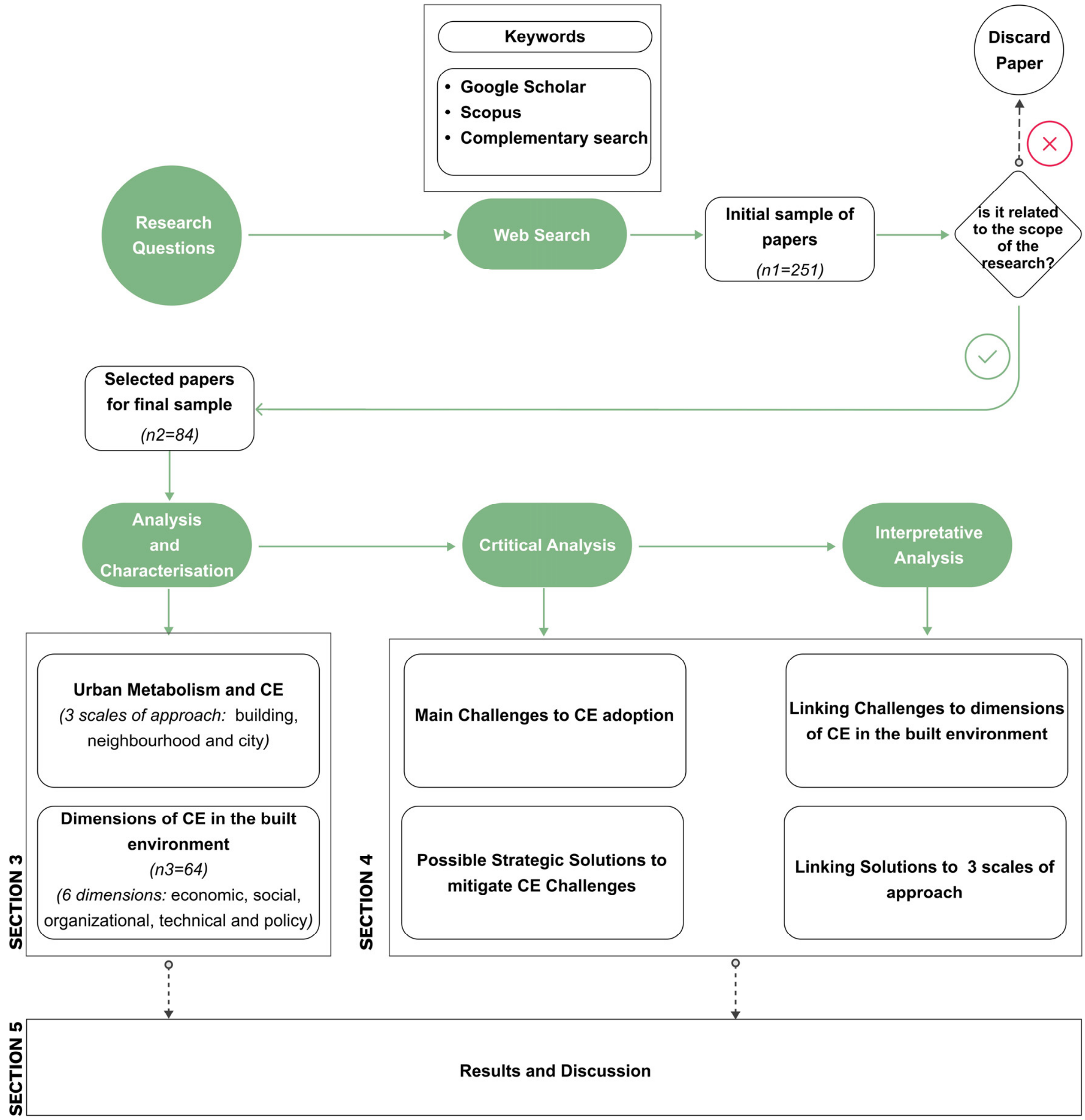

Figure 1. Schematic representation of the research methodology.

3. CE and UM within the Built Environment: Research Background

In contrast to a linear economy model, CE aims to reduce natural resource extraction, minimize waste and maximize materials utility while extending their lifespan [12]. However, there is still no widely accepted definition for CE [13], and its extensive application has been focused in the industrial sector, through industrial symbiosis, and a few to urban environment, through UM [8]. In fact, most publications regarding CE and the urban built environment—mainly journal articles and reports from EU projects—were published after 2018 (Figure 2). The most widely known definition of CE, from Ellen MacArthur Foundation (EMF), is based on a regenerative and restorative model [7]. It takes into account the amount of virgin material, the amount of unrecoverable waste and the utility of products to define CE. Although EMF calculations are for generic products, some authors such as [14,15] have adapted them to the built environment.

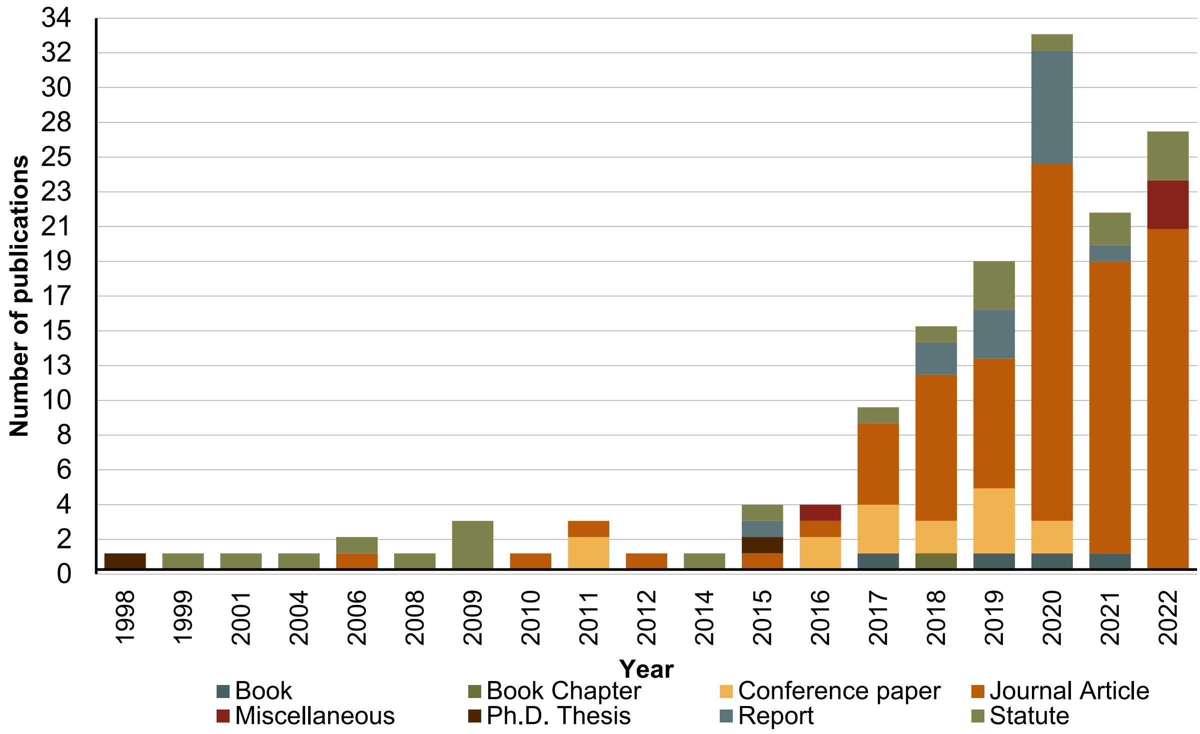

Figure 2. Reviewed literature by publication type.

Applying CE to the existing urban building stock will contribute largely to cities' decarbonization, as they are mainly defined by their built environment, and this is one of the most consuming sectors in terms of energy and resources [16]. However, this issue encloses some opportunities to develop circular strategies for cities, related to resource and energy efficiency.

Identifying improvement opportunities within urban systems interactions requires an understanding how these ecosystems perform drawing parallels to living organisms [3] and quantifying and characterizing resources flows and their environmental, social and economic impacts [17], through tools such as Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Geo-Information Systems (GIS) [18]. Although there are not many tools or studies that link CE adoption in the existing building stock to the improvement of UM [19], there is a new concept called Circular Urban Metabolism [20] that emphasizes this connection in a multi sectorial way. Specifically in the built environment, UM can contribute significantly to CE adoption by identifying the most important material and waste flows at an urban scale, monitoring CE implementation and providing top-down information not only for policy and decision makers [21], but also for improving CE adoption at neighbourhood and building levels.

The complexity of CE adoption in the built environment requires interdisciplinary research [22], a combined systems thinking [23] and a multi-level approach, to understand its several dimensions and the scope of its application in the territory.

3.1. Dimensions of CE in the Built Environment

CE practices in the built environment are just starting to be adopted and there is a multitude of challenges and research gaps to be tackled, from various perspectives. In this section, the results of the literature review of recent papers, from 2020 to 2022, provide the basis for the classification of these challenges by thematic axis [24], by lifecycle stages [25–28] or by dimensions [19,22,29,30], and furnish pathways for addressing possible solutions.

The organization of research gaps per thematic axes such as: Recycled/reused materials; Circular transition; Tools and assessment to support circular buildings; Product and building design; Stock and flow analysis of resources and materials, acknowledges the identification of research areas and the links through their dimensions [24]. On the other hand, using a lifecycle approach [25–28], allows for the identification of research gaps along the building lifecycle: procurement/construction process/stage of the building. All of the classification strategies provide integrated approaches for CE, but in order to facilitate addressing a specific part of the problem, such as circular refurbishment, the categorization of challenges by dimensions of CE in construction was adopted here, as it allows for the selection of domains closely related to CE adoption in the existing building stock.

This classification of challenges and research gaps by dimensions has been addressed by authors such as Pomponi and Moncaster [22], who have defined six dimensions for CE: economic, environmental, technological, societal, governmental and behavioural. On the other hand, Hossain et al. [19] and Gerldermans and Jacobson [29] organized research in seven dimensions, addressing, respectively, environmental, economic, management/behaviour, technological, social, innovation and policy considering six contextual aspects, social, technical, design, financial, legal, organization. I. Wuni [30] identified 95 barriers to CE adoption, and categorized them in eleven groups (cultural, market, knowledge, financial, management, regulatory, technological, supply chain, stakeholder, technical, and organizational), which fit into the above-identified dimensions.

As a conclusion, although there are various CE dimensions classifications, they have similar contents. Based on [22], this research adopts and combines the findings about challenges and research gaps into six dimensions: economic, social, organizational, technical, environmental and policy. The introduction of the organizational dimension is critical for buildings refurbishment, as it includes the standardized procedures of CE, while also addressing the communication and collaboration between stakeholders. All dimensions are interrelated and necessary to achieve a fully circular built environment.

Assessing circularity includes finding commonly accepted criteria and methods to measure and evaluate the building sector. As these tend to be objective, most publications relate to the organizational, technical and environmental aspects of CE, together with policy dimensions whilst the fewest are focused in economic and social, according to Figure 3. Moreover, the quantification of the economics requires a large amount of information and benchmarks, while the social dimension is difficult to assess, as it implies subjective indicators [31].

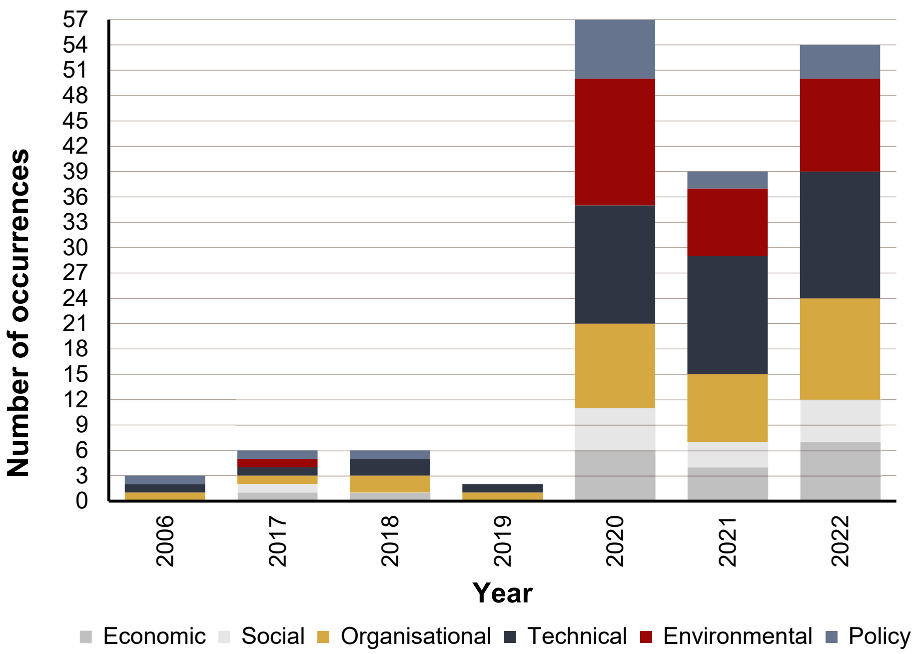

Figure 3. The intensity of the reviewed literature per research dimension.

Appendix A summarizes the identification and characterization of selected papers, per dimension, publication year and type.

3.2. Boundary Conditions for CE in the Existing Building Stock

Understanding the multitude of dimensions of CE is the first step to the implementation of CE in the built environment. However, the definition of actionable strategies implies the connection to the territory.

While UM studies have usually adopted top–down approaches [21], as they characterize urban processes at a macro scale, specific CE actions take place at the building level. On the other hand, these specific actions provide reliable data for UM studies [20], which is fundamental to understanding in detail the dynamics of the existing building stock and take it to a more sustainable level [18]. According to [32], strategies to tackle problems related to urban systems should be supported by a multi-scale research, combining geography, human activities and economy. In [33], the importance of local interventions in the materialization of global policies goals is also stressed.

Although there is no commonly established definition of boundary conditions within the built environment, [22] have approached CE adoption in three levels: macro (cities and neighbourhoods), meso (buildings) and micro (assemblies and components). This classification was also adopted by other authors and by COST Action working groups [34] when referring the built environment, although the classification adopted for Circular City was: macro scale to city level or above, meso scale to district level and micro scale to household level [34].

This research also adopts a three-tier approach based on CE dimensions and the spatial implementation of CE, as the final objective is to discuss strategies to CE adoption that might facilitate the future development of policy-based actions, linked to urban systems, which will contribute to improve UM. To this extent, macro level relates to city scale or above, meso level to a neighbourhood scale and micro level relates to building scale.

Macro level: city scale or above

Macro level includes the physical urban territories and UM: urban flows, the intangible systems where CE can be applied (economic, social, policy, manufacturing, etc.) and the transversal actions that support a CE system (cooperation between stakeholders, sustainable development goals, etc.).

Micro level: building scale

Building scale is the physical ground where CE occurs. It comprises the buildings themselves and all materials, assemblies and systems within the buildings.

Meso level: neighbourhood scale

This is an intermediate scale that receives and gives inputs both from micro and macro scales, where the resources management occur. Meso scale articulates the physical resources from buildings with the insights from UM to improve resource efficiency [6] and manages resources locally.

The larger the scale, the more complex the systems are in terms of stakeholders and disciplines [23], which requires a holistic approach.

4. Adopting CE in the Existing Building Stock to Improve UM

The thorough analysis of the literature allowed to identify and organize the main challenges for CE adoption, as a basis for defining strategies to reduce natural resources extraction and reduce the amount of unrecoverable waste. The main challenges associated with the adoption of CE in the existing building stock were categorized into the six dimensions, as follows:

Economic: Lack of platforms and storage facilities for reclaimed products (E1); Lack of platforms for CE professionals and CE jobs (E2); Estimation challenges; short-term blinkers (E3); Lack of strategies and infrastructures for new CE materials production (E4); Lack of CE business models (E5);

Social: Lack of trust and of CE vision for the building sector (S1); Lack of platforms for CE professionals and CE jobs (S2); Lack of collaboration between stakeholders (silo mentality) (S3); Willingness to go around the law (S4);

Organizational: Lack of platforms and storage facilities for reclaimed products (O1); Lack of standard practices for End-of-Life (EOL) and Construction and Demolition Waste (CDW) management at the pre design stage (O2); Collaboration and management issues (O3); Issues with manufacturers' responsibility and approaches (O4); Constraints for EOL processes implementation on site (O5); Lack of methodology and standard practices for CE design (O6); Lack of training skills (O7);

Technical: Building-related barriers (T1); Lack of materials knowledge and technical challenges for CE (T2); Challenges to EOL implementation (T3); Production-related barriers (materials and technology) (T4); Barriers to apply new CE oriented design (T5);

Environmental: Toxic materials removal (EN1); Lack of awareness of CE impact in climate change (EN2); Lack of awareness of transportation impact in CE in construction (EN3); Low of energy efficiency at operation stage (EN4); Lack of methodology of CE evaluation towards climate change mitigation (EN5);

Policy: Lack of platforms and infrastructures for reclaimed materials, components and products (P1); CDW-related barriers (P2); Lack of consistent regulatory framework for CE (P3); Reclaimed materials-related barriers (P4); Lack of knowledge among stakeholders (P5); CE business-related barriers (P6).

It was found that there are some key challenges across different dimensions, and therefore, can be gathered in four groups: 1) lack of CE jobs, business models and stakeholders; 2) EOL and CDW management; 3) Materials and 4) Design and CE assessment. The incidence of challenges in the three last groups (77%) reflect the CE principles of closing material loops, by designing and redesigning buildings, systems, products and materials for EOL [35] and the necessity of adopting standardized practices and methods for CE [36]. Moreover, this also highlights that CE adoption in construction is an integrated and multi-dimensional process and, accordingly, Table 1 reflects the connections between challenges.

Economic and Social challenges are transversal, comprising the lack of platforms for CE professionals and CE jobs, the lack of CE business models (economic dimension), the lack of trust and CE vision for the building sector, the lack of collaboration between stakeholders and stakeholders' willingness to go around the law. Households' behaviour was not considered in this research, as its focus is on refurbishment strategies from the construction sector perspective.

The organizational dimension is associated with procedures and communication challenges. However, together with technical, organizational challenges are predominantly EOL-related, reflecting buildings actual inability to be transformed, as they evolve for different functions. Well-conceived refurbishment strategies provide an opportunity to change the paradigm of linear buildings and adopt a circular perspective, but it should start in the buildings design. This is reflected in the intensity of technical and environmental challenges at the design stage (71%).

Policy strategies should address multi-dimensional challenges, including the lack of platforms and infrastructures for reclaimed materials, components and products, CDW-related barriers, the lack of consistent regulatory framework for CE, barriers related to reclaimed materials, the lack of knowledge among stakeholders and barriers related to CE businesses.

The multitude of stage-specific and transversal barriers, their inter-connections and adjustments to the specificities of existing building stock and its refurbishment process urges the systematization into the territory, to be implemented. Therefore, the next section combines possible strategic solutions to CE adoption with the previously defined boundary conditions.

Table 1. Connections between challenges to adopt CE in the existing building stock.

	E1	E2	E3	E4	E5	S1	S2	S3	S4	O1	O2	O3	O4	O5	O6	O7	T1	T2	T3	T4	T5	EN1	EN2	EN3	EN4	EN5	P1	P2	P3	P4	P5	P6
E1										•																	•	•				
E2							•																									
E3															•						•											•
E4													•							•								•	•	•		
E5												•																				•
S1																												•	•		•	
S2		•														•															•	
S3												•																				
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O5																			•			•						•				
O6			•													•					•		•	•	•	•			•			
O7							•					•			•		•	•	•	•	•										•	
T1											•					•																
T2											•					•													•			
T3														•		•						•						•	•			
T4				•									•			•													•	•		
T5			•												•	•							•	•	•	•			•			
EN1														•					•													
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P1	•									•	•													•								
P2	•			•		•					•			•					•													
P3				•		•			•		•		•		•		•		•	•	•					•						
P4				•									•							•												
P5						•	•		•			•				•																
P6			•		•																											

4.1. Strategic Approaches to Mitigate the Identified CE Challenges

The existing building stock is characterized by its inability to adapt format to function, but refurbishment activities do also constitute unique opportunities to rethink functional, spatial and constructive connections through design. Only a few studies focused on buildings refurbishment are available, which seem to be considered a better option, from an economic and environmental perspective, compared to new construction [37–39]. Moreover, refurbishments are related to urban mining, as buildings can provide valuable resources, such as incorporated reclaimed components, enhancing CE at meso and macro scales. On the other hand, transversal and multidimensional strategies are also critical to support micro scale solutions and to tackle the previously identified barriers to CE adoption, as CE in refurbishments must ideally optimize resources and generate zero waste, an objective that is only achievable with the involvement of all stakeholders in the value chain.

Table 2 summarizes the main challenges and possible strategic solutions for CE adoption in buildings refurbishment.

Table 2. Challenges and possible solutions for CE adoption in the existing building stock.

Challenges	Challenges Description	Possible Strategic Solutions	Scale	Ref.
E1 Lack of platforms and storage facilities for reclaimed products	Lack of platforms for advertising reclaimed products, components and materials	Create online platform for reclaimed products, components and materials	Macro	[26,28,40]
	Lack of storage facilities for reclaimed products, components and materials Additional cost for storage	Create free facilities for storage of reclaimed products	Meso	
E2 Lack of platforms for CE professionals and CE jobs	Lack of platforms for advertising CE professionals Lack of framed and centralised initiatives Lack of a global economic strategy to jobs and competitiveness	Create online platforms for CE professionals and CE jobs Provide training and certification to professionals	Macro	[26,28]
E3 Estimation challenges; short-term blinkers	Estimation challenges for CE (e.g., lack of material transport and treatment cost) Belief that CE approach is more expensive (high upfront investment costs, low virgin material prices, etc.) Short-term blinkers: looking for profitability only; lack of awareness of benefits for EOL anticipation	Provide economic information and a global vision of the whole lifecycle cost estimation for CE: costs of disassembly, selective demolition and renovation of buildings; investment return Demonstrate potential economic benefits associated with the adoption of CE principles with business and financial case studies Develop financial incentives to encourage CE, together with appropriate taxing (reducing taxes on labour, increasing taxes on the use of primary raw materials, exempting Value Added Tax (VAT) in products containing reclaimed materials/components, where VAT has already been paid Target customer segments that value CE approaches and lower GHG emissions	Macro	[19,24,26,27,30,39,41–45]
E4 Lack of strategies and infrastructures for new CE materials production	Lack of strategies and infrastructures for new CE materials production	Study the local or regional capacity on materials supply by anthropogenic stock and the effect on reducing transportation	Meso	[19,24,26,46–50]
		Develop new concepts for manufacturing materials and products Adopt incentive schemes and guidelines for recycled and recovered products to promote economic profitability in CE businesses	Macro	
E5 Lack of CE business models	Lack of CE business models Poor/unconvincing business case Limited funding Lack of centralised initiatives	Design strategies to introduce CE business models: reuse of materials and resources, increase the energy efficiency of buildings by passive and active planning, promote leasing, customer services and capacity building services with new ownership arrangements Create interactive platforms for sharing results Develop financial incentives to encourage CE, together with appropriate taxing	Macro	[8,19,22,24,26–28,30,40,41,43,45–47,51,52]
S1 Lack of trust and lack of CE vision for the building sector	Lack of trust in CE principles Lack of interest, knowledge/skills and engagement along CE value chain Lack of new vision for CE in the building sector (reuse, recover and recycle as a marginal practice)	Promote CE as a good practice Promote CE-related costumer services such as leasing, etc. Promote positive social side effects of CE adoption, related to longer-life buildings: employment and skilled local labour force	Macro	[12,19,22,24,28,39,45,46,53]
S2 Lack of CE professionals and lack of platforms for CE jobs	Lack of platforms for advertising CE professionals Lack of centralised initiatives Lack of a global CE job strategy	Create online platforms for CE professionals and CE jobs Provide training and certification to CE professionals	Macro	[26,28,30,52]

Table 2. *Cont.*

Challenges	Challenges Description	Possible Strategic Solutions	Scale	Ref.
S3 Lack of collaboration between stakeholders (silo mentality)	Operation in linear economy Lack of global vision for CE: lack of interest; lack of knowledge/skills; lack of awareness; lack of collaboration between stakeholders Lack of conviction of the interest of recovering products and materials	Promote the public, academic and industrial participation in CE Assess the social challenges and impacts of CE implementation in the built environment Evaluate socio-economic effects of mapping, reusing and recovering anthropogenic stocks	Macro	[12,22,24,45,46,51,54]
S4 Willingness to go around the law	Willingness to go around the law	Define collaborative boundaries	Macro	[26,55]
O1 Lack of platforms and storage facilities for reclaimed products	Lack of platforms for advertising reclaimed products, components and materials Lack of storage facilities for reclaimed products, components and materials; additional cost for storage	Create online platform for reclaimed products components and materials Promote free facilities for storage of reclaimed products	Macro Meso	[24,26,28,36,42,51,53,56]
O2 Lack of platforms and storage facilities for reclaimed products	Lack of common classification and standard practices for EOL and CDW management at the predesign stage Lack of traceability of material flows and anthropogenic stocks	Survey and scan existing buildings; Make use of BIM software for EOL management: establish BIM-based quantitative assessment for reused materials, recovered components and recycled materials (both existing and potential); create or use material databases of material stocks and markets for reclaimed products and recycled materials Promote specific training for control offices Establish new efficient procedures for the disassembly stage: cleaning; manual disassembly; reverse logistics procedures; acceptance criteria for CDW	Micro	[12,24–27,38,40,42,51,56–59]
O3 Collaboration and management issues	Lack of collaboration between stakeholders; communication issues Project management issues, different working methods and approaches Traceability of work and responsibility issues New CE roles and responsibilities	Promote multidisciplinarity and teamwork and clarify the role of all involved stakeholders; Increase training for project managers and control offices; Create new CE roles and skills and corresponding budget division Change the tendering and procurement phases for CE adoption (early selection of contractors and manufacturers, etc.) Establish guidelines for reclaimed products, using BIM software; Promote exchange and interoperability between material banks and recovered materials' facilities; Develop material hierarchy based on CE properties Create interactive results platforms for sharing relevant guidelines and new CE business opportunities	Macro	[22,26–28,30,40,41,46,54,55,57,59–61]
O4 Issues with manufacturers' responsibility and approaches	Issues with manufacturers' responsibility and approaches Uncertainty and risk	Select contractors and manufacturers early during the process; clarify responsibilities about reused, recovered and recycled products and the adoption of a take-back system Develop standards, requirements and specifications for CE products and materials and ease approval procedures; Develop guidelines on ownership of anthropogenic stock Study the local or regional capacity on materials supply by anthropogenic stock and the effect on reducing transportation	Micro Macro Meso	[12,24–28,30,48–50,62]

Table 2. *Cont.*

Challenges	Challenges Description	Possible Strategic Solutions	Scale	Ref.
O5 Constraints for EOL processes implementation on site	Constraints for EOL processes implementation on site Lack of common classification and standard practices for design process	Plan activities, devote specific budget and identify constraints at EOL; Create or update new and reclaimed material databases Set up CDW management schemes for EOL phase (diagnosis, plans, permits, facilities): polluted material management, onsite recovering, transportation for storage facilities, recycling facilities; Set up recycling processes for waste generated during (re)construction phase Raise the awareness of construction workers in the reduction of CDW	Micro Macro	[24–27,40,42,51]
O6 Lack of methodology and standard practices for CE design	Lack of common classification and standard practices for design process Lack of methodology for CE evaluation Uncertainty and risk	Define CE key concepts at building level: energy; the 9Rs; water management; waste management; materials management; emissions generated Develop technical guidance and training skills to CE design with CE; Involve design team until the conclusion of construction works Establish guidelines, standards and BIM-based quantitative assessment for CE design: spatial flexibility, reused materials, recovered components and recycled materials (both existing and potential); specify classification system (Omniclass, Uniclass, Uniformat)	Micro	[12,24,26–28,30,38,40,51,52,55,56,59,63–66]
O7 Lack of training skills	Lack of training skills	Promote training on CE skills among all stakeholders	Macro	[19,22,28,30,36,40,46,58]
T1 Building-related barriers	Building-related barriers Building modification during its lifespan	Start by considering the whole buildings' history and properties: geometry, composition, lifespan, relevant processes, buildings as systems Adapt construction processes to existing mechanical and geometric properties	Micro	[22,26,38,58]
T2 Lack of materials knowledge and technical challenges for CE	Lack of materials knowledge, data availability, data exchange and updates for CE Long product and buildings lifecycles Technical challenges for CE	Adopt passports for buildings with CE data Identify the preconditions and building integration of materials, products and systems for CE Develop collaboration design tools and strategies: scan existing buildings; make use of BIM software; tag materials; track and update components and assemblies; create or use CE databases and markets with accessible data anytime Analyse and evaluate components and material flows with system dynamic modelling	Micro Meso	[12,24,26,28,38,42,51,56,58,67–72]
T3 Challenges to EOL implementation	Barriers to selective disassembly and deconstruction processes Lack of standardized practices for CDW management Lack of consistency	Establish new efficient processes and procedures for disassembly/demolition phase: cleaning, manual deconstruction, reverse logistics procedures, acceptance criteria for CDW Set up EOL and BIM compliant management and deconstruction process requirements: tag materials; assess EOL CE Follow previously approved CDW management scheme for EOL phase or adjust buildings' deconstruction aiming at CE economically viable approach Create or update new and reclaimed material databases and building passports	Micro Meso	[12,24,26–28,42,51,68–73]

Table 2. *Cont.*

Challenges	Challenges Description	Possible Strategic Solutions	Scale	Ref.
T4 Production related barriers (materials and technology)	Materials and technology related barriers; material reuse quality, availability and onsite reuse; reclaimed materials quantity, quality and issues	Develop innovative technologies and machinery for CE disassembly/demolition, (re)construction and manufacturing processes (e.g., by using 3D printing)	Micro	[8,22,24,27,30,35,36,42,47–51,62,72]
	The industry itself—conservative, uncollaborative, risk- averse	Develop standards, requirements and specifications for CE products and materials and ease approval procedures; Develop guidelines on ownership of anthropogenic stock	Meso	
	Use of non-recoverable materials	Use eco-design principles: optimise material use; rigorous material selection; reduce/eliminate hazardous materials; increase lifespan; design for disassembly; design for standardisation; use secondary materials; select bio-based materials		
		Define consumer preferences, eco-design requirements and implications for durability and reparability of materials and products	Macro	
T5 Barriers to apply new CE oriented design	Lack of knowledge of CE design principles	Use consistent and geographically adapted data and methods to provide a reliable basis for decision-making	Micro	[12,19,22,24,26–28,30,35–38,41,42,45,49,51–53,55–59,61,62,64–66,69,72,74–84]
	Insufficient use or development of CE-focused collaboration tools, information and metrics; Lack of methodology for CE evaluation	Design with CE principles: keep as much as possible materials and systems from existing buildings, design for adaptability and flexibility, improve standardisation and modularity, design for disassembly, design out of waste, develop strategies to extend materials' useful life and efficiency, avoid the use of complex components and finishing works; Ensure sustainable management of end-of-life waste		
	Lack of consistency	Support design decision on multi-objective optimisation (client's specifications, multiple uses during building's lifespan, CE principles, environmental impact, etc.)		
	Building modification during its lifespan	Use BIM-based design tools with CE standards; Define the service life of materials and components; Design connection details; Define dimensional thresholds of components to be reused; Specify reclaimed and recycled materials; Adjust construction method		
	Short-term view of property stock risks loss of resources	Define BIM-based CE assessment index system: circularity indicators, components and materials flow analysis, lifecycle assessment for evaluating environmental impacts and costs	Meso	
EN1 Toxic materials removal	Toxic materials removal	Promote asbestos waste treatment	Micro	[67,85]
EN2 Lack of awareness of CE impact in climate change	Lack of awareness of benefits for EOL anticipation	Use consistent and geographically adapted data and methods to provide a reliable basis for decision-making; Integrate forecasts, with different time horizons Check the main design requirements for CE approach; Analyse potential direct and indirect rebound effects of climate change impacts.	Micro	[8,12,22,24,37–39,44–46,48–50,62,63,66,68,79,81,86,87]
EN3 Lack of awareness of transportation impact in CE in construction	Lack of awareness of transportation impact in CE in construction	Identify potential connection between CE strategies and GHG emissions reduction in EU for manufacturing outside the EU Evaluate the implications of transportation in CE (GHG emissions versus other environmental impacts)	Macro	[8,22,45,46,49,68,81,87]
		Demonstrate the advantages of local storage facilities for anthropogenic stocks	Meso	
EN4 Low of energy efficiency at operation stage	Low of energy efficiency at operation stage	Promote energy efficiency by planning and designing more energy efficient buildings, services and products	Micro	[37,79,84,86–88]

Table 2. *Cont.*

Challenges	Challenges Description	Possible Strategic Solutions	Scale	Ref.
EN5 Lack of methodology of CE evaluation towards climate change mitigation	Lack of methodology of CE evaluation towards climate change mitigation	Define key concepts and integrate lifecycle climate change impacts and costs in BIM-based CE assessment Develop a material hierarchy based on the GHG emissions and CE principles	Micro Macro	[12,19,22,24,28,30,36,46,48,51,63–65,74,82–84,86,88,89]
P1 Lack of platforms and infrastructures for reclaimed materials, components and products	Lack of platforms and infrastructures for reclaimed materials, components and products	Create online platform for reclaimed products components and materials Create free facilities for storage of reclaimed products in strategic places, taking in account components and material flows and making use of BIM and GIS software	Macro Meso	[27,28]
P2 CDW related barriers	CDW related barriers	Revise and rearrange construction industry to facilitate CDW management, reuse and recycling for CE Promote strategies to extend the utility of materials and components	Macro	[27,28,40,51,73]
P3 Lack of consistent regulatory framework for CE	Lack/obstructing regulation and guidelines for CE	Develop policies, incentives, regulations, taxation, public procurement, guidelines and technical standards for CE; Define indicators for the evaluation on the current level of circularity of the global economy	Macro	[19,22,24,27,28,30,35,46,51,63,75]
	No coherent vision for CE	Define a clearer vision for CE in construction; Develop studies to evaluate CE as solution for vacant buildings; social cost–benefit analysis for CE property tax; framework to support decisions on EOL strategies for buildings		
	Lack/confusing incentives for CE	Create initiatives for promoting CE in construction: living laboratories to test CE solutions, give the example by creating building passports for public facilities, engagement with stakeholders, etc.		
P4 Reclaimed materials related barriers	Reclaimed materials related barriers	Develop guidelines and incentives for reclaimed materials, components and products Develop new specific insurance for CE products to avoid over-specification and over-design Develop collaborations between different industries to CE products	Macro	[24,27,28,30,35,51]
P5 Lack of knowledge among stakeholders	Lack of knowledge among stakeholders	Develop collaborations between different industries to CE products Promote training and certifying among CE professionals; Develop good practices in companies	Macro	[24,28,30,40,52,55,63]
P6 CE business related barriers	CE business related barriers	Establish CE strategies and policies for promoting CE businesses; Create incentives and guidelines for innovation in CE Develop circular value chains involving all stakeholders Create specific insurance for the reuse of reclaimed products and materials	Macro	[24,27,28,30,51]

At the building level (micro scale), CE practices start at EOL, as refurbishment occurs when the building no longer serves its occupants' needs. Here, most technical and organization challenges can be addressed. Strategies to overcome buildings knowledge barriers and EOL pre-design practices (O2, T1, T2, Table 2) include characterizing the existing situation, setting refurbishment options, and preparing the selective disassembly/demolition stage (O5, T3, T4, Table 2). Design decisions in CE refurbishments should be supported on multi-objective optimization: clients' specifications, cost estimation, designing with reclaimed products, flexibility and adaptability, sustainable EOL, waste hierarchy, climate change impact, etc. (E3, O6, T5, EN2, EN4, EN5 Table 2).

Furthermore, inventory (T2, Table 2), selective collection and transportation for reclaimed storage facilities are EOL related and also necessary for recycling, recovery, and reuse of products, if not integrating future design. Exploring the local or regional capacity on materials supply through anthropogenic stock, at meso scale, may constitute the first step to reduce transportation and identify gaps which lead to potential business opportunities (E1, E4, O1, T2, T3, T4, EN3, P1, Table 2). However, some conditions need to be met first: to raise the awareness of construction workers in the reduction in CDW and selective collection of products (S2, S3, O5, O7, Table 2) and to create platforms and storage facilities for reclaimed products (E1, O1, P1, Table 2).

The global vision for CE in buildings refurbishment, at a macro scale, goes beyond these infrastructures, with the definition of new vision strategies for CE materials production (E4, S1, O4, T4, P4, Table 2). Additionally, developing a material hierarchy based on the GHG emissions and circularity indicators might be useful when selecting the best design options (O6, T5, EN2, EN3, Table 2). Technical guidance and specific training should be provided to practitioners for CE refurbishment design (O7, Table 2).

Figure 4 summarizes the intensity, dimensions and boundaries of the strategies to CE adoption in the existing building stock.

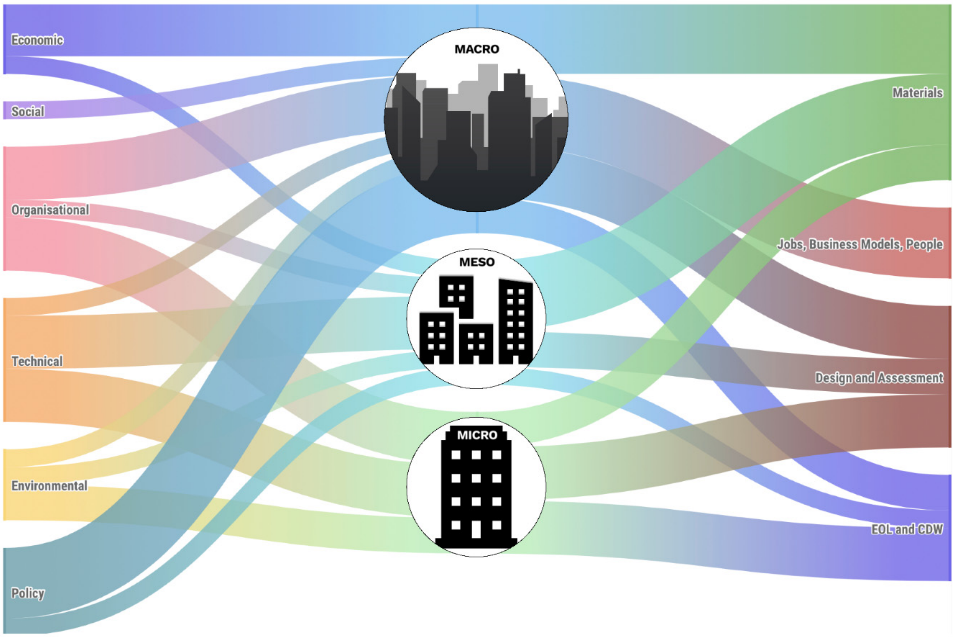

Figure 4. Intensity, dimensions and boundaries of the strategies to CE adoption in the existing building stock.

Case Study—Lisbon Building from 1919–1945

To demonstrate the application of CE strategies adoption and the possibilities of a multi-scale approach to the built environment, a typical archetype [90], corresponding to a Lisbon building built between 1919 and 1945 was selected. This archetype represents 8236 buildings in the Lisbon area [91].

The archetype's layers of Brand [92] include the Structure, Skin and Space Plan, which are characterized by the following construction elements and respective mass percentage, as indicated in parenthesis [93]:

- Structure (78.1%): exterior slabs—balconies (0.6%), interior slabs (16.1%), ground floor (11.1%), stairs—structure (16.1%), load bearing exterior walls (33.2%), and roof—structure (0.8%);
- Skin (6%): exterior walls (4.3%) and roof finishes (1.1%), railings—balconies (0.3%), exterior doors and windows (0.3%);
- Space Plan (15.9%): interior walls (9.1%), floors (3.6%), ceilings (1.9%), stairs' finishes (0.1%), interior doors (0.4%) and sanitary fittings (0.8%).

The adoption of CE refurbishment strategies (T1, T3, T5, EN5, Table 2) will contribute to avoid total demolishing and to maintain building's structure, and this represents an embodied energy saving that results in 171,454 KgCO_2eq to be avoided (67% of building's Embodied Carbon). In addition, it will allow for brick, aggregates and timber to be recycled or recovered, representing 56,654 kg of brick, 11,997 kg of aggregates and 983 kg of timber. The strategy does also create conditions for building element's reuse, namely windows and doors, corresponding to 0.7% of building's total mass and to savings of 3375 KgCO_2eq.

Overall, this Lisbon archetype case study, extended to a macro scale (the city of Lisbon), could represent savings of 27,794,419 KgCO_2eq by reusing doors and windows.

The availability of detailed information at an archetype level allows for the characterization of urban building stock and the definition of minimum embodied carbon recovery targets combined with CE scores, to operationalize policy-based incentives. It does also contribute to unveil the potential of linking micro, meso and macro scales through GIS information systems, allowing to spatialize and facilitate CE strategies for the 8236 buildings in the Lisbon area.

5. Discussion and Conclusions

This paper contributes to the body of knowledge by advancing possible UM-based strategies to enhance CE adoption in the refurbishment of existing building stock, as a critical resource-efficiency measure to contribute to carbon neutral cities and to reduce the impacts of human activity in the built environment, thus improving quality of life, economy and employment.

These strategies, which result from the identification of the barriers for CE adoption in the refurbishment of urban building stock in the existing literature on UM and CE, are categorized into six dimensions: economic, social, organizational, technological and policy.

It was found, as represented in Table 2, that economic and policy strategies, given their transversal nature, are applicable to meso and macro scales, while social strategies, that involve stakeholders, cultural and behavioural changes, are exclusively related to macro scale. On the other hand, organizational and environmental dimensions have strategic/policy components, which comprise guidelines and global assessment of environmental impacts and, therefore, should be applied at a macro scale. However, these dimensions do also include specific actions for buildings, at a micro scale, according to Table 2. Moreover, technical strategies are mainly applied at building scale, but also at a neighbourhood scale, regarding urban mining and management or reclaimed stocks. These conclusions stress that CE adoption is an integrated and multi-dimensional process. Accordingly, the interactions between challenges were also highlighted.

Although there is a strong and objective organizational, technical and environmental component to implement CE at a building level, it depends heavily on the stakeholders' networks to raise the awareness on CE, change behaviours and merge top–down and bottom–up approaches [23]. Public authorities can lead this process by creating engagement with stakeholders, enabling research and practice collaboration [19], eventually adopting building passports for public facilities and leading tests in living laboratories for CE refurbishment. Additionally, digitalization is critical to support CE adoption, from buildings to UM, to enable continuous assessment, define circularity potential, estimate urban mining [21] and monitoring the whole process. Creating quantitative assessment indexes for CE at building scale, developing a specific framework for CE buildings refurbishment and making use of existing CE frameworks for UM [94] are some examples, together with global indicators for circular cities [95] of CE assessment at multiple territorial scales.

The Lisbon case study demonstrates some critical insights provided by this research for CE adoption in the built environment and the impact of a bottom–up approach. Given the complexity of the urban systems, it is indispensable to simultaneously adopt top–down and bottom–up approaches. In fact, while some CE refurbishment principles shall be implemented at a building scale (micro scale), transversal and multidimensional strategies (macro scale) are also critical to support stage-specific solutions and tackle the previously identified barriers to CE adoption. Both micro and macro scales are related to meso scale, which relates to local neighbourhood material flows, as CE in refurbishment must ideally optimize resources, generate zero waste and extend the lifespan of the products, which can only be achievable with the involvement of all stakeholders in the value chain.

Although this not a one-size-fits-all process and cities must adapt these strategies to their local contexts, the strategic actions offered by this paper will facilitate the development of dedicated frameworks for buildings refurbishment within the principles of CE and the definition of multisectoral policy-based actions, in line with the decarbonization goals for cities, which will contribute to improving the contribution of UM-based approaches.

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Appendix A

Generic Literature Review—Identification and characterization of selected papers.

Title	Dimensions						Year	Publication Type	Reference
	Economic	**Social**	**Organizational**	**Technical**	**Environmental**	**Policy**			
A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review					x		2021	JA	[86]
A critical review of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies		x	x	x			2021	JA	[53]
A critical review on the adaptability of ventilation systems: Current problems, solutions and opportunities				x			2022	JA	[78]
A new framework for assessing the environmental impacts of circular economy friendly soil waste-based geopolymer cements	x		x	x	x		2022	JA	[48]
Adaptive Reuse of Heritage Buildings: From a Literature Review to a Model of Practice			x	x			2022	JA	[57]
Advantages of structural inspection and diagnosis for traditional buildings' refurbishment: A Life Cycle Assessment perspective			x	x	x		2022	JA	[38]
BIM-based life cycle assessment and life cycle costing of an office building in Western Europe			x	x	x		2020	JA	[64]
BRE Global Methodology for The Environmental Assessment of Buildings Using EN 15978: 2011			x	x		x	2018	R	[75]
Building circular in Brussels: an overview through 14 inspiring projects	x		x			x	2020	CP	[40]
Building design and construction strategies for a circular economy				x			2020	JA	[69]
Building envelope systems for the circular economy: Evaluation parameters, current performance and key challenges				x			2021	JA	[76]

Title	Dimensions						Year	Publication Type	Reference
	Economic	**Social**	**Organizational**	**Technical**	**Environmental**	**Policy**			
Building life cycle applied to refurbishment of a traditional building from Oporto, Portugal	x		x	x			2018	JA	[41]
Building life-span prediction for life cycle assessment and life cycle cost using machine learning: A big data approach			x	x	x		2021	JA	[65]
Carbon-neutral building renovation potential with passive house-certified components: Applications for an exemplary apartment building in the Republic of Korea				x	x		2022	JA	[79]
Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction	x	x	x	x	x	x	2020	JA	[19]
Circular economy for the built environment: A research framework	x	x	x	x	x	x	2017	JA	[22]
Circular economy in built environment—Literature review and theory development	x	x	x	x	x	x	2021	JA	[51]
Circular economy in the building and construction sector: A scientific evolution analysis	x			x			2021	JA	[47]
Circular economy in the construction industry: A systematic literature review			x	x	x		2020	JA	[36]
Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production				x			2020	JA	[70]
Circular economy pillars: a semi-systematic review				x	x		2021	JA	[74]
Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts		x	x	x	x		2020	JA	[12]
Comparing flexible and conventional monolithic building design: Life cycle environmental impact and potential for material circulation			x	x	x		2022	JA	[66]
Comparative whole building LCAs: How far are our expectations from the documented evidence?				x	x		2020	JA	[37]
Current state and barriers to the circular economy in the building sector: Towards a mitigation framework	x	x	x		x	x	2020	JA	[46]
Decarbonization and Circular Economy in the Sustainable Development and Renovation of Buildings and Neighbourhoods				x	x	x	2020	JA	[35]
Decision Support System for technology selection based on multi-criteria ranking: Application to NZEB refurbishment			x				2022	JA	[60]
Development of a design-for-maintainability assessment of building systems in the tropics				x			2020	JA	[80]
Development of a web application for historical building management through BIM technology			x	x			2019	JA	[58]
Disruptive technologies for a circular building industry				x			2022	JA	[72]
Driving decarbonisation of the EU building stock by enhancing a consumer centred and locally based circular renovation process	x		x	x			2020	CP	[42]
Dynamic health risk assessment model for construction dust hazards in the reuse of industrial buildings					x		2022	JA	[85]
Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta					x		2020	JA	[87]
End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets					x		2020	JA	[89]
Environmental impacts assessment for conversion of an old mill building into a modern apartment building through reconstruction	x	x			x		2020	JA	[39]
Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix				x	x		2022	JA	[81]
Factor dynamics to facilitate circular economy adoption in construction			x	x		x	2021	JA	[27]

Title	Dimensions						Year	Publication Type	Reference
	Economic	Social	Organizational	Technical	Environmental	Policy			
Global review of circular economy and life cycle thinking in building Demolition Waste Management: A way ahead for India	x	x	x	x	x	x	2022	JA	[28]
Green finance gap in green buildings: A scoping review and future research needs	x						2022	JA	[43]
Greening existing buildings through Building Information Modelling: A review of the recent development			x	x			2021	JA	[59]
How comprehensive is post-occupancy feedback on school buildings for architects? A conceptual review based upon Integral Sustainable Design principles		x	x				2022	JA	[54]
Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature review to a methodological approach				x	x		2020	JA	[82]
Industrial building adaptive reuse for museum. Factors affecting visitors' perceptions of the sustainable urban development potential			x	x			2022	JA	[61]
ISO 14044:2006 Environmental management—Life Cycle Assessment—Requirements and Guidelines			x	x		x	2006	S	[77]
Life cycle assessment and costing of carbon neutral hybrid-timber building renovation systems: Three applications in the Republic of Korea	x				x		2022	JA	[44]
Life cycle assessment in the building design process—A systematic literature review					x		2020	JA	[88]
Life cycle assessment of mass timber construction: A review	x		x	x	x		2022	JA	[49]
Links between circular economy and climate change mitigation in the built environment				x	x		2020	JA	[68]
Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map	x	x	x	x	x	x	2022	JA	[30]
Mapping the scientific research of the life cycle assessment in the construction industry: A scientometric analysis				x	x		2021	JA	[83]
Modelling the relationship between Building Information Modelling (BIM) implementation barriers, usage and awareness on building project lifecycle	x	x	x	x		x	2022	JA	[52]
On the embodied carbon of structural timber versus steel, and the influence of LCA methodology	x		x	x	x		2021	JA	[50]
Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery				x		x	2020	JA	[73]
Predicting the presence of hazardous materials in buildings using machine learning				x	x		2022	JA	[67]
Recycling potential in building energy renovation: A prospective study of the Dutch residential building stock up to 2050				x			2021	JA	[71]
Rhythmic Buildings- a framework for sustainable adaptable architecture	x	x		x	x		2021	JA	[45]
Ten questions concerning the potential of digital production and new technologies for contemporary earthen constructions			x	x	x		2021	JA	[62]
The circular economy in the construction and demolition waste sector—A review and an integrative model approach			x				2020	JA	[25]
The future of circular environmental impact indicators for cultural heritage buildings in Europe			x		x	x	2020	JA	[63]
Towards achieving circularity in residential building materials: Potential stock, locks and opportunities			x	x			2021	JA	[56]
Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment	x	x	x	x	x	x	2020	JA	[24]
Unveiling the actual progress of Digital Building Permit: Getting awareness through a critical state of the art review		x	x	x		x	2022	JA	[55]
Uses of building information modelling for overcoming barriers to a circular economy				x			2021	JA	[26]
What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets?				x	x		2021	JA	[84]

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