Chapter 1
Technical Barriers and Challenges to Circular Strategies Implementation

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Abstract This chapter examines the primary technical barriers and challenges that impede the transition to a circular economy within the built environment. It highlights the complexities involved in integrating circular practices into the industry which traditionally relies on linear models, government and society. The analysis explores technical barriers at the urban, building and material levels of the built environment through a problem-based approach. Findings highlight a lack of standardized methodologies, inadequate design strategies for reuse and adaptability, insufficient data on material performance, and constraints in current construction practices and regulations. Furthermore, it underscores how technical fragmentation and limited interoperability among systems hinder the advancement of circularity. The chapter

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also explores the potential benefits of digitalization, design for disassembly, and building information modelling (BIM) as a means to address these challenges. Ultimately, it emphasizes the need for coordinated efforts among stakeholders, supported by robust regulatory frameworks and innovation, to effectively implement circular economy principles in the construction industry.

Keywords Circular economy · Construction sector · Technical barriers · Challenges · Urban level · Building level · Material level

1.1 Introduction

The circular economy (CE) concept has been gaining momentum, as evidenced by the literature [1–3]. This is not just a passing trend but a crucial concept that academia, governments, policymakers, and institutions increasingly recognise and commit to. The urgency of adopting CE practices is underscored by global initiatives like the European Green Deal, which aims to achieve climate neutrality by 2050 through a "regenerative growth model" that emphasises sustainability and economic competitiveness [4]. Furthermore, the European Union has made significant strides in addressing the sustainability aspects of products through various initiatives and legislative frameworks, implemented on both a mandatory and voluntary basis [4]. This focus aligns with the principles of CE, and the transition from a linear "take-make-dispose" model to a circular one requires systemic change [5].

The shift towards a CE is a critical evolution in addressing the unsustainable practices of the traditional linear economy model. Unlike the traditional linear economy, the CE promotes a regenerative approach. Going beyond waste management and related practices, the concept of CE addresses challenges for the whole value chain,

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from design strategies to new business models, transitioning from ownership to service-based solutions, and keeping materials and products in the cycle, making them last longer [5].

The importance of adopting circular practices to tackle environmental impacts, resource shortages, and social and economic challenges cannot be overstated [3, 6, 7]. By minimising waste, optimising resource flows, and enabling transformative new patterns of production and consumption, CE can foster sustainability and well-being [8], being considered a powerful tool for achieving broader sustainability goals and a transformative model for sustainable development. Given its significant consumption of natural resources and energy, which accounts for approximately a third of the total energy consumed worldwide, the built environment plays a pivotal role in the transition to a CE and sustainable development [9]. This underscores the responsibility and potential impact of the built environment in this crucial transition.

Despite the clear benefits, the implementation of circular strategies in the built environment faces numerous challenges. The most prominent among these are technical barriers, which include difficulties in integrating circular principles into building design, construction, and material use. According to AlJaber et al. [10], technical barriers were the most frequently observed in the literature on the implementation of a CE in the building sector, followed by economic/market barriers, awareness-related barriers, implementation barriers, social barriers, and finally, support/promotion-related barriers. These technical barriers often arise from a lack of standardised methodologies, the limited availability of circular materials, and the complexity of retrofitting existing structures [11–13]. Addressing these challenges is critical not only for environmental sustainability but also for enhancing the economic viability and resilience of the construction sector.

1.1.1 Importance of Identifying Technical Barriers

Understanding and addressing technical barriers is crucial for advancing CE strategies within the built environment. These barriers often prevent the effective implementation of sustainable practices, such as the reuse and recycling of materials, energy efficiency, and waste reduction. By identifying these challenges, stakeholders, including policymakers, industry professionals, and researchers—can develop targeted solutions that facilitate the transition towards more sustainable and resilient building practices. This focus not only contributes to environmental goals, such as reducing carbon footprints and conserving resources, but also supports economic and social objectives by fostering innovation, creating jobs, and enhancing the overall quality of life.

Current research involves a comprehensive review of existing literature to pinpoint specific technical barriers. These barriers were categorised and quantified based on their frequency and relevance across different sources. The study also explored qualitative aspects to provide a deeper understanding of the contextual challenges associated with each barrier. The methodology was designed to ensure a thorough analysis, including quantitative data visualisation through diagrams and tables and qualitative insights supported by expert opinions and case studies. The insights from this report will help shape future policies and practices, ensuring a more sustainable and resource-efficient built environment.

The study employed a multi-step methodology to systematically analyse the technical barriers to circular strategies in the built environment. The process began with a quantitative data analysis, focusing on the prevalence and distribution of identified barriers across literature. Key steps include:

1. Identification and Categorisation: Barriers were identified from the literature and categorised based on their nature and impact on circular strategies. These categories included where and when the barriers occur, who is involved, and how they affect implementation.
2. Quantitative Analysis: A detailed quantitative analysis, including histograms and data tables, was conducted to quantify the frequency and relevance of each barrier category. This analysis provided a numerical basis for identifying the most critical barriers.
3. Qualitative Analysis: A qualitative review was undertaken alongside the quantitative data to explore the nuances and specific contexts in which these barriers arise. This involved a deeper examination of literature, supported by expert opinions and case studies.
4. Synthesis and Discussion: The findings from the quantitative and qualitative analyses were synthesised to form a comprehensive overview of the technical barriers. The discussion section of the report elaborates on these findings, offering recommendations and potential solutions to address the identified challenges.

This structured approach ensures a thorough understanding of the technical barriers to implementing a CE in the built environment. Based on the methodology proposed, this study intends to explore the following question: "What are the main technical barriers and challenges to implementing circular economy strategies in the built environment?" To this end, the questions proposed to be answered in this study are:

1. What are the technical barriers?
2. Where do the technical barriers occur?
3. When do the technical barriers occur?
4. Who is responsible for or involved in?
5. How does this impact the implementation of circular strategies in the built environment?

By answering these questions, this study could identify not only the main barriers but also the stakeholders, and implications for CE implementation. The insights gained from this study are essential for guiding future research, policy development, and practical applications in the sector.

1.2 Materials and Methods

The starting point of the literature review was the definition and specification of the context (built environment) and of the investigated subjects (technical barriers). The built environment was defined considering its levels, following the classification proposed by Pomponi and Moncaster [14] and Brincat [15]:

1. Urban level adapts the system boundary definition at a municipality/city/neighbourhood/urban agglomerate level.
2. Building level takes it to a building at the whole asset/system and components/products.
3. Material level focuses on the materials that are used within the construction.

The investigation of technical barriers was performed in parallel to all three levels of the built environment. A detailed description of technical barriers and their categorisation is provided in the next paragraph. Successively, the criteria for document collection and organisation are explained.

1.2.1 Technical Barriers—Definition and Classification

Technical barriers (or challenges) are described as challenges in science, engineering, industry, urban planning, and architecture that affect technicians, urbanists, architects, engineers, scientists, and entrepreneurs in the implementation of circular strategies in the built environment. They were analysed through the different levels of the built environment, considering this classification in categories [16]:

- information/data
- technical knowledge
- technical skills
- technical standards
- machines/equipment
- processes (such as assessment) and infrastructure
- methods/tools
- materials/products/building systems.

The technical barriers identified in the literature were framed according to the 5Ws approach to investigating the What, Who, Where, When, and hoW of a barrier since their answers are considered essential in information gathering and problem-solving. Specifically, this analysis can provide interesting findings for researchers, companies, and policymakers about where (layers based on the selected system boundaries), when (the life cycle stages) of the built environment, how barriers affect the implementation of a CE in the built environment (circular strategies), and who is responsible for or affected (stakeholders). Additional information addressing the questions of “why” was also included whenever available.

The 5Ws were detailed in Tables 1.1 and 1.2 based on the technical barrier classifications which were considered in this study. Within each barrier category, information related to identified barriers was collected in terms of building layers, stakeholders, life cycle phases, and circular strategies with the details of potential motivations when available. This information was elaborated for each reference using the templates of Tables 1.1 and 1.2.

The question "What" considered technical barriers identified in the literature review that fit the definition adopted in the study and then categorised according to the classification above and reported in the row "Technical barriers/challenges category and description" of Table 1.1.

The question "Who" focused on the stakeholders who are responsible for the barrier or mainly affected by the barrier. The analysis was based on the classification of stakeholders involved in a CE in the built environment defined by Munaro and Tavares [19] and reported below:

1. Clients: owners, users, consumers
2. Project professionals: project managers, designers, architects, engineers, facilities managers, investors, subcontractors, real estate agencies, builders, employees
3. Suppliers: manufacturers, process and service providers
4. Public: media, community representatives, neighbours, the press, the academy, pressure groups, civic institutions, visitors, the natural environment
5. Government: legal authorities, regional development agencies, civic institutions, government establishments
6. Others: non-governmental organisations (such as National or International Organisations for Standardisation).

Table 1.1 Template of "qualitative data collection"

	Data collected
Publication's reference	
Publication types (such as research paper, conference paper, book chapter, review, report, project deliverable, etc.)	
Brief abstract (max 100–150 words)	Aim Method Results
Technical barriers/challenges category and description	Lack of information/data
	Lack of technical knowledge
	Lack of technical skills
	Lack of technical standards
	Inadequate machines/equipment
	Inadequate processes and infrastructure
	Lack of methods/tools
	Lack of materials/products/building systems

Table 1.2 Template of "quantitative data collection"

What is the barrier category	Where it happens (when the barrier originates and when the barrier impacts)							When it happens						Who is responsible for/ involved in					
Technical barrier category	Building layer (a)							Building life cycle phase (b)						Stakeholders (c)					
	1	2	3	4	5	6	7	1	2	3	4	5	6	1	2	3	4	5	6
Lack of information/ data																			
Lack of technical knowledge																			
Lack of technical skills																			
Lack of technical standards																			
Inadequate machines/ equipment																			
Inadequate processes and infrastructure																			
Lack of methods/ tools																			
Lack of materials/ products/ building systems																			

What is the barrier category	How it affects the implementation of circular strategies in the built environment										Sources of data	Note
Technical barrier category	Circular strategies (d)										References include the barrier ref. n. reported in Table 1.1	
	1	2	3	4	5	6	7	8	9	10		
Lack of information/data												
Lack of technical knowledge												

(continued)

Table 1.2 (continued)

What is the barrier category	How it affects the implementation of circular strategies in the built environment										Sources of data	Note
Technical barrier category	Circular strategies (d)										References include the barrier ref. n. reported in Table 1.1	
	1	2	3	4	5	6	7	8	9	10		
Lack of technical skills												
Lack of technical standards												
Inadequate machines/ equipment												
Inadequate processes and infrastructure												
Lack of methods/ tools												
Lack of materials/ products/building systems												

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) Dismantling and Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

This information was collected in the column “Stakeholders” of Table 1.2.

The question “Where” was related to building layers. According to Brand [21] and Zimmann et al. [17], the built environment can be framed in seven layers, and each of them holds specific functions with different expected service life as reported below:

1. Site is the location of the building (∞ yrs).
2. Structure is the building’s load-bearing system, including the foundation and load-bearing elements (30–300 yrs).
3. Skin is the façade and building exterior (20–35 yrs).
4. Services are the pipes, wires, energy, heating/cooling and ventilation systems (15–30 yrs).
5. Space plan is the internal fit-out including walls and floors (10–30 yrs).

6. Stuff is the rest of the internal fit-out, including the furniture, lighting, and ICT (5–20 yrs).
7. System (district) is an additional layer that has been recently included with the intent to apply this approach beyond the scope of a building, in the context of a district and city [17].

Related information was collected in the column "Building layers" in Table 1.2.

With the question "When", we considered the building lifecycle model proposed by RIBA [18] and extended according to Brincat et al. [15] and reported below:

1. Strategic definition and Briefing
2. Design
3. Manufacture
4. Demolition and Construction
5. Use and Refurbishment
6. End-of-life.

Related information was collected in the column "Building life cycle stage" of Table 1.2.

Finally, regarding the question "How", identified technical barriers were related to the circular strategies affected by them, to identify evidence of their effect/impact on the CE implementation according to the framework proposed by Stijn and Gruis [20]. Stijn and Gruis [20] highlight that most of the design frameworks focused on the building level and based on Bocken et al. [22] and Potting et al. [23], they developed a circular design framework aiming to expand the approach to other levels and ensure that circularity is achieved within and beyond the designs' lifecycle. Their framework (reported in Table 1.3) intends to implement a systems approach in which components and systems are regarded from within their wider system environment. Since R0 and R1 strategies decrease the consumption of natural resources and materials applied in a product chain, by less product being needed for delivering the same function, they are generally also considered circularity strategies, even though they do not necessarily involve increasing the reuse of products and components, or reapplication of recycled materials.

1.2.2 Document Collection

The literature review search was performed using SCOPUS databases, looking at peer-reviewed journal articles, conference papers, book chapters and reports. Moreover, non-academic literature was collected, consisting of reports from European institutions, research projects, NGOs and industry by using their official websites. Only documents in English were searched (original and review articles published and in press) about the core themes, covering up to January 2024, when the searches were conducted. Excel spreadsheets were used to manage the references.

Table 1.3 Circular design framework applied to products [20]

Principle	Strategy	
Narrowing loops	RO refuse	Make the product redundant by abandoning its function and offering the same function with a radically different product
	R1 rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2 reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Slowing loops	R3 re-use	Re-use by another consumer of a discarded product that is still in good condition and fulfils its original function
	R4 repair	Repair and maintenance of defective products so they can be used with their original function
	R5 refurbish	Restore an old product and bring it up to date
	R6 remanufacture	Use parts of discarded products in a new product with the same function
	R7 repurpose	Use discarded products or their parts in a new product with a different function
Closing loops	R8 recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 recover	Incineration of materials with energy recovery

The queries with the keywords for document searching were selected for each level as specified as follows:

Urban level queries: barrier* AND "circular cities" AND urban*; barrier* AND "urban circularity"; barrier* AND "circular cities" AND urban circularity*; "barriers" "challenges" AND "circular cities" AND "urban circularity"; barrier* AND "circular economy" AND "urban"). The results of the search showed 53 documents. After the first screening, 21 articles (scientific literature) were selected for the deep review.

Building level queries: barrier* AND "circular economy" AND building*; barrier* AND "circular economy" AND "built environment"; barrier* AND "circularity" AND "built environment"; barrier* AND "circularity" AND building*). A total of 119 documents were collected belonging to scientific literature, and a deeper screening validated 57 of them. The search of non-academic literature produced 32 documents. This number was reduced to 18 after the screening.

Material level queries: "technical barrier" AND "circularity" AND "built environment" AND "material" level; "technical barrier" AND "circular economy" AND "built environment" AND "material" level; "technical barrier*" AND "circular economy" AND material*; barrier* AND "circular economy" AND material*; "technical barrier*" AND circularity AND material*; "technical barrier*" AND circularity OR "circular economy" AND material*; "technical barrier*" AND "circular economy"

AND "built environment"). The results of the search showed 365 documents. To include only technical issues, the selection was limited to Engineering, Material Science, and Energy fields. After the first screening, 62 documents (scientific literature), research reports, book chapters, PhD thesis, and MSc thesis were selected for the deep review.

Following the initial search, our literature review proceeded through nine additional steps performed at each level of the built environment. They are listed and explained as follows:

1. *Excluding duplicates*. All documents were checked, and all duplicate documents were excluded.
2. *Title and keywords filter*. Each article's title and keywords were read, and documents not related to the search theme were excluded.
3. *Abstract filter*. The abstracts of the remaining articles were analysed, and documents not related to the theme were excluded.
4. *Retrieving full papers*. Full papers were downloaded. The ones not found available, using the access provided to the authors, were ruled out.
5. *Full Reading*. All remaining available documents were read in full to provide the theoretical basis for this review. After fully reading, papers not suitable for the purpose of this research, for reasons such as not having a strong relationship with the research theme, presenting blurred interpretations, presenting overly shallow approaches, or not significantly contributing to the topics/themes were excluded. The remaining articles compose the final portfolio. Moreover, the authors double-checked whether the downloaded documents were suitable for analysis and evaluation under the headings of material, building, and urban levels.
6. *Collecting data*. Qualitative Data were collected consistently using the template shown in Table 1.1.
7. *Comparing data*. Quantitative Data were summarised for each level using the template shown in Table 1.2.
8. *Analysis*. Data were analysed and discussed using a quantitative and qualitative approach for each level.
9. *Synthesis*. The final step was identifying patterns or faults in each barrier category at all built environment levels.

1.3 Results

1.3.1 Urban Level

1.3.1.1 Quantitative Analysis of the Literature

To understand, quantify, and identify the technical barriers, quantitative and qualitative approaches have been adopted. The first step is quantitative analysis, which identifies the number of barriers according to the analysed documents and how they are distributed among the eight categories.

Analysing the documents, of the 21 articles, 14 reported barriers under the category (6) *Inadequate processes and infrastructure*, which was the category most represented in the documents. In comparison, 12 articles reported barriers under the categories (1) *Lack of information/data*, (2) *Lack of technical knowledge*, and (4) *Lack of technical standards*. Only one article reported barriers under the category (5) *Inadequate machines/equipment*, as presented in Fig. 1.1.

In terms of the number of barriers presented in each category, the category (6) *Inadequate process and infrastructure* represents the category with the highest number of barriers reported, with 147 reported among the 21 articles. Although the categories (4) *Lack of technical standards*, (1) *Lack of information/data*, and (2) *Lack of technical knowledge* were reported in 12 articles, the number of barriers reported in each of these categories are, respectively, 98, 90, and 76, as shown in Fig. 1.2.

As detailed in the Materials and Methods session, the question "Where" is related to building layers (Site, Structure, Skin, Services, Space Plan, and Stuff). The System (District) was included as an additional layer, going beyond the building scope, to

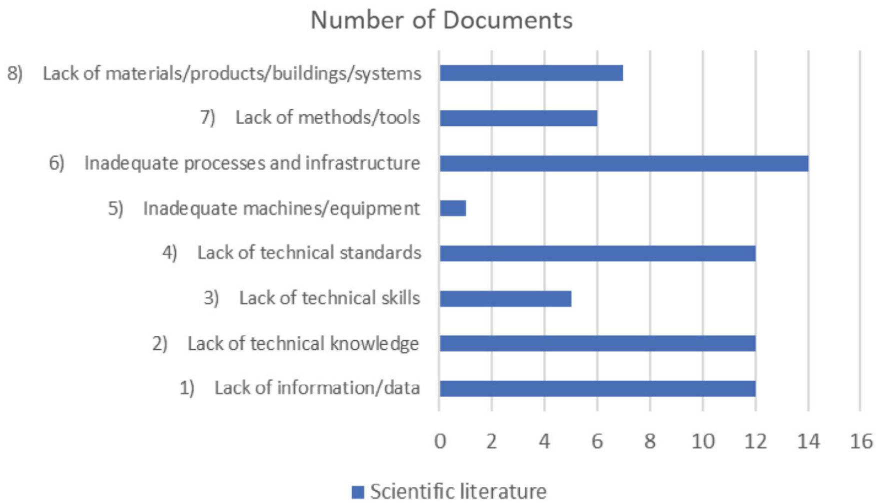

Fig. 1.1 Number of articles that reported the barrier category

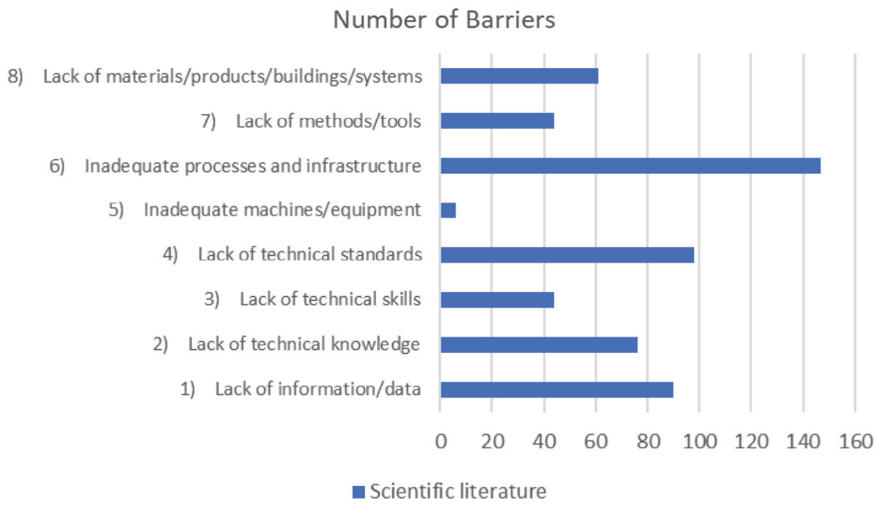

Fig. 1.2 Number of barriers reported per category

apply this approach to the urban-level context. In this regard, the barriers identified at the urban level were considered to occur only at the System (District) layer. However, not all barriers specifically addressed "Where", with only 62 barriers reported where they happen. For instance, category (6) Inadequate process and infrastructure is the most representative in the number of barriers reported, accounting for 147 barriers (Fig. 1.2). However, from these 147 barriers, only 15 specifically addressed where they happened. Figure 1.3 shows the number of barriers reported at the System (District) layer.

Analysing the life cycle phase of the examined barriers, most of them occur during the *Use and Refurbishment* phase, accounting for a total of 44 barriers reported during this phase. Followed by *Strategic Definition and Briefing*, accounting for 31 barriers, and *(Dismantling and) Construction* and *End-of-life* phases, with 28 barriers each. The life cycle phase with the lowest number of barriers is the *Manufacturing* phase, with 19 barriers reported.

Under the barriers categories, represented in Fig. 1.4, in category (6) *Inadequate process and infrastructure*, the (*Dismantling and) Construction* phase represents the highest number of barriers reported, with a total of 12 barriers reported, followed by *Use and Refurbishment*, with 11 barriers reported, and *End-of-life*, with 10 barriers reported.

The *Government* is the stakeholder reported as responsible for/involved in most of the barriers, being listed in 50 barriers within all categories. *Project professionals* and *Suppliers* are pointed out as the second and third stakeholders more responsible for or involved in the barriers. Looking at the categories presented in Fig. 1.5, (4) *Lack of standards* is the one with the most barriers reported, and *Government* and *Project professionals* are the group of stakeholders responsible for or involved in, accounting for 12 and 11 barriers, respectively.

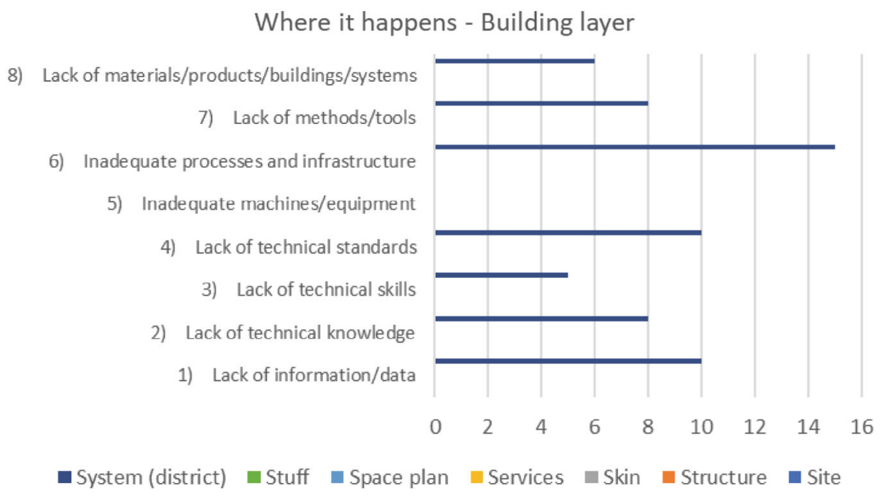

Fig. 1.3 Where the barriers happen

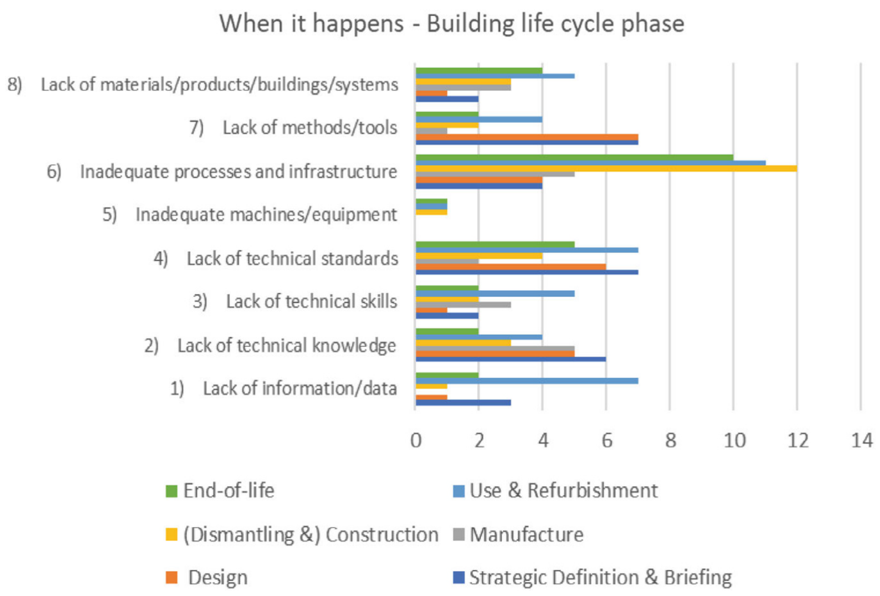

Fig. 1.4 When the barriers happen

Under category (6), *Inadequate process and infrastructure*, *Suppliers* are the group of stakeholders more related to the barriers, with 11 total. *Government* was also reported as responsible for/involved in 10 barriers of this category. In category (1) *Lack of information/data, Government* and *Project professionals* are the groups of

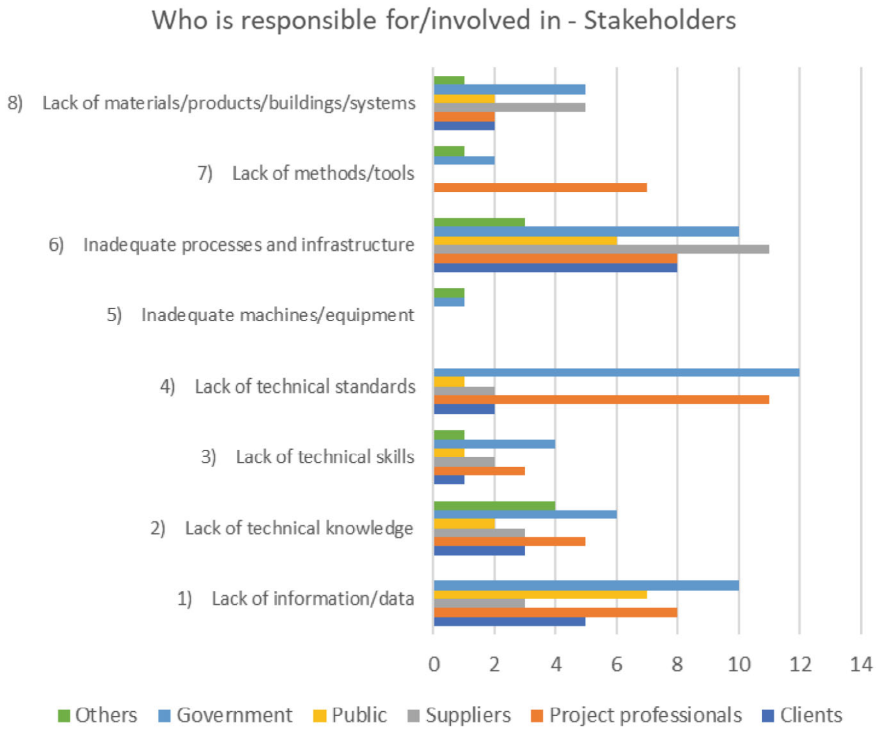

Fig. 1.5 Groups of stakeholders responsible for/involved in

stakeholders that are the most responsible for/involved in the barriers, accounting for 10 and 8, respectively.

None of the articles mentioned a relationship between the barriers and the circular strategy of R0 *Refuse.* At the urban level, most of the barriers affect R3 *Reuse*, followed by R8 *Recycle* and R7 *Repurposed* strategies. As illustrated in Fig. 1.6, (6) *Inadequate process and infrastructure* is the category where most of the barriers affect the circular strategies, with 13 barriers affecting R3 *Reuse* and 10 in R8 *Recycle.* (4) *Lack of standards* is the second category in terms of how the barriers affect the circular strategy implementation. Within this category, eight barriers affect both R3 *Reuse* and R8 *Recycle.*

It is important to notice that (1) *Lack of information/data* is the category of barrier that affects eight out of nine strategies in the circular strategy framework. It does not account for the most significant number of barriers, but it is the only category that affects almost all circular strategies.

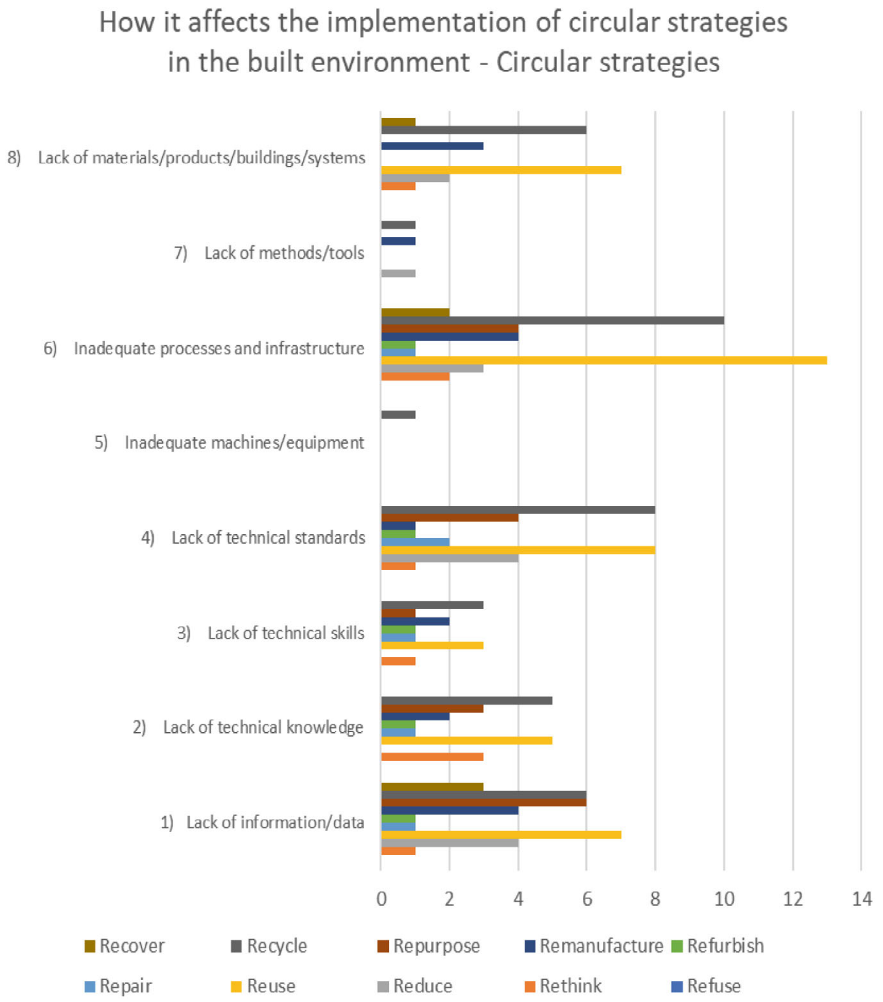

Fig. 1.6 How the barriers affect CE strategies

1.3.1.2 Collection of the List of Barriers in Each Category and Analysis of Relevance

This review synthesised findings from various studies and articles, highlighting the obstacles to adopting CE principles. The transition to a CE, particularly in urban environments and the construction sector, is fraught with numerous challenges.

After a comprehensive review of the articles, the identified barriers were systematically categorised into subcategories to provide a clearer understanding of the issues hindering the successful implementation of CE practices. These subcategories cover various challenges, from infrastructural inadequacies and technical limitations to

Table 1.4 Subcategories of barriers under Category 1 at the urban level

Subcategory	Count	Reference
Collection and sorting guidance	2	[24, 25]
Documentation and data quality	3	[19]
Data availability and accessibility	9	[10, 26–32]
Simulation and modeling	1	[19]
Knowledge transfer and integration	2	[33, 34]
Total	17	

production networks, logistics, and urban planning issues. This classification aims to facilitate targeted interventions and strategies to overcome these barriers and promote the adoption of CE practices.

Category 1: Lack of Information/Data

Implementing CE practices in urban environments and the construction sector hinges on the availability and quality of data and information. However, multiple studies have identified significant barriers in this regard. These barriers can be broadly categorized into five subcategories (Table 1.4). Each subcategory highlights specific issues that impede the efficient collection, management, and utilisation of data necessary for CE practices *Collection and Sorting Guidance.* This subcategory includes barriers related to the absence of clear guidelines for collecting and sorting construction and demolition waste (CDW). Proper guidance is crucial for efficient waste management and recycling processes.

Documentation and Data Quality. This subcategory addresses the lack of documentation for new and used building products, as well as issues with data quality and availability. Ensuring high-quality data is essential for the effective tracking and management of materials.

Data Availability and Accessibility. This subcategory includes barriers related to the availability and accessibility of data necessary for monitoring and planning CE activities. Limited data availability hinders effective decision-making and resource management.

Simulation and Modelling. This barrier pertains to the limitations of the simulation models used for planning and implementing CE practices. Incomplete models can lead to inadequate predictions and planning.

Knowledge Transfer and Integration. This subcategory includes barriers related to the transfer and integration of knowledge across different stakeholders and disciplines. Effective knowledge transfer is critical for scaling up CE practices and ensuring a comprehensive understanding among involved parties.

Table 1.5 Subcategories of barriers under Category 2 at the urban level

Subcategory	Count	Reference
Recycling and reuse technology	4	[24, 29, 35]
Technological expertise	3	[25, 30]
Design and disassembly	1	[27]
CE concept and principles	3	[27, 32, 36]
Production and manufacturing	1	[31]
Knowledge transfer and retention	2	[28, 31]
Total	14	

Category 2: Lack of Technical Knowledge

Successfully implementing CE practices in urban and construction settings requires robust technical knowledge across various domains. However, there are significant barriers related to technical knowledge that hinder these efforts. These barriers can be grouped into six subcategories (Table 1.5). Each subcategory captures specific challenges in acquiring, applying, and disseminating the technical expertise needed for CE practices.

Recycling and Reuse Technology. This subcategory focuses on the technological barriers related to recycling and reuse processes. Efficient recycling and reuse are crucial for the CE, but technological limitations can impede these processes.

Technological Expertise. This subcategory addresses the lack of specialized knowledge and skills required for implementing CE practices effectively. Technical expertise is essential for developing and applying innovative solutions in CE.

Design and Disassembly. This subcategory includes barriers related to product design and disassembly, which are critical for enabling recycling and reuse.

CE Concept and Principles. This subcategory focuses on the understanding and application of CE concepts and principles. Comprehensive knowledge of CE principles is vital for their effective implementation.

Production and Manufacturing. This subcategory addresses the technical knowledge barriers related to production and manufacturing processes. Efficient production methods are essential for minimising waste and promoting circularity.

Knowledge Transfer and Retention. This subcategory includes barriers related to the transfer and retention of technical knowledge among stakeholders. Effective knowledge transfer is critical for maintaining continuity and fostering innovation in CE practices.

Table 1.6 Subcategories of barriers under Category 3 at the urban level

Subcategory	Count	Reference
Human resources and knowledge of CE principles	2	[25, 28]
Access to business services and technical assistance	1	[37]
Public infrastructure and service providers' skills	2	[31, 34]
Total	5	

Category 3: Lack of Technical Skills

The successful implementation of CE principles and practices relies heavily on the availability of technical skills and expertise across various sectors. However, several studies have identified significant barriers related to the lack of technical skills, which can be categorised into three main subcategories (Table 1.6). Each subcategory highlights specific challenges that hinder the development and application of technical skills necessary for advancing CE initiatives.

Human Resources and Knowledge of CE Principles. This subcategory focuses on barriers to the availability of human resources with the necessary knowledge of CE principles. Understanding CE principles is essential for effectively integrating sustainable practices into urban and construction contexts.

Access to Business Services and Technical Assistance. This subcategory addresses barriers related to accessing business services and the technical assistance needed to implement CE practices. Adequate support services are crucial for overcoming technical challenges and fostering innovation in sustainable development.

Public Infrastructure and Service Providers' Skills. This subcategory includes barriers related to the technical skills and capabilities of public infrastructure and service providers. These entities play a vital role in implementing and maintaining CE initiatives on a broader scale.

Category 4: Lack of Technical Standards

The absence or inadequacy of technical standards across various domains hinders the implementation of CE practices in the built environment. The challenge presents itself in two primary subcategories (Table 1.7). These subcategories encompass specific barriers that impede the establishment of uniform guidelines and regulatory frameworks necessary for promoting sustainable practices and ensuring consistency in CE implementation.

Building Design and Construction Standards. This subcategory addresses barriers to the lack of technical standards in building design and construction practices conducive to CE principles. Practical standards are crucial for promoting eco-friendly building materials, efficient resource use, and sustainable construction techniques.

Table 1.7 Subcategories of barriers under Category 4 at the urban level

Subcategory	Count	Reference
Building design and construction standards	12	[19, 24, 26–28, 30–32, 34, 35, 38]
Regulatory framework and support	6	[31, 33, 36, 39]
Total	18	

Table 1.8 Subcategories of barriers under Category 5 at the urban level

Subcategory	Count	Reference
Inadequate recycling and waste processing technology	2	[24, 32]
Total	2	

Regulatory Framework Support. This subcategory focuses on barriers associated with the regulatory framework and government support required to establish and enforce technical standards for CE practices. Clear regulations and supportive policies are essential for incentivising compliance and fostering innovation in sustainable development.

Category 5: Inadequate Machines/Equipment

The practical implementation of CE principles in waste management and recycling heavily depends on the availability and adequacy of machines and equipment designed for these purposes. This challenge is categorised into one primary subcategory: Inadequate Recycling and Waste Processing Technology (Table 1.8). This subcategory highlights specific barriers that hinder the efficient processing and recycling of materials that are essential for CE practices.

Inadequate Recycling and Waste Processing Technology. This subcategory focuses on barriers related to the insufficiency and inadequacy of recycling and waste processing technology. Effective recycling and waste processing technologies are crucial for maximising material recovery and minimising waste in CE initiatives.

Category 6: Inadequate Processes and Infrastructure

The successful implementation of CE practices hinges on robust processes and infrastructure that support efficient resource management and sustainable development. This challenge is categorised into four main subcategories (Table 1.9). Each subcategory addresses specific barriers that impede the establishment and optimisation of processes and infrastructure necessary for advancing CE initiatives.

Infrastructure for Waste Management and Recycling. This subcategory focuses on barriers related to inadequate infrastructure for waste management and recycling.

Table 1.9 Subcategories of barriers under Category 6 at the urban level

Subcategory	Count	Reference
Infrastructure for waste management and recycling	8	[24, 25, 29, 31, 34, 35, 38]
Production networks and logistics	6	[26, 31, 35, 37, 38]
Urban planning	3	[27, 39, 40]
Challenges in implementing CE practices	4	[19, 26, 32, 33]
Total	21	

Adequate infrastructure is critical for facilitating the collection, sorting, and recycling of materials essential for CE practices.

Production Networks and Logistics. This subcategory addresses barriers associated with production networks and logistics that support CE practices. Efficient logistics and supply chain networks are essential for optimising resource flows and minimising waste in CE initiatives.

Urban Planning. This subcategory focuses on barriers related to urban planning practices that affect the implementation of CE principles. Integrated urban planning is essential for creating sustainable urban environments conducive to CE practices.

Challenges in Implementing CE Practices. This subcategory addresses broader challenges in implementing CE practices across different sectors. It encompasses barriers to policy, governance, and stakeholder engagement that are necessary to foster CE initiatives.

Category 7: Lack of Methods/Tools

The practical implementation of CE principles relies heavily on the availability and adequacy of methods and tools designed to support sustainable practices in urban planning, management systems, and design and construction. This challenge is categorised into three main subcategories (Table 1.10). Each subcategory addresses specific barriers that hinder the adoption and optimisation of methods and tools necessary for advancing CE initiatives.

Urban Planning. This subcategory focuses on barriers related to inadequate methods and tools in urban planning that hinder the integration of CE principles. Practical urban planning tools are essential for incorporating sustainable practices into urban development and promoting resource efficiency.

Management Systems. This subcategory addresses barriers associated with management systems lacking adequate methods and tools to support CE practices. Efficient management systems are crucial for optimising resource flows, tracking material use, and ensuring effective implementation of CE strategies. Design and Construction Tools.

Table 1.10 Subcategories of barriers under Category 7 at the urban level

Subcategory	Count	Reference
Urban planning	2	[19, 24]
Management systems	1	[24]
Design and construction tools	6	[10, 27, 34, 35]
Total	9	

Design and Construction Tools. This subcategory focuses on barriers related to inadequate methods and tools in design and construction that limit the implementation of CE principles. Effective design and construction tools are essential for promoting sustainable building practices, material reuse, and lifecycle assessments.

Category 8: Lack of Materials/Products/Buildings/Systems

The challenges related to the lack of materials, products, buildings, and systems for implementing CE principles are crucial barriers that impact the transition towards sustainable practices. These challenges are categorised into five subcategories (Table 1.11).

Material/Product/System Availability and Quality. This subcategory addresses barriers concerning the availability and quality of materials, products and systems essential for implementing CE practices. Ensuring a consistent supply of high-quality recycled or reclaimed materials, products, and systems is critical for sustainable construction and manufacturing processes.

Space and Storage Issues. This subcategory focuses on barriers related to spatial constraints and storage challenges that hinder the effective implementation of CE strategies. Adequate space for storing materials and products awaiting reuse or recycling is essential for optimising resource utilisation.

Cost Factors. This subcategory addresses barriers related to cost implications that deter the adoption of CE practices. High costs related to materials/products/systems procurement, processing, recovering and recycling can impede the economic viability of circular solutions.

Complexity and Composition. This subcategory focuses on barriers related to the complexity and composition of materials, products and systems used in circular practices. Understanding and managing the diverse compositions of materials and products are essential for effective recycling and reuse strategies.

Monitoring and Management. This subcategory addresses barriers to monitoring and managing material flows within the CE framework. Effective monitoring systems are crucial for tracking material usage, ensuring quality standards, and optimising resource efficiency.

Table 1.11 Subcategories of barriers under Category 8 at the urban level

Subcategory	Count	Reference
Material availability and quality	4	[31, 33]
Space and storage issues	4	[26, 37, 39]
Cost factors	2	[39]
Complexity and composition	1	[19]
Monitoring and management	1	[29]
Total	12	

Upon conducting a quantitative analysis of reported barriers from the literature, it is evident that *Inadequate processes and infrastructure* pose significant challenges to adopting CE practices in urban areas. These barriers highlight the urgent need for technological advancement, efficient resource management, and sustainable development. Bridging these skill gaps is crucial to fostering expertise within the industry and overcoming technical hurdles to CE adoption. Comprehensive infrastructure development, streamlined logistical systems, and integrated urban planning strategies are necessary to support sustainable material flows and enhance resource efficiency.

Furthermore, establishing robust *Technical Standards* is essential to ensuring consistency, reliability, and safety in materials reuse and recycling processes. This involves addressing challenges such as insufficient waste management and recycling infrastructure, fragmented production networks, logistical inefficiencies, and deficiencies in urban planning that integrate CE principles.

Moreover, the *lack of adequate urban planning tools*, management systems, and design and construction tools present additional barriers to effectively implementing CE practices. Enhancing the availability and functionality of these tools is critical for informed decision-making, optimising resource utilisation, and overcoming operational obstacles to sustainable development.

Lastly, challenges related to *limited availability and quality* of materials, spatial constraints, cost factors, material complexity, and inadequate monitoring and management practices underscore the need for strategic interventions. These include improving material availability, optimising spatial usage, mitigating cost implications, simplifying material compositions, and enhancing monitoring systems to manage sustainable resources effectively.

Furthermore, these multifaceted barriers require concerted efforts across technological innovation, policy development, and capacity-building initiatives. By overcoming these challenges, the transition towards a more sustainable urban environment can be accelerated, effectively promoting CE principles and practice.

1.3.1.3 Quantitative Data Analysis of Each Category

A summary of the collected quantitative data for each category is shown in Table 1.12.

Table 1.12 Quantitative data collection at the urban level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of information/ data							10	3	1			7	2
Lack of technical knowledge							8	6	5	5	3	4	2
Lack of technical skills							5	2	1	3	2	5	2
Lack of technical standards							10	7	6	2	4	7	5
Inadequate machines/ equipment											1	1	1
Inadequate processes and infrastructure							15	4	4	5	13	11	10
Lack of methods/tools							8	7	7	1	2	4	2
Lack of materials/ products/ systems							6	2	1	3	3	5	4

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of information/ data	5	8	3	7	10			1	4	7	1	1	4	6	6	3
Lack of technical knowledge	3	5	3	2	6	4		3		5	1	1	2	3	5	
Lack of technical skills	1	3	2	1	4	1		1		3	1	1	2	1	3	
Lack of technical standards	2	11	2	1	12			1	4	8	2	1	1	4	8	

(continued)

Table 1.12 (continued)

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Inadequate machines/ equipment					1	1									1	
Inadequate processes and infrastructure	8	8	11	6	10	3	0	2	3	13	1	1	4	4	10	2
Lack of methods/tools	0	7	0	0	2	1	0	0	1	0	0	0	1	0	1	0
Lack of materials/ products/ systems	2	2	5	2	5	1	0	1	2	6	0	0	3	0	5	1

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

Category 1: Lack of Information/Data

Where it happens. The studies addressing the lack of information/data barriers at the system (district) scale broadly describe these barriers under the headings "data capabilities and data availability" [26, 29], "limited knowledge" [10, 27, 31, 40], "the lack of integration among sources of information" [19, 24, 25, 28, 30, 33, 34], and "insufficient data" [32].

When it happens. Lack of information/data barrier at the system (district) scale has been discussed mostly in the "Use and Refurbishment" phase within the building life cycle phases [26, 27, 30, 31, 34]. However, dismantling and construction and end-of-life were evaluated in the scope of this barrier [27], as well.

Who is responsible for/involved in. The government, project professionals, and the public are primarily responsible for the lack of information/data barriers. However, clients and suppliers are also included in these responsible stakeholders [10, 24–31, 26, 27].

How it affects the implementation of circular strategies in the built environment. While it is emphasised in the literature that the lack of information/data barriers will mainly affect reuse, recycle, and repurpose [24–27, 26, 27], which are circular strategies in the built environment, it is stated that this barrier will also be effective on reduce, rethink, repair and refurbish [25, 26, 28, 30].

Category 2: Lack of Technical Knowledge

The identified technical barriers can be broadly categorised into several key knowledge gaps hindering the implementation of circular construction practices. The first one is "limited application knowledge". A lack of understanding of suitable circular construction technologies and how to effectively apply them to projects acts as a major barrier [30]. This encompasses understanding the design process for disassembly, as discussed in reference [27]. "Production and quality management challenges" is the second knowledge barrier identified. Insufficient knowledge in areas like production management and the high-quality manufacturing of recycled construction materials presents a significant hurdle [31]. "CE knowledge deficit" also provides a limited understanding of CE principles among stakeholders, including public infrastructure providers, construction professionals, and urban manufacturers, hindering widespread adoption [32]. "Scaling up challenges" are associated with the lack of knowledge required for scaling up circular construction businesses, and urban manufacturing operations pose a significant barrier [31]. The loss of traditional construction skills and the challenge of transmitting this knowledge to younger generations create a potential gap in the technical expertise needed for circular construction [28], and it can be listed as a "skills gap threatening knowledge transfer".

Immature recycling technologies [24] and a lack of technological expertise across various aspects of circular construction [25] pose significant technical challenges, and they can be listed as "technological immaturity and expertise shortages". The lack of this expertise further hinders the industry's ability to adapt to CE practices [25].

Where it happens. Analysing the identified skill gaps using the Zimmann et al. [17] levelling reveals their prevalence across various stages of urban circular construction. They are mostly linked to the district (system) level, but we can still link them to staff and service levels.

When it happens. The identified technical knowledge barriers can be mapped across the building life cycle phases, adapted from RIBA [18] and Brincat et al. [15]. In the initial stages (Strategic Definition and Briefing), understanding technical constraints [29], selecting suitable circular construction technologies and their applications [30], and integrating design for disassembly [27] are crucial. A commonly agreed-upon understanding of CE principles across the industry is necessary for effective project planning [27]. The design phase (Stage 2) requires further development of these elements, with a strong emphasis on technical expertise to ensure designs are compatible with circular construction practices [25]. Knowledge gaps in production management, high-quality manufacturing [31], and expertise in handling reused construction and demolition waste (CDW) [24] become critical during the manufacturing stage (Stage 3). Similarly, limitations in recycling technology [24] can impact the quality and viability of recovered materials. Some knowledge, like the principles of high-quality manufacturing [31], can be used in both the dismantling and construction stages (Stage 4). However, because of the limitations of current technologies for these steps in a circular framework, they need to be looked at separately [35]. The use and refurbishment stage (Stage 5) addresses the importance of stakeholder awareness of CE principles for building maintenance and potential reuse [32]. Preserving traditional construction skills alongside knowledge of reusing CDW [24] becomes vital during refurbishment projects [28]. Knowledge gaps in production management [31] and the limitations of recycling technology [24] can also impact decisions and options for material processing at the end-of-life stage (Stage 6). This mapping underscores the need to address these knowledge gaps throughout the entire building life cycle to successfully implement circular construction practices.

Who is responsible for/involved in. Our analysis of stakeholder responsibility for addressing technical knowledge gaps reveals a shared burden across various groups throughout the building life cycle [19]. Project professionals (2) play a crucial role in acquiring knowledge of suitable circular construction technologies and their application [30], while also collaborating with designers (2) to integrate design for disassembly principles and navigate the absence of a commonly agreed-upon CE concept [27]. Suppliers (3) need to address knowledge gaps in production management and high-quality manufacturing of recycled materials [31] to ensure a reliable supply chain. This knowledge gap is also relevant for government agencies (5) as they can play a role in setting standards and promoting the best practices. The loss of traditional construction skills and the need to equip younger generations [30] require collaboration between clients (1), the public (4), and the government (5) to ensure knowledge transfer and workforce development. Technical constraints [17] primarily impact the public (4) as they experience the limitations of existing infrastructure. Clients (1) and suppliers (3) share responsibility for addressing the lack of knowledge about reusing CDW [24]. Immature recycling technology [24] presents a challenge for clients (1), government (5), and other stakeholders (6) who may be involved in financing or promoting research and development efforts. Similarly, the lack of technological expertise [25] and the unavailability, which exacerbates CE adaptation [25], necessitate collaboration between suppliers (3) and other stakeholders (6) involved in technology development and implementation.

How it affects the implementation of circular strategies in the built environment. Our review reveals how technical knowledge barriers can affect the implementation of various circular construction strategies, as outlined by Stijn and Gruis [20]. Insufficient knowledge in production management and high-quality manufacturing [31] creates challenges for Reuse (R4), Remanufacture (R7), and Recycle (R9) strategies. These strategies rely on a robust system for processing and reintroducing materials back into the construction value chain, which requires skilled professionals and efficient production processes. The loss of traditional construction skills and the need to equip younger generations with the necessary knowledge [28] create hurdles for Rethink (R2), Repair (R5), Refurbish (R6), and Repurpose (R8) strategies. These approaches often involve extending the lifespan of existing buildings or components, requiring expertise in traditional construction methods alongside an understanding of how to adapt these skills for a circular approach [28]. The lack of knowledge about reusing construction and demolition waste (CDW) [41] affects not only Reuse (R4) but also Reduce (R3) strategies, as it limits the ability to divert waste from landfills. Immature recycling technology [24] poses challenges for Reuse (R4) and Repurpose (R8) strategies, as it can limit the quality and viability of recovered materials for these applications. Similarly, the lack of technological expertise and the unavailability of such expertise hinder CE adaptation [25] creating significant barriers to Reuse (R4) and Recycle (R9) strategies, which rely on efficient processing and reintegration of materials into the construction cycle. The lack of knowledge on design for disassembly [27] creates challenges for implementing Reuse (R4), Remanufacture (R7), Repurpose (R8), and Recycle (R9) strategies, as it hinders the ability to recover components and materials for future use.

Category 3: Lack of Technical Skills

Our literature review identified five key technical barriers under the "lack of technical skills" category for implementing circular construction principles in urban environments. These barriers can be broadly categorised as "skill gaps" and "knowledge deficits", impacting both the construction workforce and those involved in urban planning and infrastructure. One of the most critical challenges identified is "the lack of skills and expertise among public infrastructure and service providers" [34]. This includes knowledge of circular design principles, using recycled materials, and implementing construction methods that facilitate future disassembly and material recovery. Integrating circularity into urban construction projects becomes a major challenge without a skilled workforce equipped to implement these practices. A "lack of knowledge regarding scaling up production and understanding the contribution of urban manufacturing to the CE" presents another significant barrier [31]. Limited knowledge in this area hinders the development of robust and localised supply chains for recycled construction materials, a crucial element for achieving circularity in urban environments. "The potential loss of traditional construction skills and the need to equip young professionals with the necessary skills for circular construction" is a concern highlighted by another publication [28]. Ensuring a smooth transition and knowledge transfer between generations of construction professionals is vital to maintaining core construction skills while integrating them with circularity principles. It was also identified that "the lack of access to essential business-related services and technical assistance" as a barrier [37]. This includes access to financing, legal advice, and expertise in circular business models. We consider that having good access to or being able to access such services might be linked to other barrier categories (e.g. lack of methods/tools), however, we decided to relist it under the category of lack of technical skill, too, by considering its linkage with the professional skillsets among construction professionals needed to access those services. Without this support and skill set, construction companies and developers may struggle to navigate the complexities of implementing circular construction practices in their projects. “The shortage of human resources knowledgeable about CE principles across all stakeholders” involved in construction and urban planning hinders widespread adoption [25]. This technical barrier is also linked with other categories (e.g. it includes a lack of awareness and understanding among decision-makers, designers, and engineers), however, we decided to relist it here following the same logic given above.

Where it happens. Analysing the identified skill gaps using the Zimmann et al. [17] levelling reveals their prevalence across various stages of urban circular construction. They are all mostly linked to the district (system) level, but we can still link them to staff and service levels.

When it happens. Our review shows that skill gaps and knowledge deficits manifest across various stages of the urban circular construction lifecycle. During the strategic briefing and definition stage, two key challenges emerge a lack of expertise among public infrastructure providers [34] and limited knowledge regarding scaling up the production of recycled materials and understanding the role of urban manufacturing in the CE [31]. This knowledge gap concerning scaled-up production persists and impacts manufacturing processes as well [31]. Furthermore, the lack of access to essential business services and technical assistance likely hinders various aspects of manufacturing [37]. Interestingly, while the identified barriers don’t explicitly point to specific knowledge deficits during dismantling, construction, and end-of-life stages, the previously mentioned challenges regarding production scaling and business services may also pose difficulties in these later phases [31, 37]. The literature review suggests that skill gaps and knowledge deficits are most frequently reported during the use and refurbishment stages, highlighting the need for further research to pinpoint the specific challenges faced during these crucial lifecycle phases.

Who is responsible for/involved in. While the lack of technical skills for circular construction cuts across nearly all stakeholders in the urban construction value chain, addressing these deficits requires a collaborative effort. The literature suggests a particular focus on construction professionals, who need training and knowledge to implement circular design and construction methods. Additionally, government intervention through policy changes, funding initiatives, and support for research and development can play a crucial role in creating a supportive environment for the widespread adoption of circular construction practices.

How it affects the implementation of circular strategies in the built environment. We mapped our analysis against the 10 Rs framework by Stijn and Gruis [20] to reveal how skill gaps and knowledge deficits can link to the implementation of various circular strategies in the built environment. The lack of knowledge regarding scaling up production and the limited understanding of urban manufacturing’s role in the CE [31] pose challenges for strategies like Reuse (R4), Remanufacture (R7), and Recycle (R9). These strategies rely on a robust system for recovering, processing, and reintroducing materials back into the construction value chain, which requires a skilled workforce and a well-developed manufacturing sector. The loss of traditional skills and the need to equip young professionals with the necessary skills for circular construction [28] creates barriers to Rethink (R2), Repair (R5), Refurbish (R6), and Repurpose (R8) strategies. These strategies often involve extending the lifespan of existing buildings or components, requiring expertise in traditional construction methods alongside an understanding of how to adapt these skills for a circular approach. The lack of access to essential business services and technical assistance [37] and the shortage of human resources knowledgeable about CE principles [25] create significant barriers to Reuse (R4), Remanufacture (R7), and Recycle (R9) strategies. These strategies require not only technical expertise but also business acumen to navigate financing, logistics, and market complexities. A lack of access to support services and a shortage of personnel with the necessary knowledge can significantly hinder the economic viability and successful implementation of these circular construction strategies.

Category 4: Lack of Technical Standards

Where it happens. The studies addressing the lack of technical standards barrier at the system (district) scale indicate that these barriers are largely caused by the absence/inadequacy of standardised processes, certification, and guidelines [19, 24, 26, 27, 31, 32, 34, 36, 38, 39], not being up to date [31], the diversity of existing regulations and the difficulties they cause as a result of their development based on different spatial scales [28, 30, 33].

When it happens. The lack of information/data barriers at the system (district) scale has been discussed mostly under the headings of “Strategic Definition and Briefing” and “Use and Refurbishment” within the building life cycle phases [26, 28, 30, 31, 34–36, 36, 38]. However, design, manufacture, dismantling and construction and end-of-life phases are also evaluated within the scope of this barrier [19, 24].

Who is responsible for/involved in. Project professionals and the government are mostly held responsible for the Lack of technical standards barrier [19, 24, 26–28, 28, 30, 34–36, 35, 36]. However, clients [19, 28], suppliers [38, 39] and the public [28] are also included in these responsible stakeholders.

How it affects the implementation of circular strategies in the built environment. While it is emphasised in the literature that the lack of technical standards barrier will mostly affect reuse and recycling, which are circular strategies in the built environment [19, 24, 26, 27, 30, 38, 39], some studies state that this barrier also affects rethink, reduce, repair, refurbish, remanufacture, and repurpose [24, 26–28, 28, 38].

Category 5: Inadequate Machines/equipment

Researchers identified immature recycling technology as a major barrier [24].

When it happens. The main barrier was identified in the building life cycle phase: Dismantling and Construction, Use and Refurbishment, and End-of-life [24].

Who is responsible for/involved in. Government should put more emphasis on state-owned recycling centres because of their highest eco-efficiency. The government should encourage economic incentive measures such as shortening the loan application period and lowering the land rent for CDW management businesses. New market modes, such as the Public–Private-Partnership should also be encouraged to relieve the economic pressures on CDW treatment/recycling companies [24].

How it affects the implementation of circular strategies in the built environment. The main barrier affects the implementation of circular strategies in phase recycle, because the conditions for CDW reduction are not well developed (in China), mainly due to ineffective management systems, immature recycling technology, an underdeveloped market for recycled CDW products, and immature recycling market operation [24].

Category 6: Inadequate Processes and Infrastructure

The barriers in the category of Inadequate processes and infrastructure can be grouped as follows:

- **Waste collection and Classification Systems**: Low-quality collection and classification systems and Immature recycling technology [24].
- **Material Handling and Infrastructure**: Lack of pre- and post-use material handling systems [25], Resource-intensive infrastructure lock-in [25], Poorly developed infrastructure for waste management and recycling [10] and for support CE management [10], Insufficient or incompatible local processes and infrastructure [33], Non-integrated and refurbished infrastructure [29].
- **Integration and Networking**: Lack of integrated CDW processes, tools, and practices group [19], Lack of networking initiatives with legislative support [26], Limited integration of urban metabolism [27], Lack of reverse logistics infrastructure, Fragmentation of supply chains [35], Limited access to production networks [31, 37].
- **Spatial and Scaling Issues**: Lack of space for circular infrastructure [storage, reuse, recycling [31], Challenges in scaling up [37], Spatial precarity [39].
- **Planning and Urban Processes**: Neglecting people and 'place-making'; poor connection and limited integration of place-making urban 'processes' and urban 'metabolisms' [27, 40].

Where it happens. Technical barriers related to Inadequate machines and equipment were mainly reported at the national (government) level [24, 25], local (municipal, urban) level, and organisational (company) level [19].

When it happens. The following phases of the building life cycle most frequently reveal inadequate machines and equipment:

- Dismantling and Construction [10, 19, 24–26, 31, 35, 37–39]
- Use and Refurbishment [25, 26, 29, 31, 34, 35, 37–39]
- End of life [19, 24, 26, 31, 35, 37–39].

Who is responsible for/involved in. Responsibility in this area was most frequently identified in the:

- Suppliers [25, 26, 29, 31, 35, 37–39], and Government group [10, 25, 26, 29, 31, 34, 35, 37, 39],
- Followed by clients [10, 19, 26, 29, 35, 38], and Project Professionals [10, 19, 26, 29, 35, 38].

How it affects the implementation of circular strategies in the built environment. The impact on circular strategies has most often been identified in the process of Reuse [19, 24, 26, 27, 29, 31, 34, 35, 37–39] and in the process of Recycle [19, 24, 26, 27, 29, 31, 37–39].

Category 7: Lack of Methods/tools

Literature identifies several key issues as the main barriers and challenges associated with the lack of methods and tools for implementing circular strategies. Firstly, urban systems fail to integrate circular design and thinking sufficiently, and professionals in the built environment lack the necessary design and logistics expertise [34]. There is also a notable lack of comprehensi CE metrics, tools, and design frameworks, which are essential for assessing and guiding the effectiveness of circular practices [10]. Similarly, according to [27], the lack of standardised methodologies for evaluating CE initiatives is a significant barrier, making it difficult to measure progress and ensure successful outcomes.

The integration of technology into design tools presents a particular challenge in the construction sector, as existing tools often fail to align with circular principles, underscoring the need for advanced design technologies [27]. Furthermore, the lack of enabling digital technologies, especially those that support real-time data tracking and resource management, hinders the implementation of circular strategies, especially in construction [35].

Finally, inappropriate urban planning and ineffective management systems exacerbate these challenges because they are not designed to support circular practices, resulting in resource inefficiencies and implementation issues [24].

Where it happens. Most reports at the system (district) level highlight the barriers and challenges associated with the lack of methods and tools for implementing circular strategies. This is evident in the literature, where numerous studies have highlighted these issues in the broader context of urban and district-level planning and management. For example, the lack of comprehensive CE metrics, tools, and design frameworks [10] and standardised methodologies [27] is a significant issue at the district level, as these are essential for assessing and guiding the effectiveness of circular practices across systems.

When it happens. The barriers and challenges related to the lack of methods and tools for implementing circular strategies occur most frequently in specific phases of the building life cycle. The literature review primarily identifies these phases as follows:

1. Strategic definition and briefing: This phase experiences a high number of barriers, with seven cases identified. During this phase, the lack of comprehensive CE metrics, tools, and design frameworks becomes apparent [10]. These tools are crucial for setting strategic goals and guiding the planning process towards circular practices. The absence of standardised methodologies [27] hinders the evaluation of CE initiatives, necessitating the early establishment of effective evaluation frameworks to track project progress and outcomes.
2. Design: Again, seven barriers were identified. As Hossain et al. [27] point out, the challenge of integrating technology into design tools is particularly relevant, as existing tools often lack alignment with circular principles, thereby hindering the integration of circular strategies. In addition, the lack of enabling digital technologies affects the ability to create designs that support real-time data tracking and resource management [35]. In addition, the lack of appropriate design and logistics expertise among built environment professionals becomes apparent at this stage [34].
3. Use and Refurbishment: Four barriers were identified at this stage. Specifically, the design of ineffective management systems and inappropriate urban planning presents significant challenges, as they do not facilitate the implementation of circular practices [24].

Who is responsible for/involved in. Project professionals and government agencies are primarily responsible for addressing the barriers and challenges associated with a lack of methods and tools for implementing circular strategies. Project professionals, including architects, engineers, designers, and construction managers, play a critical role in integrating CE principles into projects [27, 31, 34, 35]. Meanwhile, government agencies are essential in creating regulatory frameworks, providing incentives, and supporting the development of standardised methodologies for CE assessment [24].

How it affects the implementation of circular strategies in the built environment. The lack of methods and tools significantly impacts the implementation of circular strategies in the built environment, particularly strategies such as Reduce, Remanufacture and Recycle [24]. This lack of appropriate methods and tools undermines the potential to reduce resource consumption, remanufacture components, and recycle materials in the built environment.

Category 8: Lack of Materials/Products/Buildings/Systems

The main barriers and challenges in the category of lack of materials/products/buildings/systems for implementing circular strategies in the built environment are multifaceted and highlighted across the literature. Several studies have identified spatial challenges as significant obstacles to the implementation of circular strategies in the built environment. One of the main issues is the scarcity of affordable sites and spatial precarity, which limit the availability of suitable locations for circular practices. This includes a shortage of affordable industrial land within urban areas and reduced space for urban manufacturing, restricting the potential for CE practices in cities [37, 39]. Additionally, the limited space to stock disassembled materials before reuse impacts the efficiency of material recovery and reuse processes [26].

Moreover, material-related issues present substantial barriers. The low cost of new materials discourages the use of recycled materials, compounded by the high cost of labor required for deconstruction and material recovery [39]. There is also limited work and interest in high-value or niche products, and a limited availability of quality recycled material from local sources [31]. Furthermore, the complexity of materials and building compositions, involving several layers and modifications over their lifespan, makes disassembly and recycling challenging [19].

Monitoring and managing urban resource flows is also a complex task that poses significant challenges for implementing circular strategies [29].

Where it happens. The barriers related to the lack of materials, products, buildings, and systems for implementing circular strategies are mainly reported at the system (district) level. This is evident in the literature, which highlights challenges such as the scarcity of affordable sites, limited industrial land within urban areas, and insufficient space for urban manufacturing and storing disassembled materials [26, 37, 39]. These barriers are particularly pronounced in urban districts, where spatial and resource constraints are more acute.

When it happens. The barriers related to the lack of materials, products, buildings, and systems for implementing circular strategies occur at various phases of the building life cycle. They can be prioritised based on their occurrence as follows:

1. Use and Refurbishment: This phase encounters the highest number of barriers (5), including limited availability of quality recycled materials, high labor costs, scarcity of affordable sites, spatial precarity, and limited space for storing disassembled materials [4, 26, 37, 39].
2. End-of-life: The end-of-life phase faces four barriers, such as high labor costs for deconstruction, scarcity of space to store disassembled materials, and difficulties in managing complex material compositions [4, 26, 37, 39].
3. Manufacture: The manufacturing phase is affected by three barriers, including limited availability of quality recycled materials, high labor costs, and lack of affordable industrial land within urban areas [31, 37, 39].

4. (Dismantling and) Construction: This phase also encounters three barriers, including the scarcity of affordable sites, limited space for urban manufacturing, and high labor costs [31, 37, 39].
5. Strategic Definition and Briefing: This initial phase has two barriers, including the scarcity of affordable sites and challenges in monitoring and managing urban resource flows [29, 39].
6. Design: The design phase encounters a challenge due to the restricted availability of high-quality recycled materials [39].

Who is responsible for/involved in. The responsibility for addressing barriers to implementing circular strategies involves multiple stakeholders, prioritised by the number of barriers they are involved in. Project professionals and the public are each involved in five barriers, such as managing design challenges and influencing market demand for circular practices [4, 26, 37, 39]. Clients and suppliers handle two barriers each, including the scarcity of affordable sites and providing quality recycled materials [26, 39]. The government is responsible for one barrier, primarily related to creating supportive policies [39].

How it affects the implementation of circular strategies in the built environment. The barriers to implementing circular strategies in the built environment affect various strategies to differing extents. The most impacted strategy is Reuse, with seven barriers, such as limited space to store disassembled materials and the scarcity of quality recycled materials [19, 26, 29, 31, 37, 39]. Recycling follows six barriers, including the complexity of materials [19, 26, 29, 31, 37, 39]. Remanufacturing faces three barriers, such as the limited availability of quality recycled materials and high labour costs [31, 37, 39]. Reduce encounters two barriers [39]. Rethink is affected by one barrier, with spatial precarity limiting suitable locations for circular practices [39], and Recover also has one barrier [29].

1.3.2 Building Level

1.3.2.1 Quantitative Analysis of Literature

The first step in the elaboration of technical barriers provided by the literature at the building level focused on a quantitative approach to understanding the number and typology of consulted documents. Moreover, a quantification of the identified barriers in total and each category was extracted. Figure 1.7 shows the number of documents providing the different barriers distinguished between scientific and non-academic literature including reports (research, technical, project deliverable) provided by European Institutions website (such as CORDIS, JRC, EPC, OPE) and global and national Associations ad Cooperatives of designers, engineers, consultants, companies (such as ARUP, Circle, UKGBC).

Lack of information/data (48 documents) and *lack of technical standards* (45) were the most consistent barrier categories, followed by *lack of technical knowledge*

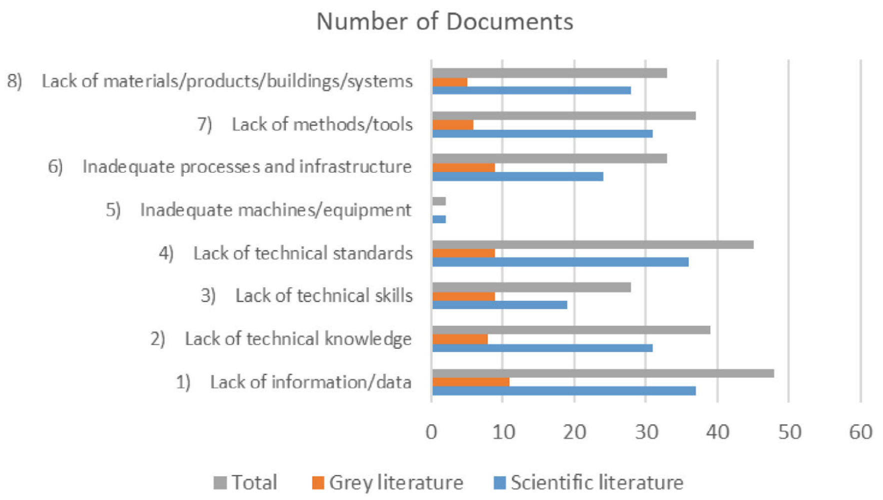

Fig. 1.7 Total consulted documents, in academic (called scientific literature) and non-academic literature (called grey literature), providing information about the different categories of technical barriers

(39) and *lack of methods/tools* (37). The remaining categories present a comparable amount of related documents, except for *inadequate machines/equipment* which were recorded in only two documents. The scientific literature prevails in all the categories.

The number of barriers discovered in terms of multiple and variation in each category is presented in Fig. 1.8.

The highest number of barriers is recorded in *methods/tools* (89) and *information/ data* (73), and they are mainly found in scientific literature. A significant number of identified barriers are also related to *materials/products/buildings/systems* (68)*, technical standards* (65)*, and technical knowledge* (60). Figure 1.9 shows the building layers in which the barriers are found.

The lack of methods and tools is primarily recorded at the structure, skin and services layers. A similar pattern is observed in the lack of information and data. This pattern is a result of the most frequent barriers. In other cases, such as lack of materials/products/buildings/systems and lack of technical standards, obstacles to the implementation of the CE were also consistently recorded in stuff. Figure 1.10 shows the building life cycle phases affected by each barrier.

It is clear how the design phase is influenced by the lack of methods, standards, skills knowledge, and data. Also, dismantling and construction and end-of-life detection have a significant influence on technical barriers. The stakeholders responsible for the technical barriers are presented in Fig. 1.11.

Project professionals and suppliers have a crucial role. In addition, the importance of governments is evident in the development and implementation of technical standards. The circular strategies affected by technical barriers are shown in Fig. 1.12.

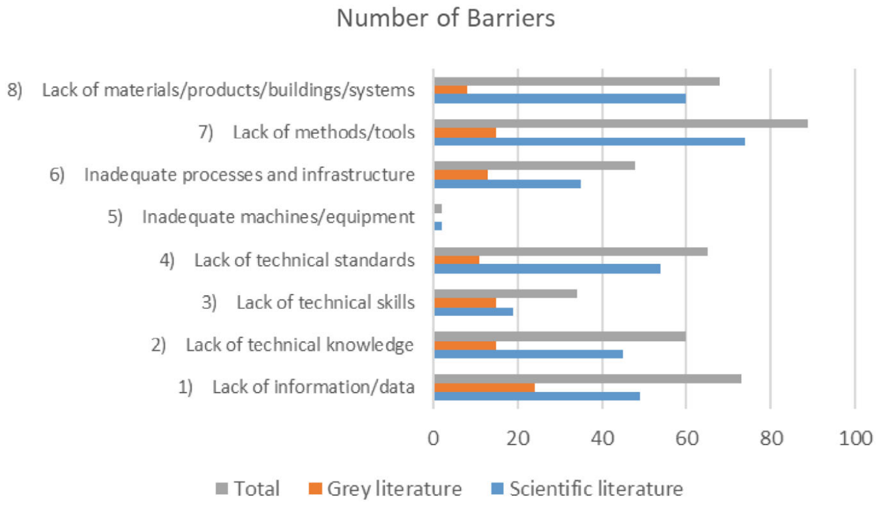

Fig. 1.8 Total barriers, and barriers provided by scientific and non-academic literature in the different categories

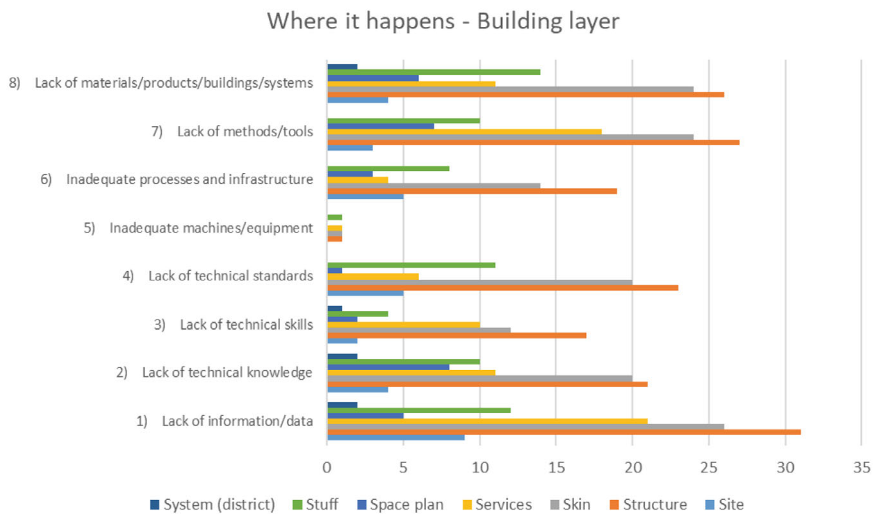

Fig. 1.9 Building layers in which technical barriers were recorded

Reuse and recycling are the circular strategies more affected by technical barriers, as already noticed at the urban level. Also, recovery shows a significant impact from the technical barriers.

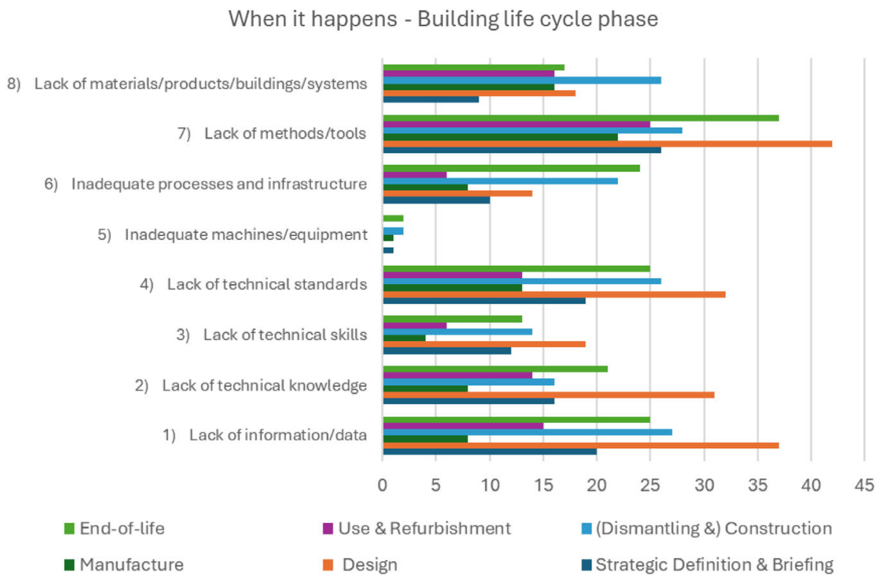

Fig. 1.10 Building life cycle stages in the different categories of technical barriers

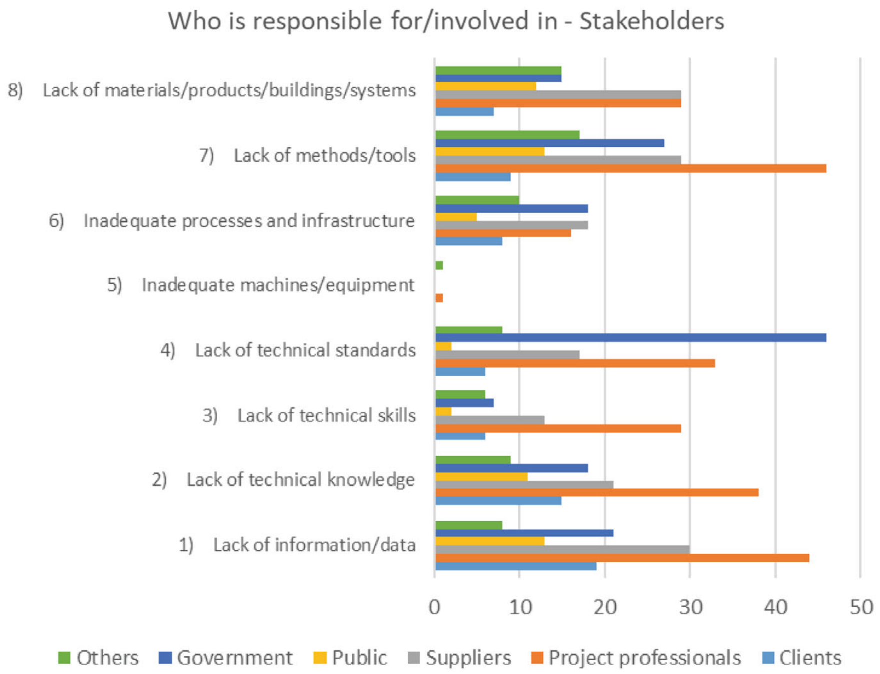

Fig. 1.11 Stakeholders involved in the different categories of technical barriers

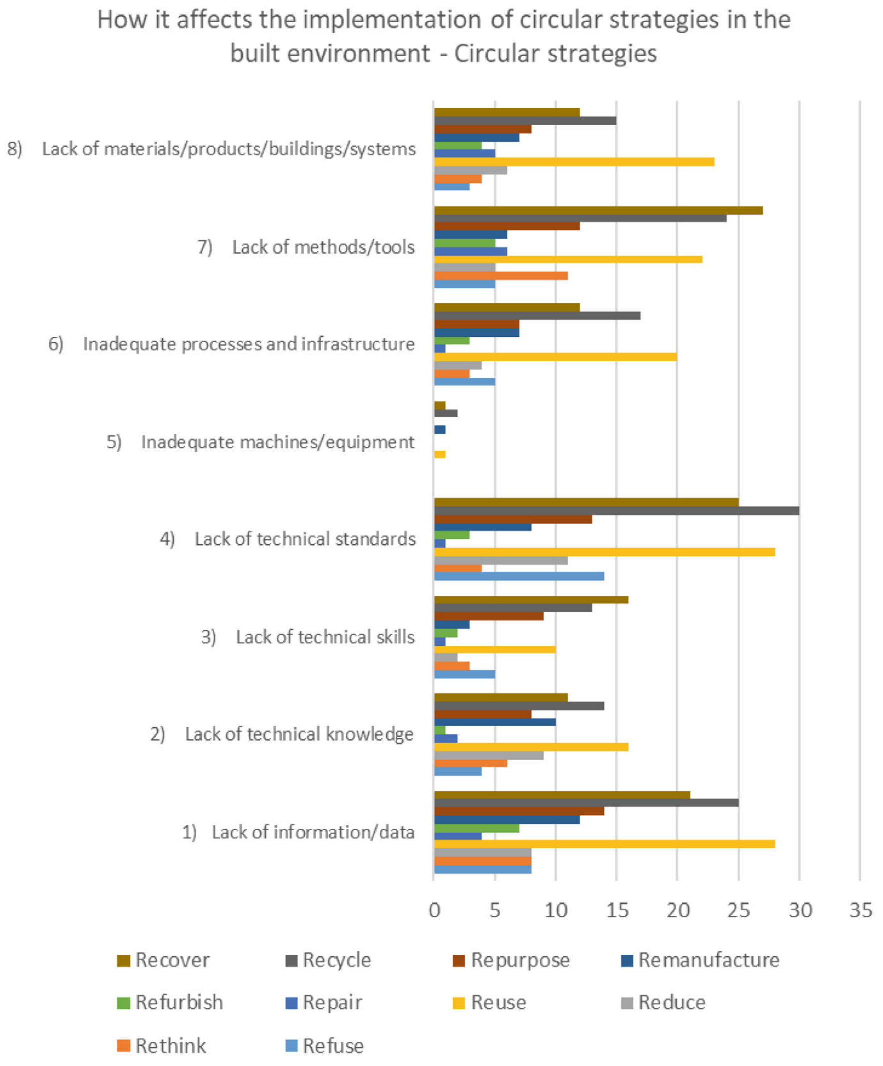

Fig. 1.12 Technical barriers categories affecting circular strategies

1.3.2.2 Collection of the List of Barriers in Each Category, and Analysis of Relevance

Category 1: Lack of Information / Data

The list of barriers in the category was produced by looking at the collected data and annotating them in Table 1.13. Repetitions or similarities were removed. In the case of a large number of barriers, subcategories were identified. Then, the more relevant barriers and subcategories are listed. Finally, a brief description of the barriers in the category and their relevance is provided.

Through the quantitative analysis of reported barriers from the collected literature, it was revealed that issues such as the lack of information on indexing material stock, tracking reused materials, related material databases, inaccuracies, and the absence of data on existing buildings can be categorised under a single theme: the lack and inaccuracy of information about the material stock. This theme emerged as the most prevalent type of information deficiency, appearing 38 times at the building level in the identified literature [6, 10, 19, 26, 34, 41–62].

Furthermore, within the category of lack of data/information, 15 technical barriers can be categorised under the theme of sustainability assessment. This theme was identified as the second most prevalent type of information deficiency at the building scale in the analysed literature [6, 53, 57–59, 62–70]. The theme of disassembly and technical information was noted 12 times [43, 53, 55, 57–59, 61, 71–73]. The lack of stakeholder awareness was reported five times among the extracted barriers within the first category [68, 74–77]. Additional themes, including digital, data interoperability, and property, had fewer occurrences, noted four, four, and two times respectively [19, 55, 65, 78–80].

Category 2: Lack of Technical Knowledge

A detailed analysis of the reported barriers revealed that they are of different levels: a considerable portion of them is of a general nature (e.g. "Lack of effective technical CE knowledge"), while others refer to specific fields of technical knowledge. Also, it is worth noting that in this category of barriers, issues related to business approaches/market conditions and societal/cultural views have been included. In the context of the present analysis, none of the reported barriers in the category of "Lack of technical knowledge" has been excluded from the considered list, although some of them could have been classified in other major categories of barriers as well. The main subcategories into which the barriers belonging to the category of "Lack of technical knowledge" are grouped as follows (Table 1.14):

(i) General: adopted also in cases where more than one axes of design and construction are highlighted to the same degree (e.g., "Technical difficulties during the design and construction process").
(ii) Design-related issues (DfD, circular design, etc.).
(iii) Materials and resources (incl. also waste, reuse of materials and components, etc.).
(iv) Sustainability (also when issues such as carbon-intensive processes and or LCA are concerned).
(v) BIM and digital background.
(vi) Construction-related issues.
(vii) Business/market/economy-associated parameters (mostly economic/financial concerns).

Table 1.13 Collection of the list of barriers in the lack of information/data category and analysis of their relevance at the building level

Lack of information/data	Quantitative analysis
Stakeholders' awareness	*5*
Lack of awareness among stakeholders	
Lack of awareness and familiarity among professionals and the public (e.g. clients)	
Lack of awareness across the board (public/industry/government)	
Lack of awareness and culture in the industry	
Lack of data, reusing, mining, stock	*38*
Lack of information on the quality of reused materials	
Lack of information on the mechanical properties of the recovered materials	
Scarcity of data	
Disassembly, technical info	*12*
Technical perceptions	
Unavailability of information on technical features in the deconstruction process	
Unavailability of disassembly information	
Sustainability assessment	*15*
Lack of broadly recognized methodologies for calculating the embodied carbon of circular technical solutions	
Assessment of environmental benefits	
Digital	*4*
Lack or overload of digital information related to products and materials	
Lack of digital data sources to feed repositories such as DBL that can promote circularity	
In the design phase, maintenance providers use more and more IoT/Condition-Based maintenance approaches, therefore requesting more data from systems on actual performance to plan maintenance. Important data/information points are missing, most of the missing are at the start of maintenance cycles and are added later	
Data Interoperability	*4*
Data exchange and interoperability issues	
Lack of interoperability between systems and data	
Property	*2*
Property owners do not have (direct) access to supply information channels of reused products, components and materials	
Limited access to future property users in the design phase	

(viii) Perceptual/cultural/societal issues (when views, readiness for change, and opinions are, among others, addressed).

It is worth noting that the aforementioned subcategories have been arbitrarily determined based on the described content of the barriers. The axis of this determination is the field of technical knowledge ("what") and not the stakeholder involved in the lack ("who").

It should be pointed out that some of the barriers could have been classified into more than one subcategory. In each one of those cases, the axis that appeared to be the determining one regarding the lack of knowledge for a specific field prevailed, and the respective subcategory encompassed the barrier. For example, although the barrier "Necessity of a key-expert-operator (one person or one company) that can manage and follow the entire circular building process. LCA sustainability experts" does have a component of a general nature, it also contains a specific reference to LCA; this the reason why it is classified under the "Sustainability" subcategory.

In any case, the "General" subcategory seems to be the prevalent one, with relevant barriers being cited 21 times [19, 34, 49, 50, 52, 56–58, 61, 66–68, 72, 81–85]. It is interesting to note that a major group in this subcategory consists of very general statements revolving around the lack of knowledge/experience/awareness/training for building circularity, CE, etc.

Category 3: Lack of Technical Skills

A list of identified barriers in the lack of technical category, and their subcategory relevance, is shown in Table 1.15.

Through the quantitative analysis of reported barriers from the collected literature, it was revealed that issues such as lack of people with the right skills for the CE [74, 86], lack of skills [34, 45, 51, 61, 77, 80, 81, 83, 85, 87, 88], lack of systemic CE education and training for supply chain members [51, 62, 72, 73], lack of training and knowledge for professionals [48, 65, 80], lack of skills in design and implementation [19, 44, 55–57], lack of awareness and communication skills [68], educational barriers [58, 59, 68] can be categorised under a single theme: lack of technical skills.

This theme emerged as the most prevalent type of information deficiency, appearing 30 times at the building level in the identified literature [19, 34, 45, 48, 51, 55–59, 61, 62, 65, 68, 72–74, 77, 80, 81, 83, 85–89].

Category 4: Lack of Technical Standards

The lack of technical standards as a barrier is mentioned 64 times in the reference documents. These mentions can be broadly grouped into four themes (Table 1.16): (i) lack of standardisation/guidelines, (ii) lack of legal policies, (iii) sustainability quality assurance and (iv) lack of flexibility.

Table 1.14 Collection of the list of barriers in the lack of technical knowledge category and analysis of their relevance at the building level

Lack of technical knowledge	Quantitative analysis
General	*21*
Complexity/confused incentives	
Sectoral barriers: 1-lack of bandwidth compounded by no coherent vision	
Lack of effective technical CE knowledge	
Lack of employee knowledge and awareness about how to integrate practices in the industry. Lack of organisational capabilities and in-house knowledge about CE	
Lack of knowledge of the appropriate technologies and how to apply them, especially in the integration of receiving systems and reverse logistics	
Lack of knowledge retention and learning networks	
Lack of expertise and knowledge in circularity in construction	
Lack of knowledge, training, and experts in CE	
Lack of awareness and knowledge of building circularity	
Poor stakeholder experience (to the extent where project professionals are concerned)	
Lack of understanding/awareness/information/technology	
Practitioners and supply chain with inadequate technical knowledge	
Political/citizen ignorance of technical aspects when making decisions	
Technical difficulties during the design and construction process	
Lack of awareness, knowledge and experience with the CE	
Lack of architects and developers with the required knowledge and willingness to adapt	
Stakeholders throughout the value chain remain insufficiently familiar with how CE principles do or could operate in the built environment	
Knowledge gap between stakeholders: designers and engineers sometimes lack the practical expertise of contractors, demolition contractors, and deconstruction engineers, and vice versa	
Matching standardisation with a variety of end uses	
Lack of knowledge-sharing of best practices in the building environment and translation to different contexts, lack of large-scale demonstration projects and experience with new technologies	
Different levels of knowledge and awareness in the value chain	
Design-related issues (design for disassembly, etc.)	*11*
Lack of practical application (actual practice) of DfMA (Design for Manufacture and Assembly) approach in construction (Studies of DfMA in construction heavily relied on simulations rather than the actual construction)	
Lack in comparison for structures constructed using DfMA and DfD (Design for Disassembly) with structures built with conventional approaches	

(continued)

Table 1.14 (continued)

Lack of technical knowledge	Quantitative analysis
Lack of execution of sustainability assessment studies to evaluate the impact of DfMA and DfD	
Most of DfMA in OSC (off-site construction) studies focuses on the structural components only	
The DfD guidelines are intended only for cold-formed steel structures	
A small body of knowledge addresses the actual usage of DfD in construction	
Lack of leadership, cost, and schedule considerations in the university curriculum for building design	
Limited circular design (incl. lack of know-how people)	
Lack of knowledge on circular design principles, and on the carbon and resource intensity of the linear economy	
Lack of expanded knowledge on circular design practices	
Limited experience with circular design within a built environment	
Materials and resources	*8*
Architects have misconceptions about waste management hierarchy, rarely find objective reasons to reuse building components and have conflicting views about DfD and resiliency	
Not enough people with specific knowledge about reused materials	
Lack of a waste management professional	
Unknown causes of design waste, perception of waste	
Lack of knowledge of reclaimed materials	
Difficulties in understanding and developing EPDs (Environmental Product Declarations)	
Lack of knowledge on reuse and recycling techniques and the capacity to implement	
Design teams are not aware or open to exploring the reuse of existing building products and installations (no quick visibility and transparency on secondary products and materials that are available and meet the required quality criteria)	
Sustainability	*6*
Lack of technical knowledge of sustainable practices	
Few building professionals have the skills to plan and deliver a carbon–neutral building	
Real estate valuation processes do not—at present—fully or reliably account for the value of sustainability, neither in terms of energy consumption nor material circularity	
Insufficient carbon literacy	
Necessity of a key expert operator (one person or one company) that can manage and follow the entire circular building process. LCA sustainability experts	

(continued)

Table 1.14 (continued)

Lack of technical knowledge	Quantitative analysis
Knowledge gaps: There are knowledge gaps regarding the long-term effectiveness of nature-based and regenerative solutions for climate change mitigation and adaptation. Current research is still inconclusive and incomplete in a series of aspects, including the effectiveness of nature-based solutions (for instance, as regards positive effects on human health and wellbeing or the comparative merits of various approaches in the long term)	
BIM and digital background	*3*
Lack of BIM specialists	
Insufficient knowledge of 3D modelling, building information modelling (BIM) and digital twins (DT)	
Lack of technical knowledge in use and capability of BIM throughout the construction cycle	
Construction-related issues	*2*
Lack the appropriate knowledge of construction workers (for example dry construction methods)	
Lack of knowledge regarding traditional joinery disassembly and reassembly	
Business/market/economy issues	*3*
Lack of business active models	
Lack of knowledge on how a CE can be beneficial financially	
Small projects include a lack of budgets to afford some of the specialised consulting	
Perceptual/cultural/societal issues	*6*
Short term perspective	
Conservative mindset	
Lack of acceptance and demand	
Three main uncertainties regarding the applicability and feasibility of PSS have been identified to date: the readiness of companies to adopt them, the readiness of consumers to accept them, and their environmental implications	
The user chooses what he is willing to exchange	
In the operation phase, some architect bureaus operate in a niche market where they first check what is already available before starting the actual design	

The theme of the lack of standardisation and guidelines in CE, DfD, DfMA and BIM was the most prevalent with the large number of appearances (38) in the literature, followed closely by the lack of legal policies (32), whether to consistently regulate or incentivise CE or DfD. The theme of sustainability and quality assurance, which refers to the lack of relevant indicators and other priorities, is found in 21 mentions, while the theme of the lack of flexibility in existing codes and regulations appeared only on 6 occasions.

Table 1.15 Collection of the list of barriers in the lack of technical skills category and analysis of their relevance at the building level

Lack of technical skills	Quantitative analysis
Lack of people with the right skills for CE	*2*
Lack of technical skills in the private sector on CE innovative building projects	
Lack of the necessary capabilities and skills for EOL value extraction	
Lack of skills	*12*
Lack of understanding of LCC, and on top of that, factoring in design for disassembly	
Not enough people with the skills for harvesting reused materials	
Lack of skilled tradesmen	
Lack of educational/training programs for industry employees	
Lack of skilled tradesmen	
Lack of standardised practices	
Lack of leadership for a CE: leadership has played a critical part in the delivery of existing circular built environment projects	
Lack of systemic CE education and training for supply chain members	*4*
Lack of knowledge and training on the environmental benefits and how to design a building for deconstruction of the design team	
Lack of expertise, knowledge flow, or in-house skill sets to repair and remanufacture	
Lack of training, skills and education support. Lack of documentation to support competence improvement	
Lack of skills and expertise	
Lack of basic digital skills and e-literacy	
The workforce is largely trained to work in a linear manner	
Lack of training and knowledge for professionals	*3*
Lack of instruction of decision-makers in an explicit and robust manner	
Lack of training of professionals	
Lack of understanding/skills in applying the principles of the CE	
Lack of information technology (IT) and AI professionals	
Lack of skills in design and implementation	*5*
Lack of adequate skills and training, including the limited use of Information and communication technologies (ICTs)	
Barriers for BIM application, such as the upfront cost of implementation, risks of adoption linked to IP and copyright laws, licensing issues between collaborating parties, and lack of technical skills and experience to drive implementation within organisations	
In the design phase, a barrier is still the classical view of the supplier/customer relationship from a property owner's point of view	

(continued)

Table 1.15 (continued)

Lack of technical skills	Quantitative analysis
Design as a barrier to future refurbishment: design that does not focus on the ability to be adapted, or partially/fully disassembled	
Design as a barrier to future refurbishment: design that does not focus on the ability to be adapted, or partially/fully disassembled	
Change of the traditional skill set of waste management on construction sites	
Lack of awareness and communication skills	*1*
Lack of awareness and skills across the value chain	
Lack of detail within requirements and uncommon language (not specific enough, and terms unfamiliar to the local sector)	
Lack of communication and limited awareness on the financial benefits of CE	
Lack of educational programs	*3*
Limited attention to CE in architecture studies and design	
Lack of education programs in circular thinking for primary and secondary school, vocational and higher technical education	

Category 5: Lack of Machines and Equipment

A list of identified barriers in the lack of machines and equipment category and their sub-category relevance are shown in Table 1.17.

Through the quantitative analysis of reported barriers from the collected literature, it was revealed that issues such as the need for infrastructure and equipment to perform deconstruction for a CE [47] and lack of suitable equipment for the process of deconstruction and material reclamation [50], can be categorised under a single theme: lack of infrastructure and equipment.

This theme emerged as the most prevalent type of information deficiency, appearing 2 times at the building level in the identified literature [47, 50].

Category 6: Inadequate Processes and Infrastructure

A list of identified barriers in the inadequate processes and infrastructure category, and their sub-category relevance, is shown in Table 1.18.

Following the analysis of the literature in the category "Inadequate processes and infrastructure", a total of six barriers have been identified. The lack of adequate logistic systems and spaces stood out as the most important barrier, appearing 22 times in the literature consulted. Within this barrier, the lack of space for the storage of materials was identified as the most relevant, in addition to other barriers such as the lack of space for the processing of recovered materials, a deficient logistic system for their supply, as well as an underdeveloped bank system of recovered materials [10, 26, 38, 47–49, 51, 61, 62, 73, 83, 94, 95].

Table 1.16 Collection of the list of barriers in the lack of technical standards category and analysis of their relevance at the building level

Lack of technical standards	Quantitative analysis
Lack of standardisation/guidelines	*38*
Lack of standardisation and/or guidelines in CE	[6, 10, 19, 26, 44–47, 47, 49–52, 55, 58, 59, 67, 68, 72–75, 78, 80–83, 86, 89, 90]
Lack of standardisation and/or guidelines in DfD	
Lack of standardisation and/or guidelines in DfMA	
Lack of BIM standards	
Lack of legal policies	*32*
Lack of legal policies to standardize DfD/CE	[6, 10, 26, 41, 45, 46, 50, 51, 53, 55, 58, 59, 65, 68, 69, 71, 73, 77, 81–83, 83, 90–93]
Lack of legal policies to incentivize DfD/CE	
Lack of a consistent regulatory framework for CE	
Sustainability and quality assurance	*21*
Lack of indicators (traceability, certification, modularity components)	[6, 10, 19, 26, 45, 47, 51, 55, 58, 59, 67–69, 71, 72, 80, 89, 90]
High priority in other issues	
Lack of flexibility	*6*
Lack of flexibility in (existing) codes and standards	[10, 45, 52, 66, 87]
Lack of flexibility in regulations for reused/salvaged materials	

Table 1.17 Collection of the list of barriers in the lack of machines and equipment category and analysis of their relevance at the building level

Lack of machines and equipment	Quantitative analysis
Lack of machines and equipment	*2*
Need for infrastructure and equipment to perform deconstruction	
Lack of suitable equipment for the process of deconstruction and material reclamation	

Category 7: Lack of Methods/Tools

A list of identified barriers in the lack of methods/tools category, and their sub-category relevance, is shown in Table 1.19.

In the category "lack of methods/tools", up to eight different barriers have been identified, the most significant barrier being the lack of CE approaches during design. This barrier was mentioned up to 28 times in the literature. Within this barrier, the lack of integration of holistic design processes and the integration of new technologies to assist design were considered the main problems. Other issues identified were incompatibility with future deconstruction of buildings, lack of adaptability design, as well as the lack of optimised repurposing plans for deconstruct and demolition, the complexity and constraints of circular design, and lack of continuous project implementation, monitoring and maintenance [10, 19, 26, 34, 43, 46–49, 55, 62, 65, 72, 79, 80, 90, 93, 94].

Category 8: Lack of Materials/Products/Building Systems

A list of identified barriers in the lack of materials/products/building systems, and their sub-category relevance, is shown in Table 1.20.

Within the category of lack of materials/products/building systems, the most relevant barrier is related to the availability of materials and products, mentioning a total of 28 times in the literature. Within this barrier, the quality and quantity of recycled materials and components are presented as the main sub-barrier. Other identified shortcomings were the availability of materials and alternatives, the lack of bio-based materials and eco-innovation, the lack of demountable elements on the market, the need for critical raw materials and the industrialisation of natural materials [6, 10, 26, 34, 38, 45, 47, 50, 56, 57, 61–63, 73, 86, 89, 93, 94].

Table 1.18 Collection of the list of barriers in the inadequate processes and infrastructure category and analysis of their relevance at the building level

Inadequate processes and infrastructure	Quantitative analysis
Lack of infrastructure for CE (general)	*6*
Lack of infrastructure for recycling	
Lack of infrastructure for CE management	
Lack of institutional infrastructure for CE	
Lack of supporting infrastructure	
Lack of adequate logistic system and spaces	*22*
Lack of or undeveloped logistic system	
Lack of storage facilities	
Lack of material bank/market	
Supply chain integration	
Lack of space for process-recovered components	
Material recovery	*12*
Lack of recycling plants	
Lack of adequate processes and technology to disassemble	
Lack of advanced recycling technology	
Presence of materials unsuitable for reuse	
Incomplete of performance optimization in waste generation and extending asset life	
Processing waste productions	
Connectivity and collaboration	*8*
Lack of digital infrastructure for connectivity	
Lack of information exchange system	
Lack of collaboration between stakeholders	
Professionals involved in the initial phases are not present at the end-of-life stage	
Linear construction	*4*
Fragmented and linear construction industry models	
Misalignment between business planning cycles and built environment asset life cycles	
Other	*7*
Outdated technology	
Lack of support between private and public sectors	
Increased construction process frames	
Jobsite physical constraints	
Performance assessment issues	

Table 1.19 Collection of the list of barriers in the lack of methods/tools category and analysis of their relevance at the building level

Lack of methods/tools	Quantitative analysis
Lack of adequate information tools	*15*
Lack of an adequate database	
Lack of adequate information management	
Disregard of circular economic implications	
Lack of information tools	
Lack of data-driven and empirically validated assessment models	
Difficulty in building data management	
Lack of methods to obtain material information	
Lack of CE design approaches	*28*
Lack of integration of holistic design approaches	
Restriction in design with reuse components	
Lack of CE strategies integration and other emerging digital technologies	
Complex design requirements	
Lack of ongoing enforcement, monitoring and maintenance of projects	
Design for deconstruction incompatibility	
Lack of adaptability design	
Lack of optimised repurposing plans for deconstructing and demolition	
Lack of coordination, management and traceability	*9*
Lack of coordination and management throughout the project life cycle	
Lack of collaboration tools use and development	
Need additional transport	
Lack of traceability systems	
Partial communication between certifications' metrics and goals	
Change in work procedures. Interoperability and compatibility issues	
Lack of adequate logistics	
Lack of guidelines, indicators and metrics	*22*
Lack of complete CE indicators and metrics	
Lack of CE guidelines	
Lack of reliable assurance for reuse products	
Lack of a tool for CE principles	
Unification of the CE concept	
Subjective assessment	
Ambiguity in weighting and scoring	
Aligning policies and technical themes in certification credits	
Lack of implementation of material passports in terms of legislation	
Lack of decision-making protocols	

(continued)

Table 1.19 (continued)

Lack of methods/tools	Quantitative analysis
Inadequate or complex digital tools	*4*
Complexity of software	
Incorrect use of BIM (Building Information Modeling)	
Lack of large-scale digital models in renovation	
Use of property software and protocols	
Lack of tools and methods	*4*
Lack of CE tools	
Lack of relevant tools for material reuse	
Lack of holistic and adequate methods	
Complexity in projects	*2*
Complex buildings	
Complexity of disassembly	
Other	*8*
Uncertainty about the future uses and the end-of-life phase	
Lack of innovation in processes during the building life cycle	
Walmart effect	
Material recovery	
The necessity of refurbishing	
Individual buildings	
Focus on recycling and waste management	

1.3.2.3 Quantitative Data Analysis of Each Category

Category 1: Lack of Information/Data

Results in this category were analyzed by looking at general quantitative data for this barrier category, and summarized in Table 1.21.

Where it happens. Within the most relevant types of barriers, (lack of data on reusing and material stock) the structure and skin are the building layers mostly affected by these barriers [10, 19, 41, 42, 44, 47, 49, 51–55, 53, 54]. The barriers related to sustainability assessment were reported on the layers of structure, skin, and service [53, 67, 69, 70]. In terms of lack of data related to stakeholder awareness, these barriers were mainly reported at the layers of site and structure [68, 74–77]. Regarding the lack of data on disassembly and technical info, the layers of structure and skin were mainly affected by the type of lack of Data/Information barrier [45, 55, 71, 72]. In terms of data deficiency in digital applications, the layer of services was addressed as the most affected layer by this type of barrier [55, 79, 80]. The structure and skin layers were also influenced by the lack of information [10, 19, 26, 41, 42, 44, 45, 47, 50–52, 52, 54, 55, 60, 62, 67, 70–72, 71, 72, 74, 79–81, 79]

Table 1.20 Collection of the list of barriers in the lack of materials/products/building systems category and analysis of their relevance at the building level

Lack of materials/products/buildings/systems	Quantitative analysis
Design/material/building complexity	*19*
Building and design complexity	
Material complexity	
Project uniqueness	
Building rigidity	
Additional procedures for material recovery	
Availability of materials and products	*27*
Quality and quantity of recycled materials and components	
Lack of availability of materials	
Lack of bio-based materials	
Lack of eco-innovation products	
Lack of material alternatives	
Industrialization of natural materials	
Lack of removable elements on the market	
Need for critical raw materials	
Lack of CE design and metrics	*5*
Lack of CE design and metrics	
Lack of design for disassembly	
Market	*3*
Mismatch of demand and supply of reused materials	
Lack of CE business models	
Undeveloped secondary material market	
Structural issues	*3*
Poor structural integrity	
Structural over-dimensioning when using salvaged materials	
Lack of technology and tools	*6*
Lack of collaboration tools	
Technology readiness	
Lack of solutions to satisfy each performance requirement	
Lack of evaluation of the reuse potential of secondary materials	
Other	*7*
Long product life cycles (building and materials)	
Lack of appropriate construction and demolition waste management	
Adequate incentives	
Lack of building maintenance	

Table 1.21 Quantitative data analysis—lack of information/data at the building level

"Lack of technical knowledge"	Where it happens							When it happens					
	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Total nr of occurrences in all the reported cases	*7*	*30*	*29*	*20*	*3*	*9*	*1*	*23*	*40*	*7*	*26*	*14*	*27*
Lack of information/data on reusing and material stock	1	16	17	11	0	4	0	6	19	4	14	6	12
Lack of information on sustainability	0	2	3	2	1	1	0	5	7	3	3	2	4
Lack of information on disassembly and technical info	2	4	3	1	0	1	0	2	5	0	4	1	3
Lack of information on stakeholders' awareness	4	4	2	2	2	2	1	4	3	0	3	4	4
Lack of information on digital applications	0	2	2	3	0	0	0	3	2	0	1	1	2
Lack of information on the interoperability of data	0	1	1	1	0	1	0	3	4	0	1	0	2
Lack of information on the property	0	1	0	0	0	0	0	0	0	0	0	0	0

"Lack of technical knowledge"	Who is responsible for/involved in						How it affects the implementation of circular strategies in the built environment									
	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Total nr of occurrences in all the reported cases	*20*	*52*	*30*	*14*	*20*	*7*	*7*	*4*	*5*	*42*	*6*	*8*	*13*	*14*	*23*	*20*
Lack of information/data on reusing and material stock	9	24	16	6	10	3	2	0	0	19	2	3	8	7	12	11
Lack of information on sustainability	2	9	5	2	3	1	0	2	2	4	1	2	2	1	1	2
Lack of information on disassembly and technical info	3	7	3	1	0	0	1	0	1	7	1	1	1	2	3	1
Lack of information on stakeholders' awareness	4	3	3	3	4	1	3	1	1	3	1	1	1	3	3	3
Lack of information on digital applications	1	2	1	1	1	1	1	1	1	2	1	1	1	8	2	2

(continued)

Table 1.21 (continued)

"Lack of technical knowledge"	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of information on the interoperability of data	1	3	1	0	2	1	0	0	0	0	0	0	0	0	3	1
Lack of information on the property	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

followed by the service layer [10, 26, 44, 45, 49, 51, 60, 62, 72, 74, 75, 79, 81], and the space plan and system layers with (3 and 1) occurrences respectively [6, 45, 74].

When it happens. Within the theme of lack of information related to reusing and material stock, the design, construction, and end-of-life phases at the phases mostly affected [6, 26, 34, 41, 44, 45, 48, 49, 62]. The same pattern appeared in the barriers listed under the theme of sustainability assessment [62–64]. The barriers listed under the theme of lack of data related to disassembly and technical information mainly affect the design and construction [45, 71–73]. Furthermore, it should be noted that the barriers related to the lack of stakeholders' awareness mainly affect the earlier and later stages of the building lifecycle: the strategic definition and briefing, use and refurbishment, and end-of-life [68, 74–77]. Also, the barriers related to the lack of data in digital applications showed influencing the stage of strategic definition and briefing [55, 79, 80]. In general, the technical barriers in this category mostly affect the design stage followed by construction stage [6, 10, 19, 26, 41, 44–46, 46, 48, 62–64, 63, 64, 74–77, 74].

Who is responsible for/involved in. Within the most prevalent type of barriers in this category, the lack of data related to reusing and material stock, project professionals and the public are mostly affected by the lack of information/data. Clients and suppliers are also influenced [26, 42, 45, 46, 75, 81, 97, 98]. This pattern was also noticed in the technical barriers listed under the themes of lack of data related to sustainability and disassemble and technical information [45, 57, 59, 61, 62, 64, 65, 68–73, 70]. Project professionals resulted in being affected by barriers listed under the themes of lack of digital information and lack of data interoperability [78–80].

The barriers listed under the theme of lack of data related to stakeholder awareness impacted clients, project professionals, and government [68, 74–77]. In general, at the most, the project professionals were the stakeholder that is affected most from the barriers in the category of lack of information and data [10, 19, 26, 34, 41, 42, 44–46, 48–50, 55–57, 59–62, 57, 59–61, 71–81].

How it affects the implementation of circular strategies in the built environment. Within the most prevalent type of barriers presented by the theme of lack of data related to reusing and material stock, it was observed that this type of barriers affects the implementation of circular strategies of reuse, recycling and repurposing, respectively [42, 75, 81, 97, 98]. Also, it was noted that the barriers listed under the second and third themes, the lack of data related to sustainability and disassembly and technical info, reusing is the most affected circular strategy [45, 53, 55, 57, 59, 62, 67, 72]. In general, among all representative themes, the reusing was the most affected circular strategy by the barriers extracted from the literature related to this category [10, 19, 26, 34, 45, 51–55, 53–55, 57, 59, 60, 62, 75–77, 72, 75, 76].

Category 2: Lack of Technical Knowledge

The barriers reported to belong to the "Lack of technical knowledge" category are 60 in total (incl. potential double references of the same barrier in different sources). However, only 53 of them have specific information reported with regard to the various fields examined in the context of the analysis (1. Where it happens; 2. When it happens; 3. Who is responsible; 4. How do they affect the implementation of circular strategies in the built environment). Furthermore, it is interesting to note that the information detected for each barrier does not necessarily cover the whole spectrum of the four aforementioned fields. In fact, information about the first section exists for 25 cases, while the respective numbers for the second, third and fourth sections are 41, 44 and 27, respectively. This information, as well as the number of identified instances in the whole population of the barriers listed in this category, are presented in Table 1.22.

The quantitative information regarding the barriers included in each one of them is shown in Table 1.23.

Where it happens. A first indication derived from the above Table is that the building layers most affected are the "structure" and "skin", with 21 [19, 26, 46, 49, 50, 52–54, 54, 68, 72, 73, 75, 78, 81, 82, 87, 89] and 20 occurrences [19, 26, 46, 49, 50, 52, 53, 68, 72, 73, 75, 78, 81, 82, 100], respectively, out of the 25 cases with existing data for this section. The less intensely appearing are the "site" [68, 75, 78, 81] and "district" [75, 78].

When it happens. Regarding the building life cycle stage, it seems that most of the stages appear with similar frequencies, apart from the "Design" stage, which is the most represented one with 31 occurrences out of the 41 cases with existing data for this section [19, 26, 34, 44, 46, 49, 50, 53, 54, 56–58, 58, 61, 72, 75, 78, 81–83, 82,

Table 1.22 Quantitative data analysis summary—lack of technical knowledge at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Total nr. of occurrences in all the reported cases	4	21	20	11	8	10	2	16	31	8	16	14	21
Nr. of cases with information in each specific section {(a), (b), (c), (d)}	25							41					
Number of cases with information in ANY one of the specific sections	53												
Total nr. of cases reported	60												

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Total nr. of occurrences in all the reported cases	15	38	21	11	18	9	4	6	9	16	2	1	10	8	14	11
Nr. of cases with information in each specific section {(a), (b), (c), (d)}	44						27									

(continued)

Table 1.22 (continued)

What is the barrier category	Who is responsible for/involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Number of cases with information in ANY one of the specific sections																
Total nr. of cases reported																

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

83, 87] and the “Manufacture” stage, which is the most underrepresented one [26, 44, 49, 73, 75, 78, 83].

Who is responsible for/involved in. The stakeholders who seem to be more involved in the identified barriers are the project professionals [19, 26, 34, 44, 46, 49, 50, 53–57, 55–57, 61, 64, 68, 72, 73, 81–83, 78, 81–83, 85]. References are made not only to designers but also to those involved in the construction and in other types of activities.

How it affects the implementation of circular strategies in the built environment. The circular strategies mostly affected are “Reuse” [19, 34, 49, 50, 53–56, 55, 56, 72, 75, 78, 81, 82, 87] and “Recycle” [19, 26, 34, 46, 48, 49, 53, 54, 61, 72, 75, 78, 81, 100], while only one occurrence has been reported for “Refurbish” [78].

Category 3: Lack of Technical Skills

Results in this category were analysed by looking at general quantitative data for this category, and summarized in Table 1.24.

Where it happens. The studies addressing the lack of technical skills barriers largely described these barriers at structure [34, 44, 45, 61, 72–74, 74, 77, 80, 81, 88] and skin building layers [44, 45, 61, 72, 73, 77] under subheadings lack of skills, lack of

Table 1.23 Detailed quantitative data analysis—lack of technical knowledge at the building level

"Lack of technical knowledge"	Where it happens							When it happens					
	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Issues of a general nature	2	8	8	4	1	2	0	3	11	2	7	1	4
Design-related issues	0	5	7	4	5	4	0	8	10	0	0	6	6
Materials and resources	0	4	1	0	0	1	0	0	4	1	4	3	5

"Lack of technical knowledge"	Who is responsible for/involved in						How it affects the implementation of circular strategies in the built environment									
	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Issues of a general nature	4	13	6	0	4	1	2	4	1	7	1	0	4	4	6	6
Design-related issues	0	2	0	0	1	1	0	0	1	1	0	0	1	0	1	0
Materials and resources	2	7	3	2	3	0	0	1	1	4	0	0	2	0	4	3

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district).
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

systemic CE education and training for supply chain members and lack of training and knowledge for professionals.

When it happens. The lack of technical skills barriers at the structure and skin layers has been discussed mostly in "Strategic definition and briefing" [34, 44, 62, 65, 72, 74, 80, 81, 86, 88] "Design" [34, 44, 45, 55–58, 57, 72–74, 72–74, 77, 80, 81], "Dismantling and construction" phases.

Who is responsible for/involved in. The government [62, 65, 72, 77, 80, 83, 85], project professionals [34, 44, 45, 45, 51, 55–57, 57, 59, 61, 62, 65, 72–74, 73, 74, 77, 80, 81, 87–89] and suppliers [34, 55, 56, 59, 68, 72, 85, 86] are mostly responsible or affected by the lack of technical skills.

How it affects the implementation of circular strategies in the built environment. The lack of technical skills barrier mostly affects Refuse [72, 74, 77, 81, 88], Reuse [62, 72, 74, 77, 80, 81, 87–89], Repurpose [45, 56, 57, 72, 77, 81, 87–89], Recycle [34, 45, 62, 72, 73, 77, 80, 81, 86–89] and Recover [34, 45, 62, 72–74, 74, 77, 80, 86–89].

Table 1.24 Quantitative data analysis—lack of technical skills at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of technical skills		13	7	3	2	2		11	15	4	13	10	11

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (d)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of technical skills	6	24	7	2	6	6	5	3	2	8	1	2	3	10	12	14

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

Category 4: Lack of Technical Standards

Results in this category were analysed by looking at general quantitative data for this category, and summarized in Table 1.25.

Where it happens. The dominant discussion on the need for technical standards lies mostly in “Structure” and “Skin”, with “Stuff” to a lesser extent. In terms of where these barriers take place, the most occurrences of the lack of standardisation and guidelines are observed in “Structure” with 13 occurrences [6, 10, 19, 45, 52, 72, 74, 75, 80–82, 82, 86] and “Skin” with 12 occurrences [6, 10, 19, 51, 52, 72, 74, 75, 80–82, 82] and further down the list is “stuff” with 6 occurrences [6, 19, 26, 47, 50, 73]. A similar pattern is observed for the lack of policies and consistent regulations with 8 occurrences for “Structure” [10, 41, 45, 71, 77, 82] and nine for “Skin” [10, 41, 45, 51, 71, 77, 82] with five occurrences for “Stuff” [10, 26, 50, 65, 73]. The pattern also continues with Sustainability and Quality assurance with 7 occurrences for “Structure” [6, 10, 19, 71, 72, 80], eight occurrences for “Skin” [6, 10, 19, 51, 71, 72, 80] and five occurrences for “Stuff” [6, 19, 26, 47]. The fourth and smaller theme on the lack of flexibility seems to be taking place in four occurrences in the “Structure” [10, 45, 52, 87] and in three occurrences respectively in “Skin” and “Services” [10, 45, 52].

Table 1.25 Quantitative data analysis—lack of technical standards at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of technical standards	5	22	20	6	1	11		19	31	13	26	13	25

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of technical standards	6	32	17	2	46	8	14	4	11	27	1	3	8	13	30	25

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

When it happens. The lack of technical standards seems to be affecting all life cycle phases considerably in almost all themes examined here. The two more pronounced phases with the largest number of occurences was Design with 31 occurences [10, 26, 41, 44–46, 46, 49, 50, 65, 71–75, 72–75, 77, 78, 80], while Dismantling and Construction [6, 10, 19, 26, 41, 44–47, 46, 47, 50, 71–75, 71–74] and End-of-Life [6, 10, 26, 41, 45, 46, 50, 52, 67, 69, 71–75, 73–75, 77, 81] followed with 26 occurrences each. This is expected as DfD as well as the actual construction/deconstruction phases require standards and guidelines. A sizable number of occurrences (19) was observed for the strategic definition and Briefing phases [6, 10, 19, 41, 44–46, 46, 49, 50, 65, 67, 71, 73, 74, 80, 92], which can be attributed to the novelty of CE and the absence of key legal policies and technical standards which hinder CE flagship projects.

Who is responsible for/involved in. On the issue of stakeholders involved, the grand majority of the mentions consider the government as an important stakeholder with 46 occurences [6, 6, 10, 19, 26, 41, 44–47, 49–53, 49, 71–75, 52, 80–83, 71–75]. This is expected as when we refer to government, this would include regulatory organisations at different levels of government as well as standardisation entities and agencies. Another key stakeholder is the project professional (32 occurrences) [6, 6, 10, 19, 26, 41, 45–47, 47, 49, 71–75, 72–75, 77, 78, 91–93] who influences standards but is also the main stakeholder that has to comply with them. Third in importance are the manufacturers (17 occurrences) [6, 26, 41, 45–47, 47, 71, 72, 74, 75, 78,

Table 1.26 Quantitative data analysis—Lack of machines and equipment at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of infrastructure and equipment		1	1	1		1		1		1	2		2

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of infrastructure and equipment		1								1			1		2	1

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

81] along similar lines as the project professionals. This pattern was evident in all 4 themes.

How it affects the implementation of circular strategies in the built environment. In terms of circular strategies the lack of technical standards seems to mostly affect recycling (30 occurrences) followed by reuse (27 occurrences) and recovery (25 occurrences), these three being ranked in the same way across all 4 themes [6, 10, 19, 26, 41, 45, 46, 50–52, 52, 59, 67–69, 71–75, 71–75, 77, 80].

Category 5: Lack of Machines and Equipment

Results in each category were analysed by looking at the general quantitative data for this category, and summarized inTable 1.26.

Where it happens. The studies addressing the lack of infrastructure and equipment described these barriers at structure [50], skin [50] and services [50] layers under the sub-heading "need for infrastructure and equipment to perform deconstruction".

When it happens. The lack of infrastructure and equipment barriers at structure, skin, services, and building layers has been discussed mostly in "Strategic Definition and Briefing" [50] "Design" [50], "Dismantling and construction" phases [47, 50] and "End of Life" [47, 50].

Table 1.27 Quantitative data analysis—inadequate processes and infrastructure at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Inadequate processes and infrastructure	5	19	14	4	3	8	0	10	14	8	22	6	24

What is the barrier category	Who is responsible for/involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Inadequate processes and infrastructure	8	16	18	5	18	10	5	3	4	20	1	3	7	7	17	12

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

Who is responsible for/involved in. The project professionals [50] are mostly affected by the lack of infrastructure and equipment.

How it affects the implementation of circular strategies in the built environment. The lack of infrastructure and equipment mostly affects Reuse [50], Remanufacture [50], Recycling [47, 50] and Recovery strategies [47].

Category 6: Inadequate Processes and Infrastructure

Results in each category were analysed by looking at the general quantitative data for this category, and summarized in Table 1.27.

Where it happens. The barriers in the inadequate processes and infrastructure category refer mainly to the structure of buildings [10, 19, 41, 42, 47, 50, 51, 53, 61, 62, 71, 80, 81, 88, 93]. In addition, a significant number of barriers have been identified in building services [10, 19, 41, 47, 50, 51, 61, 62, 71, 80, 81].

When it happens. Most barriers related to inadequate processes and infrastructure appear at the end-of-life of buildings [19, 41, 46–50, 48–50, 53, 57, 61, 73, 93–95]. On the other hand, the dismantling and construction phase was the second stage where the highest number of barriers was detected [10, 19, 26, 41, 47–49, 49, 56, 59, 61, 62, 71, 73, 81, 85, 88, 88, 94].

Who is responsible for/involved in. Suppliers [26, 41, 47–49, 49, 56, 71–73, 72, 73, 81, 83] and government [10, 19, 26, 46–50, 48–50, 53, 61, 62, 72, 73, 80] were identified as the main actors responsible for inadequate construction processes and infrastructure. Project professionals [10, 41, 42, 46, 46, 56, 57, 71–73, 80–82, 81] were also heavily implicated in this barrier, although to a lesser extent than the previous ones.

How it affects the implementation of circular strategies in the built environment. According to the literature, inadequate processes and infrastructure mainly affect the reuse strategy [10, 26, 38, 42, 49, 51, 53, 57, 59, 71, 72, 83, 88, 95, 99]. With a high but lower impact than the previous one is the recycling strategy [10, 19, 26, 38, 41, 48–50, 50, 53, 59, 61, 62, 72, 73, 80, 81].

Category 7: Lack of Methods/Tools

Results in each category were analysed by looking at the general quantitative data for this category and summarized in Table 1.28.

Where it happens. The study showed that barriers related to the lack of methods/ tools occur mostly at the building structure level [10, 34, 46–49, 48, 49, 51, 62, 65, 70, 72, 79–81, 79]. It is also prominent at skin level, although to a much lesser extent [10, 19, 34, 46–49, 48, 49, 51, 62, 65, 72, 79–81].

When it happens. The lack of methods/tools mainly happens at the building design stage [10, 19, 34, 43, 45–49, 47, 60–62, 55, 72–75, 78–81, 72–75]. The end-of-life stage was also significantly identified for this barrier [6, 10, 26, 43, 45–47, 47, 49, 55, 60, 72–74, 73, 74, 79].

Who is responsible for/involved in. The project professionals were identified as the key actors involved in or responsible for the barriers related to the lack of methods/ tools, well above the other stakeholders [19, 26, 34, 43, 45–49, 47, 48, 60–62, 56, 60–62, 62, 65, 72, 73, 75, 78].

How it affects the implementation of circular strategies in the built environment. The literature review highlights recovery as the main strategy affected by barriers related to lack of methods/tools [10, 26, 34, 46, 47, 49, 60–62, 62, 72–75, 79–81, 75, 79], closely followed by recycling [10, 19, 26, 34, 46, 49, 55, 60–62, 62, 65, 72, 74, 75, 79, 81, 94] and reuse [10, 19, 26, 34, 47, 49, 55, 61, 62, 72, 74, 75, 79, 93, 94, 102].

Table 1.28 Quantitative data analysis—lack of methods/tools at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of methods/tools	3	27	24	18	7	10	0	26	42	22	28	25	37

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of methods/ tools	9	46	29	13	27	17	5	11	5	22	6	5	6	12	24	27

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

Category 8: Lack of Materials/Products/Buildings/Systems

Results in each category were analysed by looking at general quantitative data for this category, and summarized in Table 1.29.

Where it happens. The studies addressing the lack of materials/products/buildings/ systems are mostly at the structure level [6, 10, 19, 34, 38, 44, 45, 47, 51, 55, 62, 73, 82, 87, 89, 93, 100], and to a slightly lower extent at building skin level [6, 10, 19, 26, 34, 44, 45, 47, 51, 62, 63, 73, 82, 89, 93, 96, 100].

When it happens. This barrier category occurs mainly during the dismantling and construction phase [6, 10, 19, 26, 34, 44, 45, 47, 50, 61, 62, 73, 81, 87]. Other phases mentioned, but less important, were design and the end of life.

Who is responsible for/involved in. Both project professionals and suppliers are equally responsible for the lack of materials/products/constructions/systems. Others such as the public and government are much less involved [6, 10, 19, 26, 34, 38, 44–47, 46, 47, 61–63, 61–63, 73, 81, 86, 87, 89].

How it affects the implementation of circular strategies in the built environment. The lack of materials/products/buildings/systems affects mostly the reuse strategy, far above the other approaches [6, 10, 26, 34, 45, 47, 56, 57, 62, 73, 82, 87, 89, 93,

Table 1.29 Quantitative data analysis—lack of materials/products/building systems at the building level

What is the barrier category	Where it happens							When it happens					
Technical barrier category	Building layer (a)							Building life cycle phase (b)					
	1	2	3	4	5	6	7	1	2	3	4	5	6
Lack of materials/ products/ buildings/ systems	4	26	24	11	6	14	2	9	18	16	26	16	17

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of materials/ products/ buildings/ systems	7	29	29	12	15	15	3	4	6	23	5	4	7	8	15	12

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from RIBA [18]; Brincat et al. [15]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3)Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

100]. Other strategies, such as recycling and recovery, are affected to a much lesser extent.

1.3.3 Material Level

1.3.3.1 Quantitative Analysis of Literature

The prevalence of identified barriers was quantified in total and for each category. Figure 1.13 presents the document frequency of the different barriers, as identified in the scientific and non-academic literature at the material level.

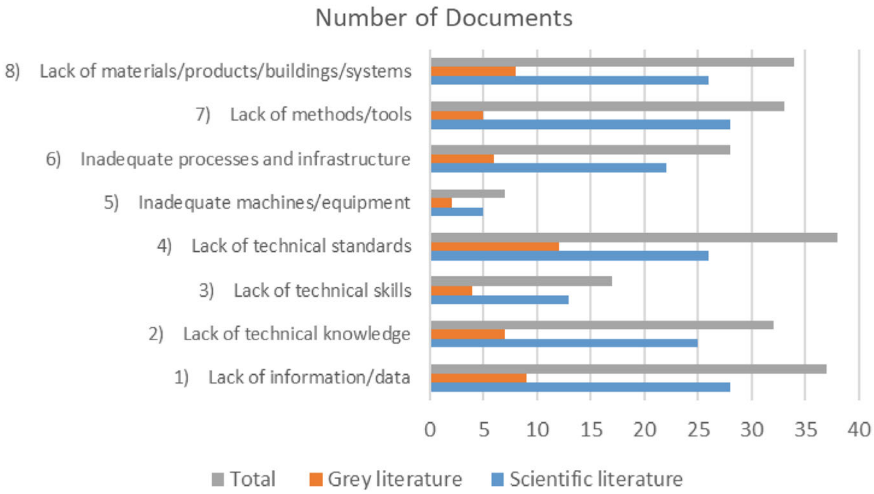

Fig. 1.13 Total consulted documents, in academic (called scientific literature) and non-academic literature (called grey literature), providing information about the different categories of technical barriers at the material level

Among the analysed 62 articles, 38 reported barriers under the category (4) *Lack of technical standards,* which formed the category most represented in the documents. *Lack of information/data* was the next most consistent barrier category (reported in 37 documents), followed by *Lack of materials/products/buildings/systems* (reported in 34 documents) and *Lack of methods/tools* (reported in 33 documents). Scientific literature was the dominant source for all reported barriers.

The main categories of technical challenges and barriers were established by quantifying the barriers that appeared across the reviewed literature, at the material level. The highest number of barriers was reported for the *Lack of materials/products/buildings/systems* category: 92 barriers across both scientific and non-academic literature, as illustrated in Fig. 1.14.

The second prominent category among the number of barriers reported was *Lack of information/data,* with 63 barriers reported in total, followed by *Lack of methods/tools*, with 59 challenges and barriers reported across the reviewed literature. *Inadequate machines/equipment* was the category found to have the least technical barriers encountered in the construction sector, at the material level.

Challenges and barriers were reported in six categories (according to Ref. [17]): site, structure, skin, services, space plan and stuff. For the material level, technical barriers and challenges were mainly reported in terms of building layers in the Structure layer for all barrier categories, followed by the Skin layer. Notably, challenges related to the space plan layer were mentioned the least frequently. Document frequency of these challenges is illustrated in Fig. 1.15, categorised by the building layers' level.

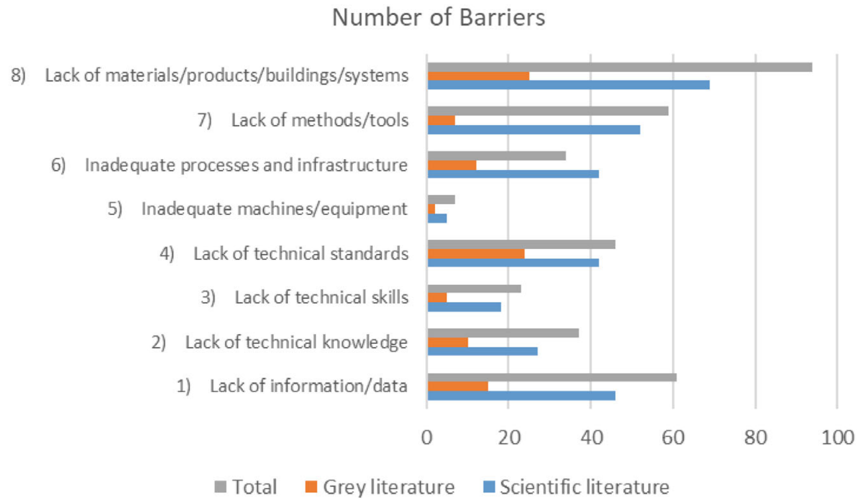

Fig. 1.14 Main categories of technical barriers, for the material level, by occurrence

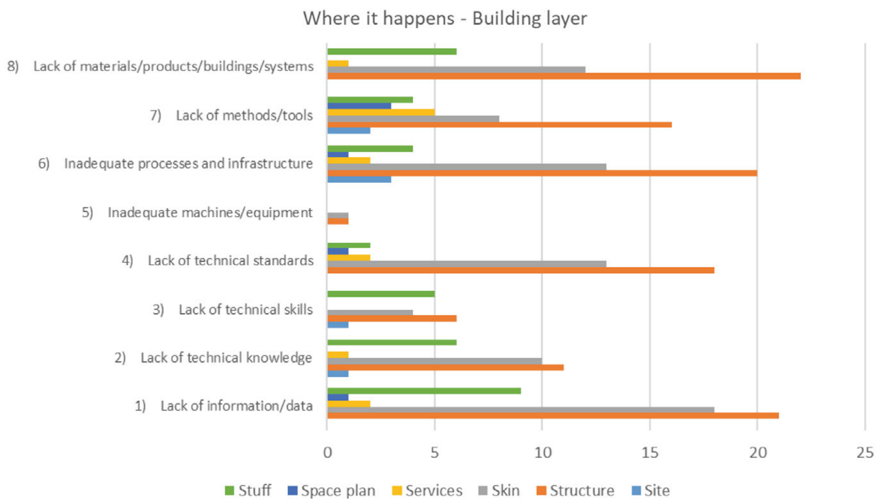

Fig. 1.15 Challenges and technical barriers at the material level regarding the layers of the building where they are reported

Regarding the building life cycle phase, the challenges and technical barriers were quantified for their occurrence in six categories (adapted from Royal Institute of British Architects [18]; Council et al. [15]): *Strategic Definition and Briefing, Design, Manufacture, (Dismantling and) Construction, Use and Refurbishment* and *End-of-life*, as shown in Fig. 1.16.

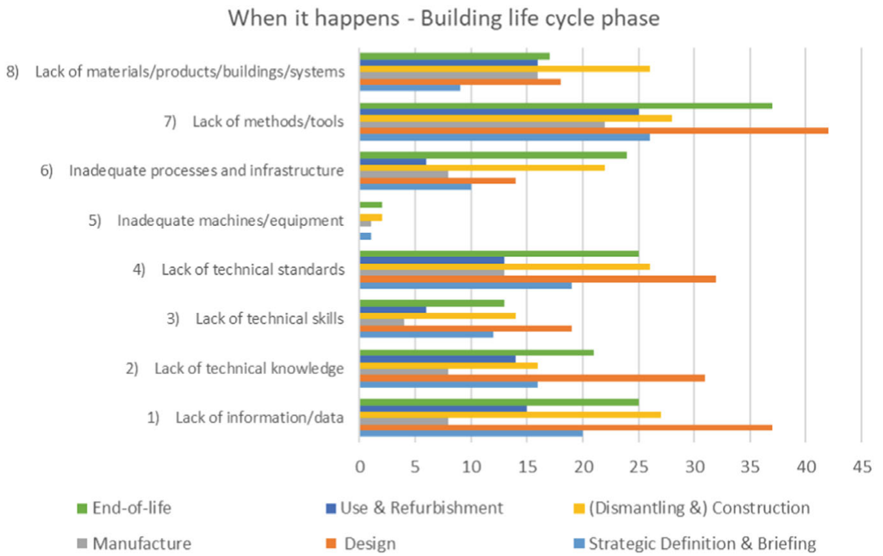

Fig. 1.16 Challenges and technical barriers for the material level, regarding their occurrence in the building life cycle phase

Design and *End-of-life* were the most prevalent building life cycle phases when barriers occurred, affected by a *Lack of methods/tools, a Lack of information/data. Lack of technical standards* and *Lack of technical knowledge*. The second most prevalent building life cycle phase when barriers occurred was (*Dismantling and) Construction*, affected mostly by the *Lack of methods/tools,* the *Lack of information/data,* the *Lack of technical standards* and by the *Lack of materials/products/buildings/systems*. The remaining categories present a comparable occurrence for the barriers and challenges reported.

Following [19], those responsible for or involved in addressing technical challenges at the material level were classified into six stakeholder groups (illustrated in Fig. 1.17). These groups include clients (those commissioning the project), project professionals (such as architects and engineers), suppliers (providing materials), the public (potentially impacted by the project), the government (with relevant regulations), and others not included in these categories.

By far the most frequently mentioned stakeholder in the studies examined was the *Government*, which was mostly responsible for *the lack of technical standards*. The following stakeholders involved in/responsible for technical barriers were found to be the *Project professionals*, who registered the highest occurrence in all technical barrier categories, except for the *lack of technical standards*. The *Public and Other* (those not included in the first five categories of stakeholders) were found to be the least responsible for/involved in the technical barriers encountered in the construction sector, at the material level.

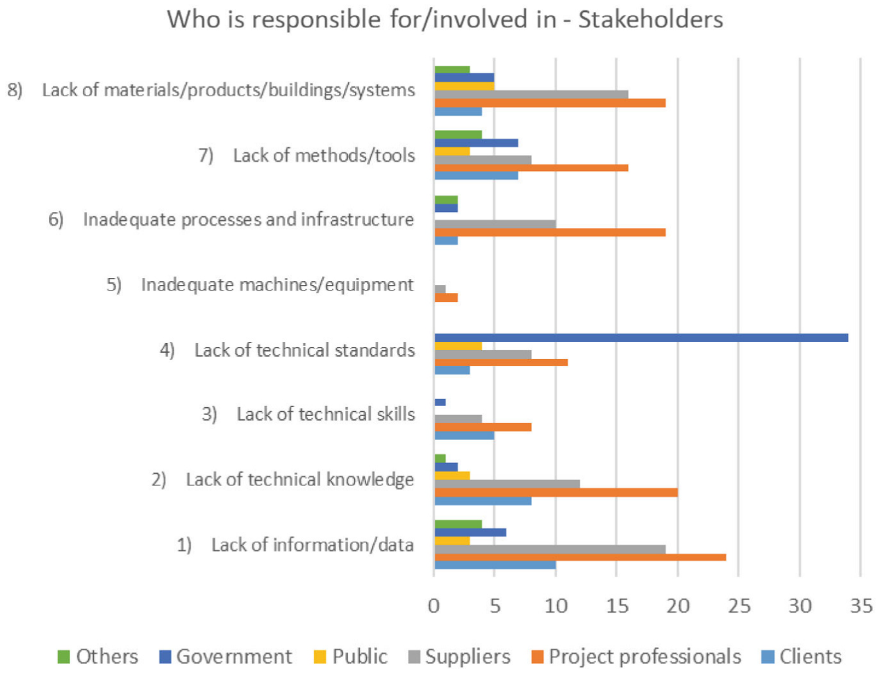

Fig. 1.17 Stakeholders responsible for/involved in technical barriers, for the material level

The research classified CE strategies in the built environment into 10 categories (according to van Stijn and Gruis [20]): *Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover*. Figure 1.18 explores how technical barriers affect the implementation of each strategy.

Reuse and *Recycle* were the most affected circular strategies by the technical barriers, followed by *Repurpose* and *Repair*. These strategies were affected mostly by barriers like *Lack of materials/products/buildings/systems, Inadequate processes and infrastructure, Lack of information/data* or *Lack of methods/tools.*

1.3.3.2 Collection of the List of Barriers in Each Category and Analysis of Relevance

A comprehensive analysis of existing research was conducted to identify obstacles hindering the implementation of CE principles. The findings underscore the significant challenges associated with transitioning to a CE for the material level in the built environment.

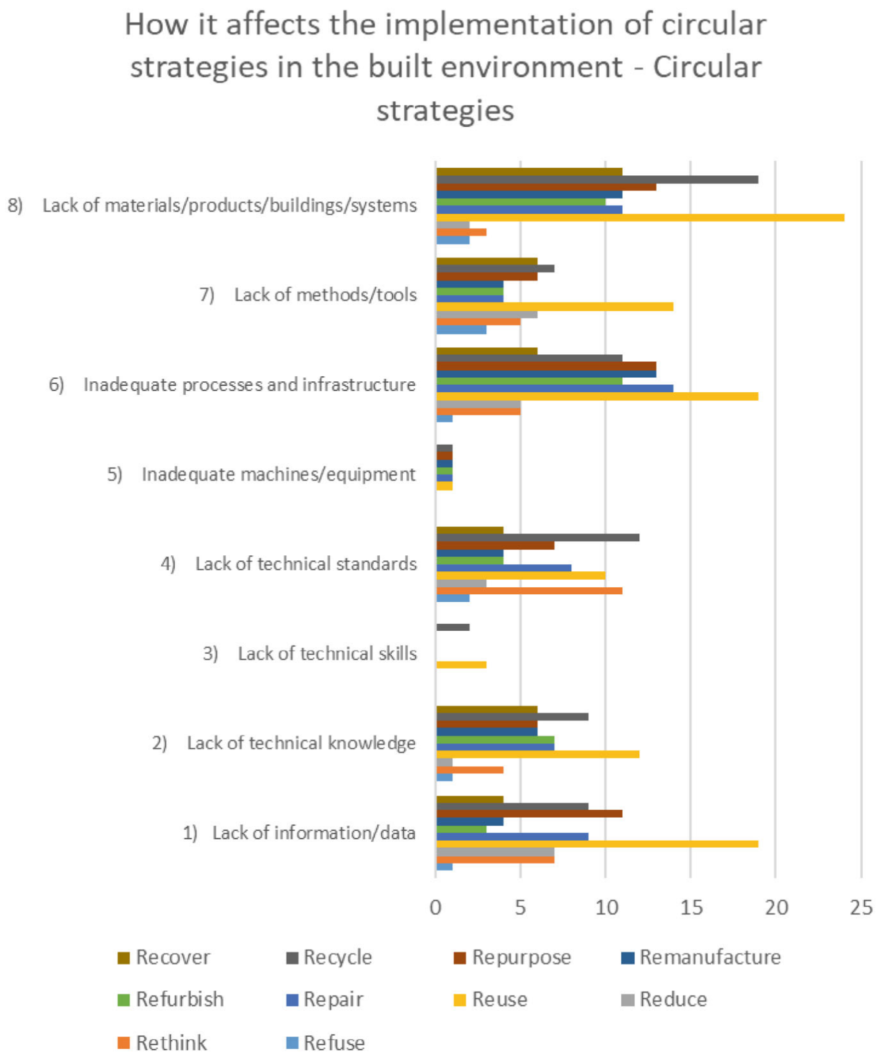

Fig. 1.18 Circular strategies at the material level affected by the technical barriers

Category 1: Lack of Information/Data

A list of identified barriers in the lack of information/data category, and their subcategory relevance, is shown in Table 1.30.

A quantitative analysis of reported barriers on Lack of information/data revealed a critical subcategory: Data Availability, Accessibility, and Accuracy. This subcategory, encompassing issues like unreliable data, lack of Material Passport updates, and

Table 1.30 Quantitative analysis of reported barriers to the lack of information/data at the material level

Lack of information/data	Quantitative analysis
Data availability, accessibility and accuracy	*33*
Lack of reliable data	
Lack of data, e.g. on impacts	
Lack of data about the availability, quality, and quantity of salvaged building components	
Lack of information update on material passports during the lifespan	
Lack of detailed data on construction materials—information gap	
Lack of quality and availability of data (privacy, trust, ownership, access)	
Traceability and certification	*14*
Lack of information on the quality of reused materials	
Certifications and responsibility for reused products	
Lack of traceability of component characteristics and performance in the value chain	
Lack of information on the mechanical properties of the recovered materials	
Lacking certification/traceability	
Lack of knowledge and awareness	*11*
Lack of knowledge and engagement throughout the value chain	
Awareness of recycled materials	
Lack of interest and awareness	
Inadequate awareness, understanding, and insight into the CE in C&D waste management	
Lack of understanding of the circular loops of MCPs	
Sustainability	*3*
Lack of monitoring the benefits of circular development	
Information on the durability issues of reused products	

limited information on salvaged components, emerged as the most frequent information deficiency at the material level, appearing 33 times across the reviewed literature [6, 7, 19, 34, 49, 90, 97, 104–123].

The next mostly mentioned technical barrier subcategory in *Lack of information/data* category was *Traceability and Certification*, which occurred 14 times across the reviewed literature [10, 49, 104, 117, 118, 122, 124–128]. This subcategory involves challenges and technical barriers at the material level, such as lacking certification/traceability, certifications and responsibility of reused products, lack of traceability of components' characteristics and performance in the value chain or, lack of information on the quality of reused materials.

A similar occurrence to *Traceability and Certification* was reported for *Lack of Knowledge and Awareness* for the material level. This subcategory appeared 11 times across the reviewed literature [10, 48, 62, 81, 115, 117, 120, 129–131] and was related to challenges and barriers such as lack of interest and awareness, inadequate awareness, understanding and insight into CE in C&D waste management, awareness of recycled materials or Low environmental awareness.

The *Sustainability* subcategory, encompassing issues like a lack of monitoring benefits of circular development or information regarding durability issues of reused products, occurred three times across the reviewed literature [34, 132].

It is worth mentioning that, sometimes, different challenges and issues belonging to the same subcategory were reported within the same literature reference.

Category 2: Lack of Technical Knowledge

A list of identified barriers in the lack of technical knowledge category, and their sub-category relevance, is shown in Table 1.31.

Through a deep bibliographical review, a total of 36 barriers were reported to be directly associated with the lack of technical knowledge. Some of them (six) expressed a general lack of knowledge on circularity, sustainability and green building issues with regard to the material level [6, 48, 50, 97, 107, 108, 110, 133–137]. Within the same framework, some indicated a lack on knowledge throughout the supply and value chain [34, 81, 113, 120] and others indicated in more detail the stage suffering more from the lack of technical knowledge. More specifically, many denoted the design stage [10, 19, 97, 120, 123, 124], but most of them concerned the end of life processes, i.e. demolition, disassembly, reuse and recycle [6, 48, 50, 97, 107, 108, 110, 133–137]. The lack of technical knowledge on the materials properties, tracking and reuse potential was also ranked among the most important barriers [19, 104, 106, 114, 116, 121, 129, 138].

Category 3: Lack of Technical Skills

A list of identified barriers in the lack of technical skills category, and their sub-category relevance, is shown in Table 1.32.

Through a deep bibliographical review, a total of 19 barriers were identified as a lack of technical skills. Most of them (nine) were not thoroughly explained and expressed a general lack of skills or competence, associated with CE, green building risk factors, or decision making [49, 50, 81, 104, 106, 108, 109, 114, 129]. In more detailed indications, some specified lack technical skills throughout the supply chain [106, 113, 114, 121], at the design [34, 120, 121] and at the end-of-life processes, i.e. demolition, deconstruction and reuse [97, 137].

Table 1.31 Quantitative analysis of reported barriers on lack of technical knowledge at the material level

Lack of technical knowledge	Quantitative analysis
Lack of awareness—general knowledge—familiarity with CE, green building or sustainability concepts	*6*
Lack of investigation of the relationship between GB risks and project outcomes	
Lack of exploration in cross-country or developing countries	
Lack of expertise and knowledge in circularity in construction	
Lack of knowledge: circular management and building, environmental impact and certification	
Unaware of the opportunities available to save carbon through the reuse approach	
Lack of awareness, interest, knowledge and engagement. Difficulties in delivering CE projects without support or a business case	
Lack of knowledge of the value and supply chain	*4*
Lack of knowledge and engagement throughout the value chain	
Lack of proper training and development programs for the members of supply chain	
Lack of skills and expertise (amongst public infrastructure and service providers)	
Lack of knowledge and engagement throughout the value chain	
Lack of knowledge on the design stage	*6*
Design team buy-in	
Lack of adequate information in building design	
Lack of effective green building design development	
Design-related issues: matching the design of the new building with the strength of the recovered elements	
Insufficient use and development of CE-focused design and collaboration tools, information, and metrics	
Limited experience with circular design within the built environment	
Lack of knowledge on the materials' properties	*8*
Materials knowledge	
Knowledge on adopting material tracking systems	
Accurate information regarding materials/tracking in SC towards recycling is not available	
Materials knowledge	
Difficulties in understanding and developing EPDs	
The perception and reaction to the geopolymer cement representing a green solution to the construction industry remains uncertain	
Lack of monitoring quality conditions	

(continued)

Table 1.31 (continued)

Lack of technical knowledge	Quantitative analysis
Limited or unknown information on the technical performance of the current asset, e.g. loading capacity of the structural frame, energy performance of the façade	
Lack of knowledge on the end-of-life procedures	*12*
Knowledge on reuse of construction materials	
Knowledge on reuse of construction materials	
Needing policymakers to enforce the use of recycled/salvaged materials to a certain extent	
Lack of knowledge and an underdeveloped market reduces the capability of CDW reduction in a CE system	
Knowledge of reclaimed materials: quantities of material recovered, identifying reclaimed components, material data availability; material data update	
Negative experiences of designers with the usage of most of the remanufactured products	
Lack of disassembly guides	
Confusion between reuse and recycling	
Impact of upfront demolition must not be ignored (impact on LCA of new project to be discussed)	
Lack of technical solutions for effective disassembly and reconnecting methods of the reused wood components	
Unknown of the most influential criteria for the reuse strategy	
Lack of knowledge on how to reuse/recycle treated wood	

Category 4: Lack of Technical Standards

The quantitative analysis of reported barriers on *Lack of Technical Standards* revealed that the most critical subcategory is the *Lack of Consistent Regulatory Framework*, appearing 25 times across the literature [10, 49, 50, 62, 81, 104, 105, 108, 109, 115, 119, 121, 122, 124, 129, 134, 135, 137, 139–141]. This subcategory involves a lack of new regulations on circularity but also contradictions between existing regulations, a lack of flexibility and a lack of obligatory use of recycled materials on building projects.

The next mostly mentioned technical barrier subcategory was Lack of *Standardisation*, which occurred 13 times across the reviewed literature [10, 49, 104, 117, 118, 122, 124–128]. This subcategory mainly involves challenges of lacking standards on the quality of the reused materials (Table 1.33).

The subcategory of *Complexity in Certification Processes* appeared six times across the reviewed literature [90, 107, 110, 114, 133, 142] and was related to challenges and barriers, such as complex certification and testing processes for recovered materials and guidelines on the number of reuse cycles.

Table 1.32 Quantitative analysis of reported barriers on lack of technical skills at the material level

Lack of technical skills	Quantitative analysis
On a general level	*9*
Lack of skills	
Inconsistency in identifying GB risk factors	
Technical competence of the users	
Not ready for radical changes to adopt CE principles	
To make an accurate decision	
Lack of skills by employees in CE	
On the supply chain	*4*
Adopting material tracking systems	
Lack of CE skills by employees in the supply chain	
Make the right decision in SC (supply chain) to implement CE in the most efficient way	
Difficulties finding someone to take the products and materials on	
At the design process	*3*
Lack of circular thinking in the design process	
Planning constraints	
Difficulty of measuring circularity (for the Netherlands)	
At the end of life processes	*3*
Complexities associated with reusing large-sized, complex-shaped, and compositionally diverse composite products	
Lack of awareness of the demolition crews (for steel reuse in Canada)	
Damage during deconstruction (for steel reuse in Canada)	

Finally, the *End-of-Life Policies* subcategory, encompassing issues like a consistent framework on the processes at the end-of-life of a material so as to be reused, occurred two times across the reviewed literature [6, 128].

Category 5: Inadequate Machines/Equipment

A list of identified barriers in the inadequate machines/equipment category, and their sub-category relevance, is shown in Table 1.34.

Compared to other barriers on the material level, inadequate machines and equipment are rarely mentioned as barriers in the analysed literature. In total, this barrier is cited 10 times (in [50, 104, 113, 120, 129, 130, 137, 143]). Nevertheless, the technological level has its importance: the lack of technologies, technological platforms, recycling processes as well as the slow technological evolution are relevant

Table 1.33 Quantitative analysis of reported barriers on the *lack of technical standards* at the material level

Lack of technical standards	Quantitative analysis
Lack of a consistent regulatory framework	*25*
Lack of regulations/legislations	
Lack of flexibility in building codes and regulations	
Contradictions between regulations	
Lack of mandatory reuse regulations for recycled products	
Inconsistent application of existing regulations	
Lack of legislation regarding the properties of the reclaimed materials	
Lack of standardisation	*13*
Material quality specifications for reuse	
Lack of standards for reused and recycled building products	
Complexity of certification processes	*6*
Complex certification and testing processes for recovered materials	
Lack of easy-to-adapt certification schemes for various materials	
Guidelines for testing secondary materials and the number of reuse cycles	
Lack of end-of-life policies	*2*
Ambiguous or inadequate end-of-life policies	
End-of-life policies only for materials considered waste	

Table 1.34 Quantitative analysis of reported barriers on inadequate machines/equipment at the material level

Inadequate machines/equipment	Quantitative analysis
Technological level	*10*
Lack of technologies/inadequate technologies	
Lack of technological platform	
Lack of technological evolution	
Lack of recycling process	

barriers for the implementation of CE in the built environment according to the identified literature. Especially Morel et al. [62] and Mahpour [129] identified inadequate machines and equipment as a barrier.

Category 6: Inadequate Processes and Infrastructure

A list of identified barriers in the lack of the inadequate processes and infrastructures category, and their sub-category relevance, is shown in Table 1.35.

Table 1.35 Quantitative analysis of reported barriers on inadequate processes and infrastructures at the material level

Inadequate processes and infrastructure	Quantitative analysis
Inadequate processes and infrastructure of material recovery	*10*
Material recoverability (selection, harmfulness, lifespan)	
Treatment technologies for secondary materials (concrete, steel, wood, glass, e.g.)	
Uncertainties/Unmet quality in recycling processes	
Inadequate infrastructure of the secondary raw material industry	
The lack of processing and retail hubs for salvaged lumbers	
Needed a fragile system and specific skill sets to deconstruct of the system	
Lack of sorting/insufficient storage/site constraints	*11*
Lack of sorting and storage spaces	
Storage of recovered materials	
Location of material recovery facilities	
Inappropriate waste collection services and recycling infrastructure	
On-site sorting to ensure that the product stream is relatively pure for reuse of wood	
CE-focused design	*3*
Insufficient use or development of designs based on CE principles	
Inefficient methods reduce the profitability of circular business cases	
Complexity of the design process	
Lack of facilities/additional complexity	*4*
Lack of facilities for reclaimed materials	
Inadequate processes of composite construction/joining technique	
Barriers for reuse/recycling of drywall are the lack of gypsum recycling facilities	
Market	*8*
Lack of structured market (bank materials, lack of platform, storage)	
Lack of reuse markets/supply chains	
Supply and demand matching	
Challenges of take-back from other companies	
Underdeveloped market for salvaged components/market for prefabrication is heavily dependent on imports	
Having no clear entry point into the market for fine recycled aggregates and recycled fines	
Lack of info/technology	*6*
Lack of information about the existing structure and materials	
Material tracking system or passport	
Inadequate CE infrastructure to support CE management	

(continued)

Table 1.35 (continued)

Inadequate processes and infrastructure	Quantitative analysis
Lack of infrastructure for implementing circularity in construction	
Lack of institutional infrastructure based on the linear economy model	
Sustainability	*3*
Lack of demonstrating a real impact on reducing carbon emissions	
Lack of principles towards construction design sustainability	
Content of hazardous substances in existing building products	
Disassembly	*2*
Existing built environment are not built for disassembly	
Difficulty in dismantling wood	
Cost	*4*
High cost needed for the collection and storage of reused elements	
Increased cost of recycling and recovering materials	
The expense of hiring a structural engineer to certify the products	

On the material level, the barrier of inadequate processes and infrastructure was identified 51 times through the bibliographical review [6, 10, 49, 50, 81, 97, 104, 106–108, 113, 114, 117, 121, 124, 125, 129, 131, 133–135, 137–139, 143–147]. Main categories within this barrier are inadequate processes and infrastructure of material recovery (10 mentions) [50, 104, 114, 121, 131, 133, 134, 143], the lack of sorting and insufficient storage (site constraints) with 11 citations [10, 97, 104, 124, 129, 135, 137, 139, 144], and market related issues with eight mentions [6, 49, 50, 104, 113, 124, 145, 146]. Market-related issues consist mainly of a lack of reuse markets, supply and demand matching and in general, a lack of developed markets for salvaged building materials. The identified references also reveal a lack of facilities and technologies [10, 49, 50, 97, 106, 117, 124, 137], CE focused design issues [49, 81, 107] as well as roadblocks related to sustainability [108, 125, 147], disassembly [49, 137] and cost [97, 131, 137, 138].

Category 7: Lack of Methods/Tools

A list of identified barriers in the lack of methods/tools category, and their sub-category relevance, is shown in Table 1.36.

Barriers due to the lack of methods and tools are reported 56 times in the identified literature; hence, it is a relevant barrier to the implementation of CE. The quantitative analysis has shown that it is most often about the lack of tools, design tools and metrics [6, 10, 19, 34, 49, 90, 97, 104, 105, 109, 114, 115, 120, 121, 125, 129, 132, 140, 148, 149]. This goes hand in hand with difficulties in adapting CE principles to already existing tools and methods. Other relevant identified categories are the lack

Table 1.36 Quantitative analysis of reported barriers to lack of methods and tools at the material level

Lack of method/tool	Quantitative analysis
Awareness of material recovery by stakeholders/producers/company holders	*6*
Lack of bandwidth compounded by no coherent vision	
Low quantity of secondary construction materials	
Applications of reuse in new construction applications are yet to be explored	
No coordination between all stakeholders in the value chain	
Lack of tool/design or adopting existing method/tool	*23*
Difficulties of the programming and design phases of adaptation for construction material	
Difficulties of changing the culture away from traditional design towards adopting flexibility	
Lack of procedures to monitor the progress toward CE transition	
Lack design tools for reusing timber or for green design	
Limited studies adopted the latest methods to assess risks	
Lack of technical assessment methods of recycled building materials	
Lack of detailed methodology for the selection of materials according to the CE principles	
Lack of digital/sensor methodologies	
Limited or lack of CE metrics/tools/design	
Lack of performance analysis and design tools for evaluating end-of-life scenarios of buildings	
Certification/Standardization/Classification	*8*
Lack of Certification	
Lack of standardisation/classification	
Lack of tools for identifying salvaged materials	
Complexity of the recycling processes	*4*
Complexity of materials and building composition for recycling processes	
Lack of project specification	
Time constraints	
Longer required time for the deconstruction of the building materials	
Testing methods	1
Required destructive testing	
Building information modelling	2
Insufficient data management (data unavailability in accessibility; data compliance as—as-built-accuracy; data requirements; data exchange and interoperability issues)	
Difficulty in modelling of continuous loops of materials	

(continued)

Table 1.36 (continued)

Lack of method/tool	Quantitative analysis
Disassembly	*5*
Complex disassembly shorts service life	
Technical challenges regarding material recovery	
Inaccessible joints	
Lack of standards for Design for Disassembly (DfD) tools	
The high operational costs	
Environmental impact	*2*
Overemphasizing recycling and non-environment friendly methods	
Governance, regulatory frameworks and political landscape	*1*
Inadequate current strategies and frameworks (cradle to cradle, industrial ecology) overlooking the underlying social, political, economic and technical aspects	

of awareness for material recovery by all the stakeholders [81, 97, 110, 120, 133, 149] and a lack of certification/standardisation and classification [6, 7, 10, 19, 104]. Furthermore, time constraints [124, 131, 136, 145] and the complex implementation of CE, sometimes linked to high cost and hurdles to recycling [7, 19, 124, 139] are cited as barriers in the identified literature. Cited rather rarely are the lack of technical knowledge and skills [81], lack of testing methods [124], insufficient implementation of BIM [7, 48], high cost [50], issues related to the disassembly [120, 134], environmental impacts [129] and regulatory frameworks [117].

Category 8: Lack of Materials/Products/Building Systems

A list of identified barriers in the lack of materials/products/building systems category, and their sub-category relevance, is shown in Table 1.37.

The quantitative analysis of reported barriers on *Lack of materials/products/buildings/systems* revealed that the subcategory *Lack of performance and quality assurance for reused/recovered materials* is the most frequent barrier reported across literature, for the material level. This subcategory, involves issues like low volume and inconsistent quality of the recovered materials, durability issues of reused products, use of polluted or low recoverability materials, low performance and/or the absence of documentation on performance of the recovered materials, hazardous or contaminated materials etc., appearing 34 times across the reviewed literature [6, 7, 10, 49, 50, 104, 105, 108, 111, 114, 124, 126, 127, 133, 134, 136, 137, 141, 148, 150].

The next three technical barrier subcategories in the Lack *of materials/products/buildings/systems* category recorded a similar number of mentions across the reviewed literature. *Lack of systems*, which occurred 14 times across the reviewed

Table 1.37 Subcategories of barriers under Category 8 at the material level

Lack of materials/products/buildings/systems	Quantitative analysis
Lack of performance and quality assurance for reused/recovered materials	*34*
Quality of materials at end-of-life (EOL)	
Use of polluted or low recoverability materials	
Ability to deliver high-quality remanufactured products	
Contamination—coatings with (now) banned chemicals	
Durability issues of reused products	
Low performance and/or the absence of documentation on performance	
Reusable goods with a good lifetime: at the time of the re-use, they are out of date and standard	
Maintaining the quality of products made from recovered materials	
Low volume and inconsistent quality	
Lacking quality assurance	
Lack of systems	*14*
Most data storage and transfer happen through external documentation	
QR codes are not a sufficient system for embedded or encapsulated materials, such as cast-in-place concrete or insulation behind an exterior wall	
Taking back products for reuse becomes a tough task for service providers due to the legal problems of retaining the sold product	
No standardization of diversity	
No space for storage	
Lack of a producer-based responsibility system in the production of construction materials	
Complexity of material recovery	*13*
Technical challenges related to material recovery	
Complexity of materials and building composition (several layers and modifications during its lifespan)	
Difficulty in recovering materials, hazardous components	
Complexity and the irreversible nature of structural connections	
Difficult to manage the dismantling and reusing, or recycling	
Lack of available materials/products for reuse	*12*
Supply chain dynamics and availability of reused materials	
Limited availability of reuse products	
Limited stock availability	
Other limitations of materials/products/buildings/systems	*16*
Low level of application of recycled products	
Using finite recyclable construction materials	
Increasing material diversity and the number of composite materials and structures	

(continued)

Table 1.37 (continued)

Lack of materials/products/buildings/systems	Quantitative analysis
Demolition projects range depending on the age of structures	
Recycled product may have unknown strengths and quality properties	
Long product life cycle	
Building component lifespan	
Design constraint for reclaimed material use	
Determination of future use of secondary materials	
The trend of using inexpensive and non-durable materials/components in construction	

literature [81, 105, 106, 114, 115, 120, 121, 129, 134, 139, 150], involved technical barriers and challenges, such as lack of producer-based responsibility system in production of construction materials, no space for storage, lack of clearly defined national goals, targets, and visions to move toward CE, no standardisation of diversity or issues like the fact that most data storage and transfer happen through external documentation.

Similar occurrence to the *Lack of systems* was reported for the *Complexity of material recovery* and for the *Lack of available materials/products for reuse,* at the material level. *Complexity of material recovery* appeared 13 times across the reviewed literature [10, 19, 48, 62, 110, 114, 120, 125, 131, 136, 137, 148] and was related to challenges such as difficulty to recover materials, building complexity/building composition—several layers, delay in deconstruction due to the complexity and irreversible nature of structural connections or difficulty to manage the dismantling and reusing or recycling. *Lack of available materials/products for reuse* appeared 12 times across the reviewed literature [6, 97, 104, 114, 120, 124, 131, 145, 150] and was related to challenges, such as limited availability of reuse products, supply chain dynamics and availability of reused materials, certain materials not widely available in every region of the world, inadequate flexibility on section sizes of reuse steel, or the location/availability/quantity of the recovered materials.

Barriers that could not be grouped in the above subcategories of the *Lack of materials/products/ buildings/systems* category were assigned to the *Other limitations of materials/products/buildings/systems* subcategory. This subcategory encloses barriers like low level of application of recycled products, usage of finitely recyclable construction materials, increasing material diversity and number of composite materials and structures, demolition projects ranges depending on the age of structures, long product life cycle, building component lifespan, design constraints for reclaimed material use and the trend of using inexpensive and non-durable materials/ components in construction. *Other limitations of materials/products/buildings/ systems* occurred 16 times across the reviewed literature [6, 48, 50, 97, 105, 111, 114, 115, 126, 127, 129, 133, 137, 141, 149].

As recorded in all previous technical barrier categories, in some cases, different challenges and issues belonging to the same subcategory were reported within the same literature reference.

1.3.3.3 Quantitative Data Analysis of Each Category

A summary of the collected quantitative data for each category is shown in Table 1.38.

Category 1: Lack of Information/Data

Where it happens. Regarding the building layers, the studies addressing the lack of information/data barriers at the material level reported that these barriers affect mostly the structure [6, 7, 19, 34, 90, 97, 109, 111, 112, 115–119, 122, 123, 125, 128, 132, 141] and the skin [6, 7, 19, 34, 90, 97, 106, 111, 112, 116, 118, 119, 122, 128, 132, 141] of a building, while at the other end of the spectrum is the space plan of a project mentioned once [112] and the site (not mentioned at all), which are the least affected by barriers regarding lack of information/data.

When it happens. Lack of information/data barriers at the material level has been evaluated as affecting mostly the Design [6, 7, 19, 34, 49, 90, 97, 112, 116, 122, 123, 125, 132] and End-of-life phases [6, 90, 97, 109, 111, 112, 114, 116–118, 118, 122, 125, 126, 128] within the building life cycle phases, followed by (Dismantling and) Construction [6, 97, 109, 112, 114, 115, 117, 119, 125, 128, 132], Strategic Definition and Briefing of the project [49, 90, 97, 108, 112, 118, 122, 123, 129] and Use and Refurbishment building phase [97, 112, 114, 117, 118, 120, 129, 132].

Who is responsible for/involved in. Considering the stakeholders involved in/responsible for the technical barriers, project professionals [6, 7, 19, 34, 49, 50, 90, 109, 111–113, 118–123, 119–123, 125] and suppliers [6, 7, 34, 49, 50, 90, 111–113, 113, 116, 120, 122, 123, 126, 128, 129, 132] are considered mostly responsible for the lack of information/data barrier at the material level. The following stakeholders are Clients [50, 112, 113, 120, 121, 125, 129, 131, 136, 141], who influence the lack of information/data barrier at the material level. The rest of the stakeholders seem to represent minor interest in the literature regarding the influence on lack of information/data barrier at the material level: Government [19, 50, 118, 120, 132, 141], Others—not included in other categories [110, 126, 128, 141] and Public [50, 120, 141].

How it affects the implementation of circular strategies in the built environment. The reviewed literature emphasizes that the lack of information/data barrier significantly impacts circular strategies in the built environment at the material level. This includes reuse [6, 10, 49, 90, 97, 108, 109, 111, 112, 117–119, 122, 123, 125, 132, 141], repurpose [49, 90, 97, 111, 112, 117–119, 122, 123, 132] and repair [6, 97, 111, 117–119, 121, 122, 131]. However, the impact extends, affecting also strategies

Table 1.38 Quantitative data collection for the material level involving technical barrier categories

What is the barrier category	Where it happens						When it happens					
Technical barrier category	Building layer (a)						Building life cycle phase (b)					
	1	2	3	4	5	6	1	2	3	4	5	6
Lack of information/data	–	21	18	2	1	9	9	15	5	11	8	15
Lack of technical knowledge	1	11	10	1	–	6	14	19	10	13	11	9
Lack of technical skills	1	6	4	–	–	5	3	5	3	5	3	7
Lack of technical standards	–	18	13	2	1	2	9	14	8	5	6	11
Inadequate machine/equipment		1	1	–	–	–	–	–	1	3	2	2
Inadequate processes and infrastructure	3	20	13	2	1	4	5	12	9	11	7	16
Lack of methods/tools	2	16	8	5	3	4	11	20	7	16	8	12
Lack of materials/products/systems	–	22	12	1	–	6	5	14	9	16	11	21

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of information/ data	10	24	19	3	6	4	1	7	7	19	9	3	4	11	9	4
Lack of technical knowledge	8	20	12	3	2	1	1	4	1	12	7	7	6	6	9	6
Lack of technical skills	5	8	4	–	1	–	–	–	–	3	–	–	–	–	2	–
Lack of technical standards	3	11	8	4	34	–	2	11	3	10	8	4	4	7	12	4
Inadequate machine/ equipment	–	2	1	–	–	–	–	–	–	–	1	1	1	1	1	–
Inadequate processes and infrastructure	2	19	10	–	2	2	1	5	5	19	14	12	13	13	11	6

(continued)

Table 1.38 (continued)

What is the barrier category	Who is responsible for/ involved in						How it affects the implementation of circular strategies in the built environment									
Technical barrier category	Stakeholders (c)						Circular strategies (e)									
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
Lack of methods/tools	7	16	8	3	7	4	3	5	6	14	4	4	4	6	7	6
Lack of materials/ products/ systems	4	19	16	5	5	3	2	3	2	24	11	10	11	13	19	11

(a) Building layers [17]: (1) site; (2) structure; (3) skin; (4) services; (5) space plan; (6) stuff; (7) system (district)
(b) Building life cycle phases (adapted from Council et al. [15]; Royal Institute of British Architects [18]): (1) Strategic Definition and Briefing; (2) Design; (3) Manufacture; (4) (Dismantling and) Construction; (5) Use and Refurbishment; (6) End-of-life
(c) Stakeholders [19]: (1) Clients; (2) Project professionals; (3) Suppliers; (4) Public; (5) Government; (6) Others
(d) Circular Strategies [20]: (1) Refuse; (2) Rethink; (3) Reduce; (4) Reuse; (5) Repair; (6) Refurbish; (7) Remanufacture; (8) Repurpose; (9) Recycle; (10) Recover

like reducing [49, 90, 109, 112, 116, 126, 132], rethinking [7, 19, 34, 112, 116, 118, 123] recover [49, 112, 117, 132] and remanufacture [49, 97, 111, 117].

Category 2: Lack of Technical Knowledge

Where it happens. Concerning the building layers, the studies highlighting the lack of technical knowledge at the material level have found that these barriers primarily impact the structure [6, 10, 19, 97, 116, 123, 133, 135, 137, 138, 141] and the skin [6, 19, 97, 106, 116, 123, 135, 137, 138, 141], as well as the "stuff" of a building [6, 106, 114, 116, 129, 135]. The layers that were barely reported in the studied bibliography referred to the site [135], the services [19] and the space plan.

When it happens. Lack of technical knowledge barriers at the material level have been evaluated as affecting every phase of the building life cycle. As the most prevalent phase the Design was emerged [6, 10, 19, 34, 48–50, 50, 81, 90, 97, 114, 116, 120, 133–135, 134, 135], followed by the Strategic Definition and Briefing [10, 19, 48, 49, 81, 97, 107, 108, 114, 116, 133–135, 135], (Dismantling and) Construction [6, 34, 48–50, 50, 81, 105, 114, 133–135, 134] and Use and Refurbishment [34, 48, 49, 81, 109, 110, 114, 133–135, 135]. The phases of Manufacture [48–50, 50, 81, 114, 133–135, 134] and End of life were also widely addressed [6, 48, 49, 81, 109, 110, 114, 134, 137].

Who is responsible for/involved in. Considering the stakeholders, project professionals [6, 10, 19, 34, 48, 49, 81, 97, 109, 110, 113, 114, 116, 120, 123, 133, 135, 137, 138, 141] and suppliers [6, 19, 48, 81, 108–110, 110, 113, 114, 120, 123] are primarily held responsible for the lack of technical knowledge barrier at the material level, followed by clients [6, 48, 81, 113, 114, 133, 135, 141]. Other stakeholders appear to be of minor interest in literature concerning their influence on this issue, including the Public [109, 120, 141], government [19, 141] and others [141].

How it affects the implementation of circular strategies in the built environment. The reviewed literature emphasises that the lack of technical knowledge barrier significantly impacts circular strategies in the built environment at the material level. This includes reuse [10, 48, 97, 107, 121, 123, 124, 133, 136–138, 138], recycle [6, 10, 48, 108, 121, 123, 135–137], repair [6, 10, 48, 121, 123, 136, 138] and Refurbish [10, 48, 121, 123, 135, 136, 138]. The lack of technical knowledge also affects Remanufacture [10, 48, 121, 123, 135, 136], Repurpose [10, 48, 121, 123, 135, 136] and Recover [10, 48, 121, 123, 135, 136]. The strategies Refuse and Reduce were the least indicated, in Refs. [120] and [10], respectively.

Category 3: Lack of Technical Skills

Where it happens. Concerning the building layers, the studies highlight the lack of technical skills at the structure [49, 97, 108, 109, 137] the skin [97, 106, 137], as well as the "stuff" of a building [50, 106, 120, 121, 129]. The layers that were barely reported in the studied bibliography referred to the site, the services and the space plan.

When it happens. At the material level, the Lack of technical skills has been identified as a barrier affecting each phase of the building life cycle. End of life has been referenced the most [49, 81, 97, 108, 114, 137], followed by Design [34, 49, 81, 108, 114] and Dismantling and Construction [81, 97, 108, 114]. The phases of Strategic definition [81, 108, 114], Manufacture [81, 108, 114], and Use-Refurbishment were also addressed [81, 108, 114].

Who is responsible for/involved in. Considering the stakeholders, project professionals [34, 81, 108, 113, 114, 137, 140], clients [50, 81, 104, 108, 114] and suppliers [81, 108, 114] are identified as mostly associated with the lack of technical skills barrier at the material level.

How it affects the implementation of circular strategies in the built environment. The reviewed literature does not emphasise on the impact that the lack of technical skills barrier has on the implementation of circular strategies in the built environment at the material level. The only reported strategies are reuse [49, 137] and recycle [137].

Category 4: Lack of Technical Standards

Where it happens. Regarding the building layers, the studies addressing the lack of technical standards barrier at the material level reported that it mostly affects the structure (18 refs) [6, 7, 97, 116, 118, 119, 122, 128, 133, 135, 137, 138, 140–142, 146, 147] and the skin (13 refs) of a building [6, 97, 116, 118, 119, 122, 128, 135, 137, 138, 140, 141]. On the other hand, very limited studies mentioned that the barrier affects the services (two refs) ([6, 140]), space plan (one ref) [140] and staff (2 refs) ([6, 34]). The site layer is not related to this barrier.

When it happens. The lack of technical standards barrier at the material level has been found to be critical at the Design (14 refs) [81, 97, 107, 116, 118, 119, 124, 128, 135, 138, 140, 141] and End-of-life phases within the building life cycle (11 refs) [6, 81, 97, 107, 118, 128, 133, 135, 137, 139, 140]. Nine studies have also evaluated the lack of technical standards as an important barrier at the Strategic Definition and Briefing Phase [81, 97, 118, 119, 128, 135, 138, 140, 141], followed by Manufacture (eight refs) [81, 107, 135, 137, 140, 142, 146, 147] Use and Refurbishment (six refs) [81, 107, 108, 135, 139, 140] and Dismantling and Construction (five refs) [81, 107, 135, 137, 140].

Who is responsible for/involved in. In terms of the stakeholders involved, the Government is considered the most responsible one for the lack of technical standards barrier at the material level (34 refs) [6, 7, 50, 81, 97, 104, 105, 107–110, 114–116, 118–121, 116, 118, 119, 134–139, 128, 129, 131, 134]. The Project Professionals (11 refs) [6, 7, 10, 81, 97, 116, 118, 133, 135, 140, 146] are also considered responsible or highly involved in the barrier. The rest of the stakeholders seem to have lower influence on the lack of technical data barrier at the material level: Suppliers (eight refs), [10, 81, 90, 107, 140, 142, 146, 147], Public (four refs), [97, 107, 128, 141], Clients (three refs), [10, 107, 140], Others—not included in other categories (0 refs).

How it affects the implementation of circular strategies in the built environment. The reviewed literature emphasises that the lack of technical standards barrier has a considerable impact on implementing circular strategies in the built environment at the material level. 12 refs mentioned that it affects the Recycle strategy [6, 10, 90, 118, 119, 122, 128, 133, 135, 138, 142, 146], followed by Rethink (11 refs), [7, 10, 116, 118, 119, 135, 138, 140, 142, 146, 147], Reuse (10 refs), [6, 10, 90, 97, 118, 122, 124, 128, 137, 140] and Repair (eight refs), [6, 10, 49, 90, 122, 128, 133, 140]. The circular strategies Refurbish [6, 10, 128, 140], Remanufacture [6, 10, 128, 140], and Recover [10, 90, 122, 128] were mentioned in four refs each, as influenced by the lack of technical standards barrier.

A large number of studies examining technical barriers at the material level, suggested that the lack of a consistent regulatory framework [49, 50, 81, 104, 105, 109, 115, 116, 134] along with inadequate standardisation procedures for recovered materials [6, 97, 114, 118, 120, 131, 136] play a key role in the application of CE in construction.

Category 5: Inadequate Machines/Equipment

Where it happens. The examined literature that deals with the barrier of inadequate machines and equipment rarely identifies relevant building layers. Structure and skin are identified once each [137]. The site, services, space plan and stuff are not related to this barrier.

When it happens. No specific life cycle phase stands out. The barrier of Inadequate machines and equipment on the material level is discussed in the following phases: Manufacture, Dismantling and Construction, Use and Refurbishment, End-of-life [113, 130, 137, 143]. This barrier does not occur in the life cycle stages of strategic definition and design.

Who is responsible for/involved in. Project professionals and suppliers are identified as responsible for the lack of adequate machines and equipment [120, 129, 137]. Clients, the public, governments and others are not met in the bibliographical review.

How it affects the implementation of circular strategies in the built environment. No clear conclusion can be drawn by analysing the identified literature. The barrier, Inadequate machines and equipment, doesn't seem to affect one CE strategy, particularly at a wide extent. The lack of adequate machines and equipment affects the following CE strategies, while each of them is addressed only once: Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle [137]. The barrier is not influencing the refuse, rethinking, reducing and recover strategies.

Category 6: Inadequate Processes and Infrastructure

Where it happens. On a material level, the barrier of inadequate processes and infrastructure mainly takes place in the structure of a building (20 refs) followed closely by the skin (13 refs) [6, 10, 49, 97, 106, 117, 121, 124, 125, 131, 133–138, 143, 145–147]. The other building layers, namely the site, services, space plan and stuff, are rarely addressed.

When it happens. The bibliographical review shows that the lack of processes and infrastructure has an impact mainly on the end-of-life of a building [6, 10, 49, 50, 108, 113, 124, 125, 135, 137, 138, 143, 144, 146, 147]. Besides, the design as well as the construction and dismantling stage, are life cycle phases that often deal with the lack of adequate processes and infrastructure. Furthermore, the strategic definition, manufacture and the use and refurbishment phase are mentioned as relevant life cycle phases in the identified literature (with 5, 9 and 7 citations respectively).

Who is responsible for/involved in. Mostly responsible for/involved in the lack of processes and infrastructure are project professionals and suppliers, with 19 and 10 citations respectively [6, 10, 49, 50, 97, 106, 108, 113, 124, 125, 135, 137, 138, 143, 144, 146, 147]. However, the clients, the government and other stakeholders are also cited as responsible. The quantitative analysis did not reveal that the public is involved or responsible for this particular barrier.

How it affects the implementation of circular strategies in the built environment. Reuse is the most affected CE strategy when analysing the lack of adequate processes and infrastructures. It is cited 19 times in total in the following references [10, 49, 97, 117, 121, 124, 125, 131, 133, 135, 137, 138, 143, 145, 147]. Besides the reuse strategy, it could be identified that the Repair, Refurbish, Remanufacture, Repurpose and Recycle strategies are severely impacted.

Category 7: Lack of Methods/Tools

Where it happens. In line with barrier six, the structure is the building layer that is the most impacted (cited 16 times) by the lack of methods and tools, followed by the skin layer (cited eight times). The following references discuss structure and skin as relevant building layers: [6, 10, 19, 90, 109, 110, 112, 124, 125, 132–134, 139, 140, 148, 149]. Some references cite the site, services, space plan and stuff as impacted by the lack of methods and tools, but the occurrence per building is quite low, which shows a limited impact from the lack of methods and tools.

When it happens. According to the identified literature, the lack of methods and tools mainly occurs in the design (20 citations) and dismantling and construction (16 citations) life cycle stages. Those are referenced 36 times in: [7, 34, 48, 49, 81, 90, 97, 109, 112, 114, 115, 117, 124, 125, 129, 131–133, 140, 148]. Not to be neglected is the impact on the strategic definition, manufacture, use and refurbishment and end-of-life stages, as those are cited several times with 11, seven, eight and 12 citations respectively.

Who is responsible for/involved in. Project professionals are mostly responsible for the lack of methods and tools (16 mentions), which is discussed in the following literature: [6, 7, 19, 34, 48, 49, 81, 90, 97, 109, 112, 124, 125, 132, 140, 148]. However, clients, suppliers and governments are also involved. Considering the lack of methods and tools, the Public and others are not often met as involved stakeholders in the identified literature.

How it affects the implementation of circular strategies in the built environment. The lack of methods and tools mainly affects the reuse strategy, with 14 mentions in the identified literature. This is addressed in the following references: [6, 7, 19, 97, 110, 112, 117, 124, 125, 131, 132, 140, 145]. All of the other circular strategies are also impacted by the lack of methods and tools, but rather on a moderate level.

Category 8: Lack of Materials/Products/Buildings/Systems

Where it happens. Studies addressing the Lack of materials/products/buildings/systems barriers at the material level reported that, regarding the building layers, these barriers affect mainly the structure [6, 7, 10, 48–50, 97, 105, 111, 119, 121, 124, 125, 131, 133, 136, 137, 141, 148, 150] and the skin [6, 7, 10, 106, 111, 119, 137, 141, 149, 150] of a building, while the other layers of the building (space plan, site, services) are rarely addressed and therefore, appear not to be affected by this barrier.

When it happens. Lack of materials/products/buildings/systems barriers at the material level has been evaluated as affecting mostly the End-of-life [6, 7, 10, 48, 50, 81, 111, 114, 115, 120, 125, 126, 133, 137, 139, 148, 149] and (Dismantling and) Construction [10, 50, 97, 104, 114, 115, 120, 124, 125, 127, 129, 131, 136, 145, 148, 149] within the building life cycle phases, followed by Design [6, 10, 48–50, 50, 97, 106, 114, 115, 119, 120, 141, 148] and Use and Refurbishment of the project [48–50, 50, 114, 115, 119, 120, 131, 136, 139].

Who is responsible for/involved in. The project professionals [6, 10, 48, 50, 97, 111, 114, 119, 125, 129, 137, 139, 141, 148, 150] and the suppliers [6, 7, 48, 50, 97, 106, 111, 114, 115, 119, 120, 124, 126, 141, 148, 150] are mostly responsible for the Lack of materials/products/buildings/systems barrier. Public [97, 115, 120, 126, 139], clients [115, 136, 139, 141] and government [81, 97, 114, 115, 126] are also included in the responsible stakeholders, but they seem to represent minor interest in the literature regarding the influence on Lack of materials/products/buildings/systems barrier, at the material level, than the suppliers and project professionals.

How it affects the implementation of circular strategies in the built environment. The reviewed literature emphasises that the Lack of materials/products/buildings/systems barrier significantly impacts circular strategies in the built environment at the material level. The most affected circular strategies are: reuse [6, 7, 10, 49, 97, 110, 111, 114, 119, 121, 124, 125, 127, 129, 131, 133, 134, 136, 137, 145] and recycle [6, 7, 10, 48, 50, 110, 111, 114, 115, 126, 129, 134, 137, 148, 149], followed by repurpose [7, 10, 48, 50, 114, 125, 129, 137, 148], repair [7, 10, 114, 119, 129, 134, 137], remanufacture [7, 10, 114, 119, 125, 129, 137], recover [7, 10, 48, 50, 97, 121, 125, 126, 136, 148, 149] and refurbish [7, 10, 110, 114, 129, 137], with the last four circular strategies being affected similarly. As recorded in all previous technical barrier categories, in some cases, different challenges and issues belonging to the same subcategory were reported within the same literature reference.

1.4 Discussion

Looking at general patterns, we observed that the lack of standards and the lack of data are both the most relevant barrier categories at all levels. They both appear as the most recurring barrier categories among the first three at all levels. The urban and building levels also report the lack of knowledge as a recurrent type of barrier, while at the building and material levels, it is acknowledged that the lack of approaches, methods and metrics is a common challenge. Additionally, we observed specific challenges: the lack of adequate infrastructure is recognized as the main barrier category at the urban level; the lack of materials, products and systems is reported as a relevant challenge at the material level.

Also, we noticed concentration on the skin and the structure layers at the building and material level, while building layers which have a shorter life in a building—the services, space plan and stuff—are less discussed. Considering, for example, that an interior door is highly re-useable, it is surprising that the space plan lacks research on applications of the 10R approach for a CE. Also, it is worth noticing that, in these layers, the implementation of material/product/systems passports is most beneficial. So, the lack of research or literature on applications in these building layers is unexpected despite evidence of their relevance.

The life cycle stages that result in being mostly affected by barriers at all levels are the construction and the end-of-life stages. At the urban level, refurbishment is also reported as a recurring stage in the literature on barriers and challenges, while the design phase is frequently acknowledged at the building and material levels. In terms of strategies for a CE, we noted a concentration on the Reduce, Reuse, and Recycling strategies across the 3 levels of the built environment. This trend may be because the 3R approach has been widely discussed and adopted for many years, but it may have limited people's thinking. The 10R approach widens the opportunities for sustainable practice while removing the false idea that Recycling is the ultimate aim or the justification to provide for sustainability. This pattern is consistent with results from another study, which reported that the construction industry is focused on recycling and reuse as the main "R" strategies, while the manufacturing industry tends to achieve higher levels of circularity due to broader implementation of remanufacturing and industrial symbiosis [151]. Finally, we observed that professionals, suppliers and governments are consistently documented as stakeholders mostly affected by or responsible for technical barriers at all levels.

Each level has discussed below trends, patterns and gaps observed in the study implemented within their level.

1.4.1 Urban Level

At the urban level, the barriers are reported mainly under the category of *Inadequate processes and infrastructure,* followed by categories of *Lack of technical standards*, *Lack of information/data*, and *Lack of technical knowledge*. This can be related to the characteristics of the urban environment, where the *Government* is mainly responsible for the processes of CE implementation. Moreover, *Project Professionals* and *Suppliers* were identified as the other stakeholders involved in the process, being directly affected by the barriers encountered in *Inadequate processes and infrastructure, Lack of technical standards*, *Lack of information/data*, and *Lack of technical knowledge*. Consequently, the barriers are reported mostly during the *Use and Refurbishment, Strategic Definition and Briefing, (Dismantling and) Construction,* and *End-of-life* phases. Another characteristic of the urban level is how it affects the

CE strategies, with most barriers affecting *Reuse* and *Recycle* strategies. In terms of "Where", as explained in the previous section, the barriers are primarily reported at the District (System) layer.

Analysing category by category, the barriers under the *Lack of information/data* category have been identified as "data capabilities and data availability", "limited knowledge", "the lack of integration among sources of information", and "insufficient data". Within the life cycle, they are primarily reported in the *Use and Refurbishment* phase. The *Government* is the main stakeholder responsible for this, followed by Project *Professionals.* The literature has shown that the barriers related to the *Lack of information/data* mainly affect *Reuse, Recycl*e and *Repurpose* CE strategies.

The second category, *Lack of technical knowledge*, presents barriers related to the knowledge gap in understanding the CE concept, such as "limited application knowledge", "production and quality management challenges", "CE knowledge deficit", "scaling up challenges", "skills gap threatening knowledge transfer", and "technological immaturity and expertise shortage". They are mostly linked to the district (system) level; however, some can be connected to staff and service levels. Manly reported in the *Strategic Definition and Briefing, Design*, and *Manufacturing* phases, they can also be mapped across the different life cycle phases, underscoring the need to address these knowledge gaps throughout the entire life cycle to implement circular construction practices successfully. The *Government* plays an essential role in setting standards and promoting best practices, ensuring knowledge transfer and workforce development, and may be involved in financing or promoting research and development efforts. Thus, this is the main stakeholder involved in this category. These barriers can affect the implementation of many CE strategies, especially *Reuse, Recycle,* and Repurpose. For instance, insufficient knowledge in production management and high-quality manufacturing creates challenges for *Reuse* and *Recycle* strategies. The loss of traditional construction skills directly affects the Repurpose strategy. The lack of knowledge about reusing construction and demolition waste (CDW) and immature recycling technology pose challenges to *Reuse* and *Repurpose* strategies. Similarly, the lack of technological expertise and the unavailability of such expertise hinder CE adaptation and create significant barriers to *reuse* and *recycle* strategies.

Five key technical barriers were identified under the *Lack of technical skills* category, namely "the lack of skills and expertise among public infrastructure and service providers", "the lack of knowledge regarding scaling up production and the contribution of urban manufacturing to the CE", "the potential loss of traditional construction skills", "the lack of access to essential business-related services and technical assistance", and "the shortage of human resources knowledgeable about CE principles across all stakeholders". They are all mainly related to the district (system) level but can also be related to staff and services levels. Even though the skill gaps and knowledge deficits manifest across various stages of the urban circular construction lifecycle, they are predominantly during the *Strategic Definition and Briefing* and *Manufacture* stages. The literature suggests a particular focus on *Construction Professionals* as the leading group of stakeholders responsible for or affected by the lack of technical skills. Additionally, *Government* intervention can play a crucial role in creating a supportive environment for the adoption of circular construction practices. The barriers identified in this category pose challenges for CE strategies like *Reuse*, *Remanufacture*, and *Recycle.*

Under the category of *Lack of technical standards,* barriers are primarily caused by the “absence/inadequacy of standardised processes”, “certification and guidelines”, which frequently are not updated, “the diversity of existing regulations”, and consequently, the different levels of development and spatial scales causing difficulties in their understanding and correct implementation. These barriers were mainly discussed during the life cycle phases of *Strategic Definition and Briefing* and *Use and Refurbishment.* Due to their intrinsic characteristics, the *Government* and *Project Professionals* are the groups responsible for or are affected by these barriers. In terms of CE strategies, the barriers under the *Lack of technical standards* category affect the majority of *Reuse* and *Recycle* strategies.

Inadequate machines/equipment is the category with the lowest number of articles reporting it, appearing in only one article. The primary barrier identified in this category is the “immature recycling technology”. The life cycle phases related to it are *Dismantling and Construction, Use and Refurbishment,* and *End-of-life*; consequently, the CE strategy most affected by this category is *Recycle.* The *Government* is mainly responsible for overcoming this barrier by encouraging economic incentive measures and recycling centres.

In terms of *Inadequate processes and infrastructure,* the barriers identified can be classified into five main groups: (1) *Waste collection and Classification Systems*, in which “Low-quality collection and classification systems”, “Immature recycling technology” are the main barriers identified; (2) *Material Handling and Infrastructure*, with “Lack of pre and post-use material handling systems”, “Resource-intensive infrastructure lock-in”, “Poorly developed infrastructure for waste management and recycling and for support CE management”, “Insufficient or incompatible local processes and infrastructure”, and “Non-integrated and refurbished infrastructure” as the main barriers; (3) *Integration and Networking,* grouping “Lack of integrated CDW processes, tools, and practices group”, “Lack of networking initiatives with legislative support”, “Limited integration of urban metabolism”, “Lack of reverse logistics infrastructure”, “Fragmentation of supply chains”, and “Limited access to production networks”; (4) *Spatial and Scaling Issues,* with “Lack of space for circular infrastructure”, “Challenges in scaling up”, “Spatial precarity”; and finally, (5) *Planning and Urban Processes*, where the barriers identified are “Neglecting people and ‘place-making’” and “Poor connection and limited integration of place-making urban ‘processes’ and urban ‘metabolisms’”. These barriers can be classified into three different levels: the national (Government) level, local (municipal, urban) level, and organizational (company) level. Hence, they occur mainly during *Dismantling and Construction*, *Use and Refurbishment,* and *End-of-life* phases. *Suppliers* and the *Government* are the main ones responsible for these barriers, followed by *Clients*, and *Project Professionals.* The impact on CE strategies has most often been identified in *Reuse* and the process of *recycling* strategies.

In the *Lack of methods/tools*, the main barriers and challenges identified in the literature include the “lack of appropriate design” and “logistics expertise”, this is because circular design and thinking are not sufficiently embedded in urban systems. Furthermore, there is a lack of comprehensive CE metrics, tools and design frameworks, as well as a lack of standardised methodologies for evaluating CE initiatives, making it challenging to implement and measure progress and ensure successful outcomes. The literature also indicates a lack of enabling digital technologies, especially those that support real-time data tracking and resource management. These barriers and challenges are primarily reported in the broader context of urban and district-level planning and management. They occur most frequently in specific life cycle phases, such as *Strategic definition and briefing*, *Design,* and *Use and Refurbishment*. *Project professionals*, including architects, engineers, designers, and construction managers, are the group most affected by these barriers. Meanwhile, *Government* agencies are responsible for overcoming the barriers once they are responsible for creating regulatory frameworks, providing incentives, and supporting the development of standardised methodologies for CE assessment. The lack of methods and tools significantly impacts the implementation of circular strategies, particularly strategies such as *Reduce*, *Remanufacture* and *Recycle.*

Finally, under the last category of barriers, *Lack of materials/products/building systems,* spatial challenges have been reported as significant barriers to implementing circular strategies in the built environment. The scarcity of affordable sites and spatial precarity can limit the availability of suitable locations for circular practices. Moreover, material-related issues present substantial barriers associated with the low cost of new materials versus the use of recycled materials. Also, monitoring and managing urban resource flows is a complex task posing significant challenges for circular strategy implementation. Those barriers occurred during the *Use and Refurbishment* phase, highlighting in this phase the limited availability of quality recycled materials, high labour costs, scarcity of affordable sites, spatial precarity, and limited space for storing disassembled materials and during the *End-of-life* phase, in which high labour costs for deconstruction, shortage of space to store disassembled materials, and difficulties in managing complex material compositions are reported. *Project professionals* and the *public* are the stakeholders most involved in or affected by these barriers. They are involved in barriers such as managing design challenges and influencing market demand for circular practices. Ultimately, the most impacted CE strategy is *Reuse*, with barriers such as limited space to store disassembled materials and the scarcity of quality recycled materials.

1.4.2 Building Level

The implementation of CE strategies in buildings is mainly affected by a lack of information/data and a lack of technical standards followed by a lack of technical knowledge and a lack of methods/tools. These barriers limit the implementation of CE strategies mainly in the structure, skin and service layers of buildings. Regarding the CE implementation phases, the design, dismantling and construction and end-of-life are mainly affected involving project professionals and suppliers and limiting them in the application of the reuse, recovery and recycling strategies. Governments can have a crucial role in the implementation of technical standards to remove these barriers and support the reuse, recovery and recycling of materials, components and systems in buildings.

The *lack of information and data* appears frequently in literature as the first common barrier category. The barriers reported in this category can be listed in several themes. The most prevalent barrier theme is the lack of data related to reusing and material stock, followed by sustainability and disassembly and lack of technical info. In general, throughout this category, the barriers affect project professionals in the implementation of reusing as a circular strategy at the design stage in the layers of structure and skin. From the quantitative analysis, we can deduce that this pattern is shown in the lack of data related to reusing and material stock, the lack of data related to sustainability, and the lack of data related to sustainability. Lack of data related to stakeholder awareness shows a completely different pattern. These types of barriers affect clients and the government in implementing the circular strategies of reusing, repurposing, recycling, and recovering on the site and structure layers at the strategic definition and briefing, the use and refurbishment, and the end-of-life stages. The barriers listed under the theme of lack of data related to digital applications are less explored in the literature. Data showed these barriers mainly affect project professionals in implementing circular strategies of reusing, recycling, and recovering of the service layer in the stages of strategic definition and briefing, and design.

In the *technical knowledge-related barrier* section, the prevalent barriers that were determined in the previous steps are further discussed, so that the main trends in their temporal and spatial dimensions, as well as in their impacts and involved stakeholders, are detected.

The main subcategories of technical knowledge-related barriers are:

- issues of general nature,
- design-related issues and
- materials and resources.

The barriers of general nature, including among others knowledge and awareness gaps among the involved parties, lack of knowledge on circularity principles, concepts and relevant technologies, difficulties and complexities of various levels, happen at almost all building layers except for district; the layers that seem to be more frequently reported are "Skin" and "Structure". As expected, the barriers belonging to this subcategory concern all the examined building life-cycle stages; the stage of "Design" is the one that is by far the most involved one, followed by "Services". With the "Project Professionals" being the leading party among the stakeholders, these barriers have been reported to affect the implementation of the vast majority of the examined circularity strategies; "Reuse" is the one that seems to be mostly affected, with "Recycle" and "Recover" being rather close to it.

The design-related issues (e.g., lack of knowledge on circular design principles, including Design for Disassembly and Design for Manufacture and Assembly) are mainly detected, concerning building layers, at the "skin", with the "structure" and "space plan" following closely. "Services" and "stuff" are also clearly represented. The main life cycle stages involved are primarily "Design" and secondarily "Strategic Definition and Briefing" (the other stages are present to varying degrees), while out of the stakeholders participating (reported for a few cases), the project professionals prevail. The circularity principles affected are "Reduce", "Reuse", "Remanufacture" and "Recycle".

Finally, the barriers included in the third subcategory "Materials and Resources" (among which misconceptions about waste management hierarchy, lack of knowledge about reused and reclaimed materials, as well as about reuse and recycling techniques, are listed) seem to mainly concern the layer of "Structure". The most intensely reported life-cycle stage is the "End of life", closely followed by the "Dismantling and Construction" and the "Design". The most frequently mentioned stakeholder group are by far the "Project professionals". The reported circular principles are "Rethink", "Reduce", "Reuse", "Remanufacture", "Recycle" and "Recover", with "Reuse" and "Recycle" being the ones that are more strongly represented.

In the *Lack of Technical Skills*, through the quantitative analysis of reported barriers from the collected literature, it was revealed that issues such as lack of people with the right skills for a CE, lack of skills, lack of systemic CE education and training for supply chain members, lack of training and knowledge for professionals, lack of skills in design and implementation, lack of awareness and communication skills, educational barriers were categorised under one theme: Lack of technical skills.

This theme emerged as the most prevalent type of information deficiency, appearing 30 times at the building level in the identified literature.

The theme lack of technical skills emerges as the most significant barrier to the implementation of CE practices. This theme encompasses a variety of specific issues that can be categorized as reported in the Table 1.39.

Quantitative analysis underscores a widespread recognition of the lack of technical skills as a barrier in various stages and layers of the built environment. The studies collectively indicate that addressing these barriers requires coordinated efforts from government bodies, project professionals, and suppliers. The effective implementation of circular strategies such as refuse, reuse, repurpose, recycle, and recovery is significantly hindered by these technical skill deficiencies, highlighting an urgent need for enhanced education and training programs tailored to the principles of CE. Findings are reported on the Table 1.40:

The integration of quantitative and qualitative data offers a comprehensive understanding of the lack of technical skills as a relevant barrier category to CE implementation. The quantitative analysis provides a clear picture of the prevalence and distribution of these barriers, while the qualitative insights explain the specific issues and their broader implications. This combined approach enables a more effective identification of intervention points and strategies to address these barriers and promote the successful adoption of CE practices in the built environment.

Lack of technical skills often arises due to several factors, including lack of education and training, complexity of technology, innovation and adoption lag, cost and resource constraints and regulatory and policy environment, which may not

Table 1.39 Lack of technical skills categorization

Lack of people with the right skills for CE
Lack of people with the right skills for CE: This barrier highlights a general shortage of individuals who possess the necessary competencies for CE initiatives, indicating a fundamental gap in the workforce's capabilities *Lack of the necessary capabilities and skills to EOL value extraction*: This barrier points to the specific skills needed to manage the end-of-life phase of products, a critical aspect of CE
Lack of skills
Lack of skills: A broad and pervasive issue, this barrier indicates a general deficiency in the required skills across the board *Lack of technical skills in the private sector on CE innovative building projects*: This specific barrier underlines the gap in technical expertise necessary for innovative CE projects in the private sector *Not enough people with skills for harvesting reused materials*: This highlights a niche but essential skill set required for effective material reuse *Lack of skilled tradesmen*: A recurring barrier that shows a shortage of skilled labor necessary for CE projects *Lack of educational/training programs for industry employees*: Points to an insufficiency in structured training programs that could help bridge the skill gap *Lack of expertise, knowledge flow, or in-house skill sets to repair and remanufacture*: This indicates a specific shortage in repair and remanufacturing skills within organisations *Lack of skills and expertise*: A general barrier highlighting a broad lack of necessary expertise *Lack of standardized practices*: Without standardized practices, it's challenging to develop and implement consistent skill sets *Lack of understanding/skills in applying the principles of the CE*: Highlights a fundamental gap in the comprehension and application of CE principles *Lack of basic digital skills and e-literacy*: This barrier reflects the need for foundational digital competencies, which are crucial in modern CE practices *Lack of information technology (IT) and AI professionals*: Indicates a gap in advanced technical skills, particularly in IT and AI, which are increasingly important in CE *Lack of leadership for a CE*: Leadership skills are essential for driving CE initiatives, and this barrier points to a gap at the management level
Lack of systemic CE education and training for supply chain members
Lack of systemic CE education and training for supply chain members: Reflects a gap in comprehensive educational programs tailored for the supply chain *Lack of knowledge and training on the environmental benefits and how to design a building for deconstruction of the design team*: Specific training gaps in designing for deconstruction and environmental benefits *Lack of training, skills, and education support. Lack of documentation to support competence improvement*: Points to a lack of support and resources necessary for skill enhancement *Lack of understanding/skills in applying the principles of the CE:* Re-emphasises the need for better education on CE principles
Lack of training and knowledge for professionals
Lack of instruction of decision-makers in an explicit and robust manner: Decision-makers require clear and robust training to implement CE effectively *Lack of training of professionals:* A general barrier pointing to insufficient professional development programs *Lack of information technology (IT) and AI professionals:* Advanced technical skills are crucial, and this gap affects the ability to leverage IT and AI in CE

(continued)

Table 1.39 (continued)

Lack of design and implementation skills
Professionals are commonly not trained to design NZCB (net zero carbon buildings): This points to a specific training gap in designing sustainable buildings Lack of adequate skills and training, including the limited use of Information and communication technologies (ICTs): Reflects a broader issue in technical and ICT skills Barriers for BIM application such as upfront cost of implementation, risks of adoption linked to IP and copyright laws, licensing issues between collaborating parties and lack of technical skills and experience to drive implementation within organisations: Highlights specific technical barriers in implementing Building Information Modeling (BIM) In the design phase, a barrier is still the classical view of supplier/customer relationship from a property owner point-of-view: Points to a need for rethinking traditional relationships and incorporating CE principles *Design as barrier to future refurbishment: design that does not focus on the ability to be adapted, or partially/fully disassembled*: Reflects a gap in design thinking and skills *Change of the traditional skill set of waste management on construction sites*: Indicates a need for updating waste management skills to align with CE
Lack of awareness and communication skills
Lack of awareness and skills across the value chain: Highlights the need for broader awareness and skills development throughout the entire value chain *Lack of Communication and limited awareness on the financial benefits of CE*: Reflects a need for better communication skills and understanding of CE's financial benefits
Lack of educational programs
Limited attention to CE in architecture studies and design: Indicates a gap in architectural education focused on CE *Lack of education programs in circular thinking for primary and secondary school, vocational and higher technical education*: Reflects a need for integrating CE education at all levels *The workforce is largely trained to work linearly*: highlighting the need to shift from linear to circular training programs *Lack of detail within requirements and uncommon language (not specific enough and terms unfamiliar to the local sector)*: Indicates a need for clear and standardised educational materials

support or incentivize the adoption of CE technologies, creating barriers to their implementation.

Lack of technical skills can slow adoption rates due to a lack of technical know-how, leading to missed economic opportunities. They can also have an environmental impact, as the benefits of reduced resource consumption and waste generation may not be realised. Additionally, organisations that cannot innovate and adapt to CE practices may lose competitiveness in their markets over time.

To advance the CE, it is essential to invest in education and training programmes that focus on CE principles and the necessary technical skills. Collaboration between academia, industry, and government should be fostered to share knowledge, best practices, and innovations in circular technologies. Supporting research and development is crucial to innovating new technologies and methodologies that simplify and enhance CE practices. Additionally, establishing supportive regulatory frameworks and policies will incentivise the adoption of these practices. Providing financial

Table 1.40 Finding summary about lack of technical skills

Prevalence at structure and skin layers
The barriers are more frequently reported at the structure layer (13 instances) than at the skin layer (7 instances)
Key project phases affected
Design phase is the most affected with 15 instances Strategic definition and briefing, dismantling and construction, and end-of-life phases also show significant impacts with 11, 13, and 11 instances, respectively
Stakeholders Involved
Project professionals are the most frequently cited group (24 instances), indicating their critical role in addressing these barriers Governments and suppliers are also key stakeholders, with 6 and 7 instances, respectively
Impact on Circular Strategies
The barrier affects all circular strategies, with the highest impact on recovery (14 instances) and recycling (12 instances) Refuse (5 instances), reuse (8 instances), and repurpose (10 instances) are also significantly impacted

support through incentives, grants, or subsidies can help organizations overcome the initial costs associated with implementing CE technologies.

Non-technical barriers that should be acknowledged include: (1) Lack of Awareness and Understanding; (2) Policy and Regulatory Hurdles; (3) Market Barriers; (4) Financial Constraints; (5) Cultural and Behavioural Factors.

The lack of technical skills is a significant barrier to the implementation of CE practices in the built environment. Addressing this barrier requires a multifaceted approach, including enhanced educational programs, targeted professional training, supportive policies, and improved communication and collaboration across the value chain. By focusing on these areas, we can develop the necessary skills to drive the transition to a more sustainable and CE.

The *lack of international/regional/national standards and guidelines* appears frequently in literature as a common barrier category. It seems to affect both design and (de)construction waste management, whether it is about rules for design for disassembly and adaptability (ISO 20887 not ready at the time), circular design or circular construction waste management. There is also mention of the lack of flexibility in the existing codes and regulations across the spectrum of circular design and waste management. Although the European Waste management protocol offers incentives for reuse and circularity, it seems that this has not percolated (or communicated) to national member states' legislation in an effective way. This is coupled with the absence of reliable procedures for evaluating reuse materials in terms of quality and durability, as well as logistics/accounting pertaining to their stock and subsequent use. Numerous of these barrier mentions are currently considered to be addressed by the aforementioned ISO, as well as a new EN standard currently under work by CEN TC350 Subcommittee 1, titled "CE in the construction sector" with delegates from different European member states from industry, public sector and academia.

In the *lack of machines and equipment*, through the quantitative analysis of reported barriers from the collected literature, it was revealed that the need for infrastructure and equipment to perform deconstruction for CE and the lack of suitable equipment for the process of deconstruction and material reclamation can be categorised under the lack of machines and equipment category (Table 1.41).

This theme emerged as the most prevalent type of information deficiency, appearing 2 times at the building level in the identified literature.

Barriers in this category are uniformly present across structure, skin, and services layers, indicating a widespread issue affecting the entire building lifecycle. This barrier category is particularly prominent during the dismantling and construction and end-of-life phases. This underscores the importance of having the right infrastructure and equipment at crucial stages of the building lifecycle to facilitate CE practices. Reuse, remanufacture, recycle, and recover strategies are all significantly impacted by the lack of infrastructure and equipment. This indicates that the barrier affects multiple aspects of CE, hindering the overall effectiveness of circular strategies.

Reuse, remanufacture, recycle, and recover strategies are all significantly impacted by the lack of infrastructure and equipment. Project professionals play a crucial role in mitigating this barrier by advocating for and investing in the necessary infrastructure and equipment. Addressing this barrier will enhance the ability to reuse,

Table 1.41 Lack of machines and equipment categorization

Need for infrastructure and equipment to perform deconstruction for CE
Core Requirement for CE Practices: Infrastructure and equipment are foundational to executing deconstruction in a manner that maximizes material recovery and reuse. Without proper facilities, even the most skilled workforce cannot efficiently deconstruct and repurpose materials *Impact on Material Flow*: The absence of dedicated infrastructure can disrupt the flow of materials through the supply chain, leading to inefficiencies and increased waste. Effective CE implementation requires a seamless process where materials can be easily processed and redistributed *Investment Needs*: Establishing the necessary infrastructure requires significant investment. This barrier highlights the financial and logistical challenges that organisations and governments face in creating a supportive environment for CE practices
Lack of suitable equipment for the process of deconstruction and material reclamation
Technical Capability: Suitable equipment is essential for efficient and effective deconstruction. Advanced tools and machinery can enhance the precision and speed of deconstruction activities, facilitating higher recovery rates of reusable materials *Safety and Efficiency*: The right equipment ensures that deconstruction processes are not only efficient but also safe. Improper or inadequate equipment can pose risks to workers and may result in lower-quality reclaimed materials *Innovation and Adaptation*: This barrier highlights the need for continuous innovation in deconstruction technology. As CE practices evolve, so must the equipment used, adapting to new materials, methods, and sustainability standards

remanufacture, recycle, and recover materials, thereby promoting sustainability and efficiency in the built environment.

The main technological barrier encountered in the category of *inadequate processes and infrastructure* at the building level was the lack of adequate logistic systems and spaces. This barrier emerged predominantly over the others, with specific reference to the lack of space for the storage of recovered materials in other buildings. Therefore, the main challenges occur when the end-of-life phase of the building begins, mainly in elements related to the structure of the building. In this case, suppliers are the main agents involved, affecting the development of reuse actions.

In the *lack of methods and tools*, the lack of CE approaches in the design of buildings stands out as the main barrier related to the lack of methods/tools. Mostly, the lack of design approaches that consider the whole life cycle of buildings, and the integration of new technologies during this process are especially relevant during building design. Therefore, project professionals are the main actors involved in this barrier, affecting considerable recovery strategies.

Relating to the *lack of materials/products/buildings/systems*, the quality and quantity of recycled materials and components mostly appear as the main technical barrier in terms of lack of materials/products/constructions/systems. This barrier, which considerably affects the building structure, occurs during the dismantling and construction phase. Project professionals and suppliers are principally responsible for this obstacle, affecting the implementation of the reuse strategy over other approaches.

1.4.3 Material Level

At the material level, technical barriers to CE implementation predominantly pertain to a *Lack of technical standards*. Subsequently, challenges related to *Lack of information/data*, *Lack of materials/products/buildings/systems*, and *Lack of methods/tools* are encountered. This can be attributed to the characteristics of the material level within the built environment, where the *Government* is considered to be the main responsible for the implementation of CE processes, followed by *Project Professionals* and *Suppliers* who were identified as the other stakeholders involved in the process/responsible for the technical barriers that impede the implementation of CE in the built environment at the material level. As a result, the barriers are reported mainly during the *Design, End-of-life,* and *(Dismantling and) Construction phases,* while *Reuse* and *Recycle* were the most affected circular strategies by the technical barriers, followed by *Repurpose* and *Repair*. These strategies were primarily hindered by barriers like a *Lack of materials/products/buildings/systems*, *Inadequate processes and infrastructure*, *Lack of information/data* or *Lack of methods/tools*.

The barriers under the *Lack of information/data* category have been classified as “Data Availability, Accessibility and Accuracy”, “Traceability and Certification”, “the Lack of Knowledge and Awareness”, and “Sustainability related issues”. Regarding the building layers, the studies addressing the *lack of information/data* barriers at the material level reported that these barriers affect mostly the *Structure* and the *Skin* of a building, and within the life cycle, they are mostly reported in the *Design* and *End-of-life* phases. *Project Professionals,* followed by *suppliers,* are the main stakeholders involved in/responsible for these technical barriers, at the material level. The literature has shown that the barriers related to the *Lack of information/data* mostly affect *Reuse, Repurpose, Recycl*e, and *Repair* CE strategies. Addressing the data gap is crucial to overcoming these challenges and unlocking the full potential of circularity in the construction sector. Some solutions to overcome the *lack of information/data* barrier in circular construction at the material level could be "Transparency through Technology and Collaboration" solutions, "Education and Regulation" and "Data-driven Decision Making and Innovation".

Five technical barriers subcategories were identified in the category of *Lack of technical knowledge*, specifically "Lack of knowledge on the end-of-life procedures", "Lack of knowledge on the materials properties", "Lack of knowledge on the design stage", "Lack of awareness—general knowledge—familiarity with CE, green building or sustainability concepts", and "Lack of knowledge through the value and supply chain". These barriers primarily impact the *Structure* and the *Skin* of a building, and they are the most prevalent in the *Design, Strategic Definition and Briefing,* and *(Dismantling and) Construction* phases. Taking into account the stakeholders, *project professionals* and *suppliers* are primarily held responsible for the lack of technical knowledge barriers at the material level. According to the reviewed literature, the *lack of technical knowledge* barrier significantly impacts circular strategies in the built environment at the material level. This includes, especially *Reuse*, *Recycle*, *Repair,* and *Refurbish. Lack of technical knowledge* hinders the adoption of CE practices, leading to a poor and inefficient supply chain, reducing the penetration of reused materials on the market, and triggering the risk of material availability. The consequences influence the whole life cycle of construction with wider and significant impacts. To align with circular economy strategies, all stakeholders must adapt their practices and cultivate new knowledge and skills. Concurrently, governments and policy makers should prioritise research and knowledge development on material flows to enhance their control and inform strategic decision-making. Integrating CE principles into university curricula for architects, engineers, and construction professionals can foster a new generation of practitioners equipped with the knowledge and skills to navigate a circular built environment.

The third barrier category, *Lack of technical skills*, refers to the lack of the necessary expertise of individuals or organizations to effectively design, implement, or manage circular systems. The barriers reported in the scientific literature related to the *Lack of technical skills* could be divided as "the lack of technical skills on a general level", "the lack of technical skills in the supply chain", "the lack of technical skills in the design process", and "the lack of technical skills in the end-of-life processes". They were mainly related to *Structure* and *Skin*, concerning the building levels, but the skill gaps and knowledge deficits were reported to affect each phase of the building life cycle at the material level, predominantly during the *End-of-life* and closely followed by *Design, Dismantling and Construction*, *Manufacture* and

Use-Refurbishment stages. The literature primarily identifies *Construction Professionals* as the key stakeholder group responsible for addressing the *lack of technical skills*. Additionally, *Suppliers* and *Clients* also play a role in being responsible for the *Lack of technical skills* in the implementation of the CE in the built environment at the material level. The barriers identified in this category pose challenges to CE at the material level for strategies such as *Reuse* and *Recycle*. Following the *lack of technical knowledge*, this barrier can be overcome through education, research, and innovation.

The barriers reported in the reviewed literature related to the category *Lack of technical standards,* could be divided as "Lack of consistent regulatory framework", "Lack of standardisation", "Complexity of certification processes", and "Lack of end-of-life policies". Regarding the building layers, the studies addressing the *lack of technical standards* barrier at the material level reported that it mainly affects the *structure* and the *skin*. These barriers have been found to be critical at the *Design* and *End-of-life* phases within the building life cycle, closely followed by the *Strategic Definition and Briefing* phase and *Manufacture*. The *Government* is held responsible for the vast majority of the *Lack of technical standards* at the material level, followed by *Project Professionals* who are directly affected by these barriers. The reviewed literature emphasises that the lack of technical standards barrier has a considerable impact on circular strategies in the built environment at the material level, affecting more or less in the same manner the *Recycle*, *Rethink*, *Reuse,* and *Repair* strategies. The vast majority of the analysed studies highlight the importance of Governmental actions toward the establishment of specific regulatory frameworks and technical standards on the reuse and recovery of materials in the construction industry. Incentivising measures are also expected to encourage local governments to develop their territory according to the principles of the CE and switch to the use of materials in line with CE principles.

Inadequate machines/equipment is the category with the lowest number of studies reporting it, appearing in seven studies. Barriers identified in this category, such as "Lack of technologies/inadequate technologies", "Lack of technological platform", "Lack of recycling process" or "Lack of technology evolution" affect the *skin* and the *structure* within the building layers. No specific life cycle phase stands out as being affected by this barrier: *Inadequate machines and equipment* at the material level are discussed in the following phases: *Manufacture, Dismantling and Construction, Use and Refurbishment, End-of-Life*. *Project professionals* and *suppliers* are identified as responsible for the lack of adequate machines and equipment in the built environment. However, no clear conclusion can be drawn by analysing the identified literature in terms of how this barrier affects the implementation of circular strategies in the built environment: each of the solutions, *Reuse, Repair, Refurbish, Remanufacture, Repurpose,* and *Recycle,* is addressed only once. To overcome the barrier of *inadequate machines/equipment, there* should be increased research, development, and technological innovation, while advanced technologies should be applied to process C&D waste management.

In terms of *Inadequate processes and infrastructure,* the barriers identified can be classified into several main groups: "Lack of sorting/insufficient storage/site constraints", "Inadequate processes and infrastructure of Material Recovery", "Market", "Lack of info/technology", "Lack of facilities/additional complexity", "CE-focused design", "Sustainability" and "Disassembly". At the material level, the barrier of *inadequate processes and infrastructure* mainly affects the *structure* of a building, followed closely by the *skin* of the building. *Project professionals* and *suppliers* are the main ones responsible for these barriers, which have impacts mainly at the *end-of-life* of a building. Besides, the *design* and the *construction and dismantling* stages are life cycle phases that often deal with the lack of adequate processes and infrastructure. The impact on CE strategies driven by *Inadequate processes and infrastructure* barriers has most often been identified in *Reuse* strategies. To effectively address the deficiencies in material recovery processes and infrastructure, a holistic framework for embedding CE principles within the built environment is essential: the company culture should be ready to apply innovative methods effectively, the governments should support the construction companies economically, interaction between stakeholders should be more effective to create links between demolition contractors and stockists, ineffective C&D waste processes should be addressed by advanced technologies and by promoting upcycling and reusing strategies. Incentives, such as tax breaks, subsidies, and financing options specifically designed for circular construction projects, can help offset initial costs and create a more level playing field. Furthermore, promoting successful case studies and highlighting the economic benefits of circularity can inspire greater adoption of CE-oriented processes and infrastructure.

In the *Lack of methods/tools*, the main barriers and challenges identified in the literature include the subcategories "Lack of tool/design or Adopting to existing method/tool", "Certification/ Standardisation/Classification", "Awareness of material recovery by stakeholders/producers/company owners", "Complexity of the recycling processes", "Disassembly". The literature also indicates a lack of enabling digital technologies, such as BIM and interoperability issues, a lack of non-destructive testing methods, and issues related to environmental impact. In line with all the previous barriers, the *structure* is the building layer that is the most affected by the *lack of methods and tools*, followed by the *skin* layer. Barriers occur more frequently in the *Design* and *Dismantling and Construction* stages. *Project professionals* are primarily responsible for the *lack of methods and tools* in the environment built at the material level. However, *clients, suppliers,* and *governments* are also involved. The *lack of methods and tools* impacts the implementation of all circular strategies, with the greatest impact on the Reduce strategy. The lack of tools and hurdles to adapt to existing methods and tools are discussed in the identified literature, and ways to overcome these barriers are addressed. There is a need for widespread BIM use, design guidelines for circular buildings and related technologies for tools, material passports and regulatory frameworks. With the support of researchers, all other stakeholders in the value chain have the power to overcome technological barriers, such as the lack of digital technologies that help to make deconstruction more efficient and cost-effective, while governments should support the construction industry financially.

In terms of *Lack of materials/products/buildings/systems,* the barriers identified can be classified into five main groups: "Lack of performance and quality assurance for reused/recovered materials", "Lack of systems", "Complexity of material recovery", "Lack of available materials/products for reuse" and "Other limitations of materials/products/buildings/systems" that encompasses limitations such as "Low level of application of recycled products", "Long product life cycle", "Design constraint for reclaimed material use", "The trend of using inexpensive and non-durable materials/components in construction" or "Increasing material diversity and number of composite materials and structures". Studies addressing the *Lack of materials/products/buildings/systems* barriers at the material level reported that, regarding the building layers, these barriers affect mainly the *structure* and the *skin* of a building, while the other layers of the building are rarely addressed and therefore, appear not to be affected by this barrier. These barriers have been evaluated as affecting in a high manner the *End-of-life, (Dismantling and) Construction, Design* and *Use and Refurbishment* of the project, showing that the scarcity of materials and products suitable for circular construction stems from a complex web of design limitations, knowledge gaps, economic factors, and practical challenges in deconstruction and material recovery. *Project professionals* and *suppliers* are mostly responsible stakeholders for the *Lack of materials/products/buildings/systems* barrier category. The CE strategies most affected by the *Lack of materials/products/buildings/systems* are the *Reuse* and *Recycle* strategies, with barriers such as "low volume and inconsistent quality of the recovered materials", "no space for the storage of disassembled materials", "difficulty to recover materials", "hazardous components" or "design constraint for reclaimed material use". Solutions to overcome the *Lack of materials/products/buildings/systems* mentioned in the literature were related to the need for research, development and innovation, education and awareness-raising efforts, financial incentives, regulatory frameworks and collaboration throughout the entire supply chain.

1.5 Conclusions

This study investigated technical challenges that affect the implementation of circular strategies in the built environment through a literature review. The investigation was conducted by examining barriers identified in the academic and non-academic literature at various levels (urban, building, and material) of the built environment.

We observed general patterns in (1) the types of barrier categories that most affected the implementation of circular strategies in the built environment, (2) the life cycle phases and (3) building layers in which technical challenges are observed, (4) the circular strategies mainly implemented and (5) the stakeholders involved or responsible for them. The lack of standards and the lack of data are both the most recurrent barrier categories at all levels. The life cycle stages that result in being mostly affected by barriers at all levels are the construction and the end-of-life stages. In the adoption of circular strategies in the built environment, the focus is placed on the 3R approach (Reduce, Reuse, Recycle). It highlights that while the 3R approach has been widely adopted, it may have limited broader thinking on sustainability. The 10R approach, which includes additional strategies like remanufacturing, offers more opportunities for sustainability and shifts focus away from recycling as the ultimate goal. Additionally, we noted a lack of focus on building layers with shorter lifespans (e.g., services, space plans), where strategies like material passports could be highly beneficial. Finally, we observed that professionals, suppliers and governments are consistently documented as stakeholders mostly affected by or responsible for technical barriers at all levels.

In the literature review focused on **urban-related technical barriers** to implementing circular strategies, the analysed studies and papers identified a variety of barriers. To enhance our understanding, these barriers were categorized into eight distinct groups.

- The most prominent category was *Inadequate processes and infrastructure.* Literature provides numerous evidence on challenges associated with the infrastructure for waste management and recycling. Additionally, the absence of efficient production and supply-chain networks and logistics that support CE practices were frequently noted as a significant technical barrier within this category.
- *Lack of technical standards* is another significant barrier. Technical standards are particularly missing in building design and construction, to promote eco-friendly building materials, efficient resource use, and sustainable construction techniques. There were also identified the barriers associated with the regulatory framework and government support.
- A substantial number of studies identified barriers related to the *Lack of information/data.* From the urban perspective, availability and quality of data and information are prerequisites for efficiently implementing CE strategies and practices in the construction sector. Barriers such as absence of clear guidelines for collecting and sorting construction and demolition waste (CDW), lack of documentation for new and used building products and issues with the quality and availability of data, as well as transfer and integration of knowledge across different stakeholders and disciplines, were the most widely reported barriers in this category.
- Several barriers were identified in the subcategory *Lack of technical knowledge.* Technical knowledge is especially vital in areas such as recycling and reuse processes, design and disassembly of products and production and manufacturing processes. The technological expertise and skills and knowledge transfer in this area are crucial for innovation, development and upscaling CE practices across the sector.
- Among all the barriers identified, the primary stakeholder highlighted was the government, followed by project professionals. However, suppliers and clients also play an important role as stakeholders.
- The most affected CE strategies at the urban level are Reuse, followed by Recycle and Repurpose. Relevant stakeholders should concentrate their efforts to mitigate these barriers and facilitate wider and more efficient implementation of these strategies in the building sector.

At the building level, we have identified the following range of CE barriers:

- The implementation of CE strategies in buildings is mainly affected by the *lack of information/data, technical standards, technical knowledge and methods/tools*. Because of these barriers, project professionals and suppliers are mainly affected in the application of the reuse, recovery and recycling strategies during the design, dismantling and construction and end-of-life phases.
- Regarding *lack of data*, barriers relate to reusing and material stock followed by lack of data for sustainability assessment and lack of technical info for disassembly. These barriers mainly affect the implementation of reusing on the building structure and skin.
- In the *technical standard barrier* category, the main barriers concern the lack of standardisation/guidelines, lack of legal policies, and sustainability quality assurance affecting professionals in recycling, reuse and recovery during the design and (de)construction waste management phases. Also, the absence of reliable procedures for evaluating reused materials limits the reuse.
- Regarding the *technical knowledge* category, the main barriers reported are of general nature, followed by the design-related- and the materials and resources-related ones. The barriers occur mainly at the skin and structure layers and most predominantly at the design stage; all circular strategies are affected, with reuse and recycling holding the lead.
- The main barrier in the *lack of methods/tools* category is the lack of CE approaches in buildings' design. The design stage of building structure and skin is affected by the lack of design approaches considering buildings' whole life cycle, and new technologies' integration in it. Professionals are mainly involved; recovery, recycling and reuse strategies are considerably affected.
- Insufficient investment in *infrastructure and equipment*, coupled with a deficit in training and expertise among professionals, significantly contributes to these challenges. Existing infrastructure often supports linear economy practices, which do not align with the requirements related to the implementation circular strategies.
- Technical barriers have multifaceted negative impacts, including slow adoption rates, missed economic opportunities, environmental impact, and loss of competitiveness. Governments and organisations need to prioritise investments in specialised infrastructure and tools tailored to support CE practices. This includes developing facilities and acquiring equipment capable of handling the complexities involved in reclaiming and repurposing materials. There is also a critical need to focus on education and training, along with substantial investment in research and development. Furthermore, collaboration across sectors is paramount. By fostering partnerships between academia, industry, and government entities, stakeholders can share valuable insights, best practices, and innovations in CE technologies.
- Non-technical barriers also need to be considered. Regulatory barriers, such as the lack of supportive policies and regulations, can impede the adoption of circular practices. Financial barriers, including high initial costs and a lack of financial incentives, can deter organisations from investing in CE practices. Cultural and

behavioural barriers, such as resistance to change and limited awareness of the benefits associated with CE practices, can prevent their widespread adoption. Market barriers, including limited demand for reclaimed materials and products, can undermine the economic viability of circular strategies.

At the material level, the extensive literature review and the deep analysis of the bibliographical sources from the scientific and non-academic literature revealed the following:

- The *Lack of technical standards* has been identified as the most significant barrier for implementing the CE principles in the built environment at the material level, followed by the *Lack of information/data*, *Lack of materials/products/building systems* and *Lack of methods/tools*. The technical barriers at the material level were mainly associated with the building structure and skin, and they affect mostly the Design and End-of-life building life cycle phases, with significant impacts on the implementation of the circular strategies, Reuse, Recycle, Repurpose and Repair. Among the stakeholders that are involved in the implementation of circular strategies at the material level, the Government was considered as the primary responsible for the technical barriers, especially with regard to the lack of technical standards, followed by the project professionals and the suppliers.
- The *lack of technical standards* embraced barriers that are related to the lack of consistent regulatory framework, i.e. absence of regulations on circularity, but also contradictions between existing regulations, limited flexibility and enforcement of using recycled materials on building projects and standardisation, as well as with the lack of standardisation, mainly as regards the quality and the properties of the reused materials. The lack of information/data was associated with the data availability, accessibility and accuracy, as well as the materials' traceability and certification. Both of these two major barrier categories at the material level affect primarily the Design and End of Life phases within the building life cycle.
- In the general barrier represented by the *Lack of materials/products/building systems* it was indicated that issues like the low availability and inconsistent quality of the recovered materials, the durability of reused products, the use of polluted materials or materials of low recoverability, the low performance and/or the absence of documentation on the performance of the recovered materials, etc., hinder the wide implementation of CE strategies on the built environment. Moreover, the *Lack of systems,* involving merely storage space and logistics, was discerned among the more distinguished categories of this specific technical barrier. The building life cycle phases End of life and Dismantling and Construction are primarily affected by the Lack of materials/products/building systems, but also by the Lack of methods and metrics.

Recommendations for stakeholders:

- Effective implementation of CE practices is often hindered by inadequate infrastructure. Therefore, investments in development, modernisation and extending supply-chain networks tailored to CE practices in the built environment are highly recommended.

- Technical standards and supportive policies should be developed and enforced to promote eco-friendly building materials, efficient resource use and sustainable construction techniques.
- The relevant stakeholders should address the lack of quality and accessibility of data on CDW management. Establishing clear guidelines for collecting, sorting and documenting CDW for example, via Data sharing platforms, can facilitate more circular material use.
- Support collaborative initiatives between stakeholders, encourage partnership and knowledge sharing. Also, partnership among academia, policy-makers and building professionals should be encouraged to drive innovations and overcome barriers in CE implementation.
- Governments can have a crucial role in removing technical barriers at the building level and supporting the reuse, recovery and recycling of materials, components and systems in buildings. Government should introduce incentives, subsidies and initiate development of policies that support economic viability of CE practices.
- While the ISO, as well as a new EN standard currently under work, may help to overcome technical standard barriers, governments can also play a decisive role in promoting technical standards and the European Waste Management protocol in national legislations.
- Technical knowledge gaps intersect the whole chain of stakeholders involved in CE implementation in the construction sector. Training activities organised by various actors in the field tailored to the specific needs of stakeholders, knowledge sharing, inclusion of relevant courses in university curricula/development of educational programs and emphasis on the development of good examples/best practice case-studies on various aspects of the required knowledge (e.g., product design for disassembly) can provide the basis for actual advancements.
- The lack of methods and tools dictates the need for the development of practical guidelines, standards and policies for various processes in the building sector (e.g. reclaimed materials, DfD), as well as of design-support tools f. Also, the creation of tools and the development of indicators/models for the assessment and monitoring of circularity in buildings will play an important role, along with the development of accessible databases and the use of new (digital) technologies.

The systematic bibliographic research not only provided the technical barriers that hinder the implementation of CE in the built environment at the material level, but also indicated recommendations and solutions to overcome them and promote the transition from the linear construction scheme towards a more circular approach. The recommendations are applicable to material, urban and building levels, with key insights focusing on:

- Education and awareness raising among all stakeholders to drive change across all levels of industry and society, e.g. through the integration of CE principles into educational programmes and lifelong courses, the training and upgrading of the workers' skills, the initiation of public campaigns, etc.

- Support of research and innovation in relevant fields, in order to further develop and exploit technological advancements, such as Industry 4, radio frequency identification (RFID) material tagging and other digital tools, e.g. BIM, AI, digital twins, neural networks, etc.
- The establishment of relevant regulations, standards and codes to promote circular construction, along with the integration of contractual requirements for the design, construction and procurement, aligned with CE principles,
- The development of cost-effective and trusted certification protocols and testing processes for assessing the materials' properties, thus fostering their recovery and reuse potential, in consort with the development of design guidelines, multi-criteria decision procedures, material passports and well-designed indicators,
- The provision of financial incentives, such as increasing demolition and landfill fees, combined with subsidies, tax breaks, and low-interest loans for companies implementing circular design and business models, as well as increasing the financial value of reused materials, e.g. through advanced sorting or higher inclusion rates in new products,
- Strengthening collaboration throughout the entire supply chain in order to bring together clients, suppliers, contractors, and designers to ensure that circular principles are embedded throughout the project lifecycle.

The limitations of the study are related to the lack of a robust scientific approach when research investigates barriers. This is evident in the varying methods of investigation and interpretation adopted in the bibliographic references examined. Findings of different levels of generality, as well as of different focusing and target audiences, were dealt with, leading together with the involvement of several researchers of different backgrounds in this study, to the integration of a degree of subjectivity into the analysis. This issue runs through several steps of the process and intersects all the levels examined. Beginning from the initial phase of the barrier classification into the identified categories (lack of data, lack of technical standards, etc.), through the reporting of their dimensions and relevant aspects (where/when/who is involved/ how is circularity implementation affected), and reaching the final stage of identifying subcategories of barriers within each main category, fragments of subjectivity in the adopted approaches and assumptions can be detected, which are due also to the different depth of interpretation in the reviewed sources. However, despite the inaccuracies that may have affected the analysis in its details, general trends have indeed been identified, and the central conclusions are based on a solid basis. Moreover, the non-academic literature provided less detailed information; therefore it limitedly complemented the scientific literature on this topic.

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