Chapter 7
Circular Material Usage Strategies—Principles

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Abstract The construction industry significantly contributes to global greenhouse gas emissions, raw material extraction, and waste production. Implementing circular economy (CE) principles in this sector could greatly reduce these impacts. However, adoption within the industry remains slow due to barriers such as limited knowledge and experience. This chapter aims to assess and help overcome these obstacles by providing a comprehensive analysis of circular material usage principles and strategies in construction. It also highlights opportunities and enablers of change, including innovations and emerging technologies in recycling, digitization, robotic systems, new materials, and processing techniques. Four case studies illustrate the application of circular theory through a Bio-Building, Urban Mining and Recycling (UMAR) Experimental Unit, Open-spaced apartment, and an "*Escuela Politécnica Superior*". The conclusions emphasize the need for strong regulatory frameworks, awareness initiatives, and international cooperation. Integrating technological advancements

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L. Bragança et al. (eds.), *Circular Economy Design and Management in the Built Environment*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-3-031-73490-8_7

like AI, robotics, and blockchain is crucial for optimizing waste management. Additionally, education on circular practices is vital. By fostering global collaboration, standardizing circular construction approaches can lead to a more sustainable and resilient building industry.

Keywords Circular economy · Buildings · Circular materials · Strategies · Principles · Overview

One of the main waste flows in the European Union (EU) is construction and demolition waste (CDW), representing in 2018 around 36% of total waste generated [1]. Besides soils, concrete, bricks, gypsum, wood, glass, metals, plastic and solvents are the most often CDW found in the EU-27 countries [2], exhibiting not only a high resource value, but also a high potential for re-use and recycling [1]. Even with high financial penalties, illegal fly-tipping of CDW continues to take place (Fig. 7.1). In this context, the EU has made the management of CDW a priority [3] and the Waste Framework Directive (WFD) 2008/98/EC [4] imposed a mandatory recovery target (70% recovery rate of CDW in weight by 2020). Included in these recovery activities are "the preparation of non-hazardous CDW for re-use, recycling and other material recovery, including backfilling operations" [1].

This chapter presents an updated review of circular material usage principles and strategies within the construction sector. First, some basic concepts about circular economy and material usage are presented as an introductory framework. Next, the main principles for circular material usage at the design stage are described. After, the circular material usage strategies and principles in construction activities are presented, including: extending lifespan and end-of-life strategies, collaborative approaches and business models, technological innovations, main barriers and enablers of circular material usage. Finally, to conclude this subsection, some best

Fig. 7.1 Construction and demotion waste illegally discarded in the middle of a forest

practices related to the previous theoretical concepts about circular material usage in the building industry, are illustrated using some selected case studies.

7.1 Understanding Circular Economy and Material Usage Section

The circular economy (CE) is a model of production and consumption which focuses on retaining existing materials and products as long as possible and reducing waste [5]. Circularity aims to move away from the traditional linear model of 'take-make-dispose' where materials are extracted, manufactured into products, and ultimately disposed of. Instead, it focuses on creating a closed-loop system where materials are continuously reused, recycled, or regenerated to minimize the need for new resources and reduce the environmental impact. In the built environment, there is no clear and accepted definition of a CE [6]. However, a circular built environment can be a sustainable approach which caters to the growing needs of the sector without causing additional detrimental impacts on the environment.

The EU has agreed to reduce greenhouse gas emissions by 55% by 2030 (of 1990 levels) and to become carbon neutral by 2050 [7]. Although figures fluctuate year on year, the Circular Economy Action Plan [8] attributes 50% of extracted material and 35% of the EU's waste generation to construction. The sector accounts for 5–12% of total greenhouse gas emissions through material extraction, construction product manufacture, and building work. This includes cement, aluminium, steel, brick and glass production which account for approximately 9% of global energy related CO_2 emissions [9]. Confounding this issue, 10–15% of building material is wasted during construction and the majority of demolition waste is currently landfilled in the EU [10]. National construction and demolition waste (CDW) recycling rates vary greatly across Europe, from 10 to 90% [11]. A CE has the potential to reduce global CO_2 emissions from building materials by 38% by 2050 [12, 13].

According to the Ellen MacArthur Foundation [14] the three principles of a CE are: the elimination of waste and pollution, the use of circular products and materials and thirdly, the regeneration of nature. Within these principles, there are several subcategories and concepts which will be discussed below.

7.1.1 Eliminating Waste and Pollution

The first principle aims to move away from a linear system whereby raw materials are extracted, consumed and eventually thrown largely into landfills and incinerators. In circular design, raw materials use is minimized, and materials can be designed to remain in use for multiple cycles by following the R principles. There are many versions of the R principles for a CE which are based on the original 3;

Prioritised for a Circular Economy	Reduce	R1 Refuse	Don't use it, make a product redundant e.g. is the structure necessary, can you use something existing?
		R2 Rethink	Rethink use, can it be shared or serve multiple functions e.g. sharing of equipment between sites, adaptive use
		R3 Reduce	Use less of it e.g. efficient / optimised design, off-site manufacture
	Reuse	R4 Reuse	Reuse of product, e.g. reuse of windows elsewhere on the site
		R5 Repair	Repair or maintain, keeping original function e.g. weatherproofing
		R6 Refurbish	Refurbish, restore or update e.g. retrofit
		R7 Remanufacture	Use parts in a new product with same function e.g. remanufactured construction equipment
		R8 Repurpose	Use product or parts in new product with different function e.g. structural bricks to decorative internal
	Recycle	R9 Recycle	Process materials which can be same or lower quality, e.g. recycled aggregate
Low priority		R10 Recover	Energy recovery via burning e.g. Biomass from timber construction industry

Fig. 7.2 Circularity hierarchy of principles in the product chain with examples from construction. Based on a table by Potting et al. [19]

Reduce, Reuse, and Recycle. This can then be subdivided multiple times to make to up to 14 and even 22 Rs [15, 16]. Reike et al. [17] identified 38 "re-" words, as listed next by alphabetic order: "re-assembly, recapture, reconditioning, recollect, recover, recreate, rectify, recycle, redesign, redistribute, reduce, re-envision, refit, refurbish, refuse, remarket, remanufacture, renovate, repair, replacement, reprocess, reproduce, repurpose, resale, resell, re-service, restoration, resynthesize, rethink, retrieve, retrofit, retrograde, return, reuse, reutilize, revenue, reverse and revitalize". Ten of the most common include: Refuse/Reject, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. Figure 7.2 indicates the hierarchy of these, prioritized from 1 to 10 based on maximizing resource efficiency, minimizing waste generation, and highest value creation and retention. Recycling and recovery are ranked lowest because of the loss of complex state and the need for higher energy inputs [18].

7.1.2 Use of Circular Products and Materials

Circular Materials used within construction can be largely divided into two groups; low or zero-carbon materials such as wood and reused or recovered materials with minimal reprocessing or transport-related emissions [20]. The technical cycle and the biological cycle support circular material use and are illustrated in Fig. 7.3.

The technical cycle on the right involves materials such as metals, concrete, plastics, glass, or synthetic composites in building products. At the end of a structure's life, or construction products' life, these materials are recovered from the demolition or deconstruction process, sorted and processed before being reprocessed or reused in construction or other applications. The inner loops in the Fig. 7.3 butterfly

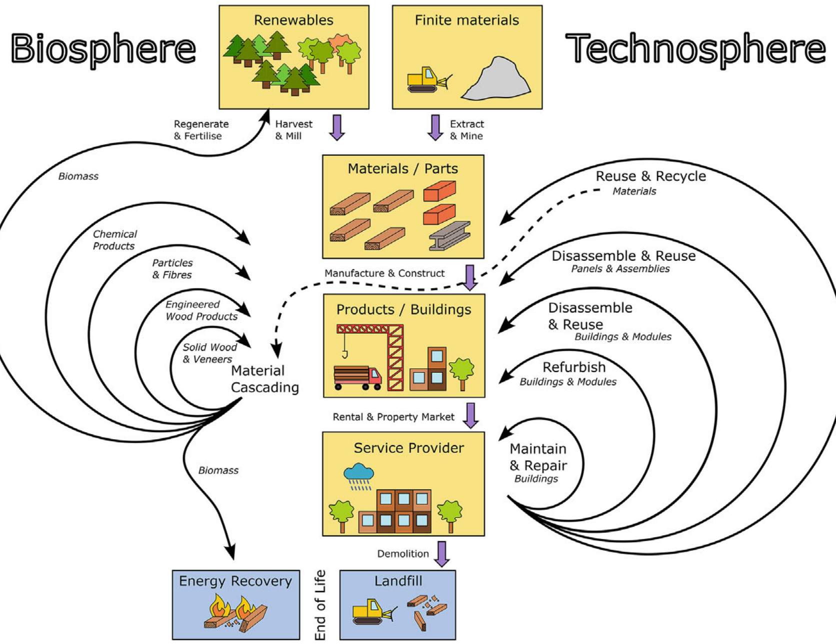

Fig. 7.3 Circular economy butterfly diagram interpreted for the construction industry by Ottenhaus [22]

diagram applied to the construction industry, retain most value in the material or product. This is based on the more general circular economy butterfly diagram [21], in which the innermost loop, 'Maintenance', prolongs the life of the material or product. This is followed by 'Reusing' and 'Redistributing' which keeps materials in their original form and displaces the need to manufacture new items or extract new materials. 'Refurbishing' and 'Remanufacturing' then include some processing and the outmost loop, 'Recycling', is a last resort when other options are not possible.

The biological cycle, or bio-loop, only includes materials that can be safely regenerated in the biosphere via composting or anaerobic digestion such as timber, bamboo or straw. Materials from the technical cycle can end up in the biological cycle, once they can no longer make a product. The inner loops of the left side of the butterfly diagram shows the 'cascading principle' which is the cascading use of renewable resources, with several reuse and recycling cycles [23]. For the construction industry, this is most applicable to timber, which could begin its first product life as solid timber beams and end its fifth life being incinerated for energy recovery [24]. Cascading ensures that biogenic carbon remains in the system for a longer period of time, resulting in lower environmental burdens and can support other industries such as farming via feedstock or soil fertilizer [25].

7.1.3 Regenerate Nature

Circular construction can contribute to the regeneration of nature by incorporating strategies that support ecological restoration, biodiversity enhancement, and sustainable land management practices. The aforementioned biological cycle contributes to biodiversity and ecosystem health by promoting the use of renewable materials that can be regrown and replenished. Maintaining materials in use also contributes to this principle as less land is required for sourcing virgin raw materials, which allows more land to be returned to nature.

While circular construction materials hold great potential for sustainable and resource-efficient building practices, there are several challenges that need to be addressed to facilitate widespread adoption. The details of the challenges faced can be specific to each stakeholder's role. However, they can be broadly grouped as economic, informational, institutional, political and technical challenges [26] with commonly encountered subcategories listed in Table 7.1.

A key challenge in the sector is the volume of existing buildings not designed for deconstruction, containing toxic materials, and lacking detailed documentation [28]. Reused materials require additional time and more qualified labour, and there is a lack of market mechanisms to aid recovery [6]. A system needs to be developed

Table 7.1 Challenge areas for a circular built environment compiled from review articles [6, 26, 27]

Challenge subcategories	Challenge
Economic	– Lack of grants/unclear financial case
	– Lack of financial aid, incentives or short-term benefits
	– Low value of circular materials
	– Cost of upfront investment
Informational	– Lack of research, education and information
	– Lack of awareness, interest and knowledge
	– Lack of best practice case studies and leadership
Institutional/structural	– Lack of strategic vision and collaborative platforms
	– Fragmented supply chains
	– Lack of market mechanisms for recovery
Political	– Lack of regulatory instruments/regulatory pressure
	– Lack of tax actions
	– Lack of circular vision
Technological	– Lack of integrated processes, tools, and practices
	– Lack of an information management system
	– Complexity of buildings
	– Technology and infrastructure readiness

which supports the use of circular materials which includes quality assurance, standardization, certification and classification, mechanisms for transport and storage and access to the market [26, 29].

Finances, or lack of financial case, were identified as a leading barrier for stakeholders [6, 10, 27]. For circular construction materials, this includes the high availability and low cost [27] of virgin raw material, the cost of deconstruction, the work involved in providing the material for reuse, the cost of recycled/reused materials, and the lack of reward or penalty [26].

Institutional or informational challenges include the lack of guidance and tools, and lack of knowledge [26]. Stakeholders throughout construction value chains in Europe are unfamiliar with how CE principles do or could operate in the built environment, with many unable to identify first steps in initiating the transition to a CE [10].

Addressing these challenges requires collaborative efforts from various stakeholders, including policymakers, industry professionals, researchers, and end users. Overcoming these barriers will pave the way for a more widespread adoption of circular construction materials, however there is a need initially to provide evidence, compile best practice examples and develop guidance.

7.2 Design Principles for Circular Material Usage

7.2.1 Designing for Circularity

There are several principles within the design stage to promote circularity in building constructions. These principles can be clustered into the following points [30, 31]:

- Design standardized products and materials, using regular and simple modular shapes to avoid waste.
- Design to decrease the need to extract and produce virgin materials.
- Design using recovered materials: by detecting unused materials from technical or natural flows and transforming them into circular materials which can be incorporated within the production of new materials and products, promoting the design of materials with high recycled content.
- Design durable materials so that they can prolong their use in the building and therefore increase lifetime and delay the end-of-use cycle.
- Design considering the setting procedure of the materials, so that the materials can be easily disassembled: Materials should be designed thinking that, when placed in a construction project, they should allow deconstruction and promote reuse and recycling. For example, using mechanical joints to avoid the use of binders and adhesives.

7.2.2 Material Selection and Management

The construction sector, in particular, plays a pivotal role in transitioning towards a less resource-intensive economy by maximizing the use and recovery of resources in building design and construction. Sustainable material sourcing and efficient recycling techniques are crucial for achieving a circular economy.

1. *Criteria for Selecting Circular Materials*

The EU emphasizes the significance of applying circular economy (CE) principles across all economic sectors, with a particular focus on water and energy conservation, waste prevention, material recycling, promotion of reuse and repair, and utilization of secondary raw materials [32].

CE in the construction sector aims to maximize the use and recovery of resources and buildings, reducing the environmental impact. Thus, it is of importance that designs aim to extend the useful life of buildings through rehabilitation, using recyclable materials; and the usage of new industrialized long-life materials based on recovered and valued resources. Additionally, adopting new industrialized long-life materials derived from recovered and valued resources can contribute to sustainable practices [33]. By implementing these recommendations, the construction sector can play a pivotal role in transitioning towards a less resource-intensive economy and fostering circularity. This approach aligns with the broader objectives of the CE, such as reducing waste generation, conserving resources, and promoting sustainable material use.

2. *Sustainable Material Sourcing*

Regarding the availability of raw materials, critical raw materials are of particular importance as their great economic importance for the European Union (EU); very sensitive to supply interruption; and being their extraction of a significant impact on the environment. Critical raw materials—e.g., lithium, are often present in electronic devices. The current low recycling rate of these materials means that significant economic opportunities are being lost. Thus, the fundamental directions that the circularity strategy must take at the European level are those that consider the need to incorporate these materials into reduction, reuse and recycling practices. To achieve autonomy with respect to these materials, the EU proposes diversified and undistorted access to global raw materials markets, while seeking to reduce external dependence on these materials as well as the environmental pressures associated with their import [32].

3. *Material Efficiency and Recycling Techniques*

The EU insists on the importance of incentives for the adoption of efficiency measures in the use of resources and for increasing recycling, eco-innovative performance, and investments in green products and services [32]. To move towards an economic model of material efficiency, economic priorities and lifestyles must be in line with reducing excessive economic material dependence by applying the principles of circularity—i.e., reduce and reuse before recycling [32]. Fundamental aspects of CE

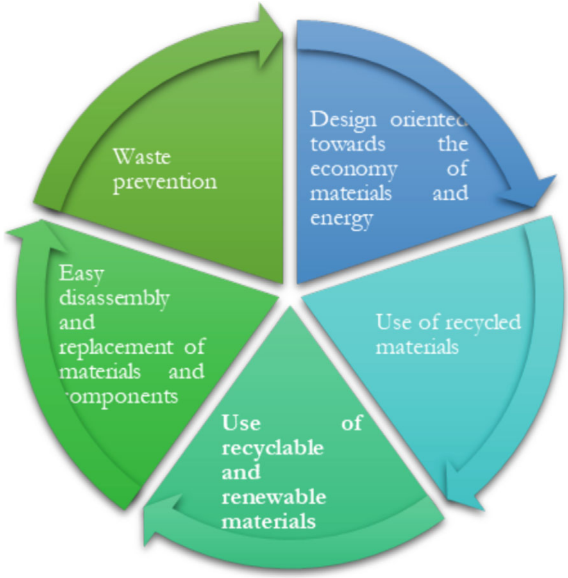

Fig. 7.4 Important recycle points (*Source* authors, based on S*ituación y evolución de la economía circular en* by Morató et al. [32])

related to recycling are: (i) design oriented towards economy of materials and energy, use of recyclable and renewable materials, and easy disassembly and replacement of materials and components; and, (ii) recycling and recovery of non-reusable materials [33].

Waste prevention continues to pose a major challenge in all Member States of the EU, including those with high recycling rates [32]. The use of recycled materials can contribute to partially covering the total demand for materials, thus reducing the extraction of raw materials. Creating efficient secondary materials markets enables higher value recycling cycles since most materials are recycled after disassembly. The principles are outlined in Fig. 7.4.

4. *Lifecycle Assessment and Material Management*

Production systems concerning efficient use of materials—given priority to activities allowing the development of CE principles from the beginning of the production process phases, and not only in its final dimensions; i.e., recycling and reconversion of waste—would serve as recommendations aimed at the change of economic models and the transition towards a less resource-intensive economy. Efficient use of materials in production systems is a critical aspect of the CE. It is essential to prioritize activities that promote CE principles from the beginning of the production process phases, rather than only focusing on recycling and reconversion of waste in its final dimensions.

This approach would serve as a recommendation aimed at changing economic models and transitioning towards a less resource-intensive economy. Innovative and effective methodologies to analyse the flow of materials and specific circularity indicators linked to the lifecycle are fundamental to addressing the transition to a circular model. These methodologies can help identify areas where material efficiency can be improved, and waste can be minimized [32]. They can also help to optimize resource allocation by identifying opportunities for reuse, recycling, or recovery of materials. By adopting such methodologies, companies can reduce their environmental footprint, enhance their competitiveness, and contribute to the development of a sustainable economy.

7.3 Circular Material Usage Strategies and Principles in Construction Activities

This sub-section is dedicated to reviewing the principles and strategies for circular material usage in the construction industry. First, some strategies for extending lifespan, as well for end-of-life products/materials are outlined. Next, some collaborative approaches and business models to foster a circular economy in the construction sector are described. Later, some technological innovations for circular material usage are assessed and exemplified. This is followed by a review of the main barriers and enablers of circular material usage in the building sector. Finally, some examples are presented of circular economy best practices within the construction sector regarding material usage, here identified as "case studies".

7.3.1 Extending Product Lifespan and End-of-Life Strategies

Very often, the economy is filled with things that have been designed without asking: What happens to this at the end of its life? [34]. Therefore, it is very important to define at the design stage what will be the end-of-life strategies to promote CE of construction products and materials. The construction industry is making a gradual progressive transition to CE, as assessed and concluded by Charef et al. [35]. In fact, circular strategies are starting to be implemented by the building industry, as demonstrated by Nußholz et al. [36]. He analysed 65 novel real-world cases of new build, renovation, and demolition projects in Europe, regarding the circular solution applied, level of application in buildings, and decarbonization potential reported.

Several researchers developed and made use of disruptive technologies to foster the circular building industry. Setaki and Timmeren [37] outlined how disruptive, often digital, technologies can potentially enable a CE in the building industry, primarily within the two most wasteful phases of the building cycle, the construction and demolition phases. Moreover, regarding additive manufacturing, Tavares et al. [38] performed a state-of-the-art review regarding the evaluation of benefits and barriers of additive manufacturing for the circular economy, presenting also a framework proposal. Furthermore, artificial intelligence is being increasingly used to enhance the implementation of systemic circularity in the construction industry, as recently reviewed by Oluleye et al. [39].

As mentioned by Marsh et al. [40], the construction CE principles could be grouped as follows:

- Reduction of material use (through specification and design);
- Long-lasting design (increased durability);
- Maintenance, repair and refurbishing;
- Reuse and remanufacturing;
- Recycling.

One of the key principles for CE is to keep the products and materials in use, for as much time as possible [41], i.e., long-lasting design by increasing longevity [40]. The goal is to maximize the utilization time of products and materials, promoting reuse, refurbishment, remanufacturing, and recycling. By extending the life of products, their value is retained, and the need for extracting and processing new resources is reduced. Nevertheless, Kirchherr et al. [42] concluded: "*that the CE is most frequently depicted as a combination of reduce, reuse and recycle activities*". They also noticed that "recover" is also often added to the previously listed CE activities, accomplishing this way a 4Rs framework, instead of 3Rs.

Besides increasing the durability of materials and products, it is also important to foster their repairability. Furthermore, a remanufacturing process should be implemented, and the product should be upgraded to its highest value, whenever possible.

With so many existing possibilities and possible approaches to address CE in existing buildings, it is very relevant to estimate the recoverable value of in-situ building materials. Mollaei et al. [43] developed a new computational tool to "choose the optimal combination of reuse, recycling and disposal options for those materials", taking into account "cost, value, duration, environmental impacts, and building component precedence in demolition and deconstruction activities".

According to Marsh et al. [40], the CE principles/strategies could be structured into three main groups, depending on the lifecycle stage, as listed in Table 7.2. As seen before, it could be defined many other strategies and included in this table. One example is the product/material recover from an end-of-life building to be later reused, remanufactured or recycled. Another example could be the thermal energy recovery from a combustible material (e.g., plastic or rubber) during a burning process. Obviously, both previous examples are for the end-of-use lifecycle stage.

Table 7.2 CE principles/strategies structured as function of the life-cycle stage: adapted from Marsh et al. [40]

Lifecycle stage	CE principles/strategies
Design-stage	– Reduction of material through specification and design
	– Long-lasting design
In-service	– Maintenance
	– Repair
	– Refurbishing
End-of-use	– Reuse
	– Remanufacturing
	– Recycling

This sub-section will focus mainly on strategies to extend product lifespan and on the available end-of-life strategies to foster circular material usage in construction activities.

1. *Extending product lifespan*

- *Increasing Durability by Maintenance, Repair and Refurbishment*

Maintenance, repair and refurbishing are all in-service strategies for slowing resource flows, by extending the technical lifetime of products and components [40]. Maintenance corresponds to a universal upkeep, and correspondent damage prevention works to building components (such as applying protective coatings). Repair and refurbishment are the overhaul of limited damage to a component, or the replacement of a spoiled component wholesale with a new one [40].

Designers should think about how their product could fit into the technical or biological cycles after use, so that product could be made with that onward path in mind. This way, products destined for technical cycles would benefit from being easy to repair and maintain, easy to take apart, and made of modular components that can be replaced [44]. They should be durable enough to withstand the wear and tear of many users. Moreover, they should be made from materials that are easily recycled.

The most efficient solution would be to use self-healing materials to extend their lifetime and, at the limit, to make "immortal" products or components, as studied by Haines-Gadd et al. [45].

2. *End-of-life strategies*

- *Upgrading and Remanufacturing*

During the previously mentioned durability increasing processes, when the product can no longer be used, its components should be, whenever possible, remanufactured and upgraded [46].

Upgrading and remanufacturing are both product end-of-use strategies, intended to slow resource flows by continuing the use of still-functional components from end-of-use products in new products. Atta [46] delineated the involvement of digital technologies in supporting the implementation of circular service-based models built on remanufacturing in current construction practices.

Strategies for upgrading and remanufacturing of building components should be predicted at design stage. Van Stijn and Gruis [47] developed an integral design tool for circular buildings components (CBC), called "CBC-generator". This software it is a parameter based "three-tiered design tool, consisting of a technical, industrial and business model generator", where the designers could select and compare several design options.

- *Reuse, Reverse Logistics and Take-Back Programs*

These are also end-of-use strategies. In fact, the most effective way of retaining the highest value of products is to maintain and reuse them. Taking a window as an example: it is more valuable as a window than as a pile of components and materials (PVC or aluminum from the frame, glass, etc.). So, the first steps in the technical cycle are focused on keeping products whole to retain the maximum possible value. This could include business models based on sharing, so users get access to a product rather than owning it and more people get to use it over time (e.g., rent equipment during the construction stage). It could involve reuse through resale. It could mean cycles of maintenance, repair, and refurbishment.

Reverse logistics (RL) which could be defined as a set of activities which are conducted after the sale of a product to recapture value and end the product's lifecycle, is also important to foster CE in the construction sector [48]. It typically involves returning a product to the manufacturer or distributor or forwarding it on for servicing, refurbishment or recycling. In construction, RL "refers to the movement of products and materials from salvaged buildings to a new construction site" [48]. This way we are promoting material reuse, as well as deconstruction and disassembly.

More recently, Ding et al. [49] performed a review about forward and reverse logistics for CE in construction and concluded that "while similar methods and CE strategies are used in Forward Logistics (FL) and RL, RL operations require more integration between supply chain actors to close the loop for CE in construction".

A take-back program is essentially when a brand 'takes' or 'buys' back its own materials or products. These are either cleaned, fixed and then resold by the brand at a discount or dismantled and reused in other collections or recycled in some other way. This strategy is also starting to be implemented by the construction industry [50, 51].

There is already a trade market for second hand building products and materials, such as windows and doors (see Fig. 7.5), lumber, flooring, furniture, masonry, tiles, stones, sheathing boards, appliances, architectural/decorative, lighting, heating and cooling devices, electrical, plumbing, etc., to be commercialized and reused [52–54].

(**a**) Window (rebuydeal.com [52]) (**b**) Door (rotordc.com [54])

Fig. 7.5 Examples of second-hand building products, for reuse, being traded online

- *Material Recovery*

Material recovery refers to the process of retrieving and reusing materials from construction and demolition waste (CDW). It involves identifying valuable materials within the “waste” stream and salvaging them for reuse or resale [55]. Material recovery typically involves activities such as deconstruction, which involves carefully disassembling structures to preserve valuable components. Recovered materials may include lumber [56, 57], cross laminated timber [58], bricks [59], and other items that can be repurposed in future construction projects. The goal of material recovery is to reduce waste generation, conserve resources, and minimize the environmental impact associated with extracting new raw materials.

It should be noted that CDW may have several sources, such as man- or nature-made, as illustrated in Fig. 7.6. Regarding the man-made sources of CDW, these authors split it into 3 groups, namely: (1) Public works construction and maintenance; (2) Building construction works, and; (3) Building renovation and demolition works. The main contents of these CDW, including the nature-made sources, are also mentioned in this illustration (Fig. 7.6).

Ramos et al. [60] evaluated a local scale dynamics to promote the sustainable management of CDW and concluded that these strategies must rely on investment in local solutions to optimize logistics and cost issues, cooperation between stakeholders, and improving the market for recycled aggregates. Additionally, they stated that it is essential that support is provided such as information, awareness and training, focusing on good practices onsite and oversight procedures. While material recovery

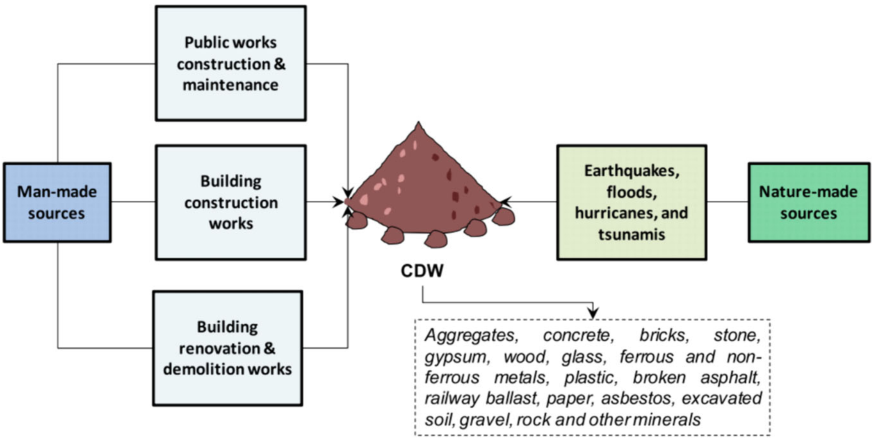

Fig. 7.6 Classification of CDW according to the source of origin [61]

focuses on salvaging and reusing whole components or materials, recycling involves breaking down waste materials to create new products or raw materials, as will be described next.

- *Material Recycling*

Recycling is an end-of-use strategy to close resource flows, by reprocessing materials to use in another product and hence avoid both waste and extraction of raw material [40]. Parts that cannot be remanufactured can be broken down into their constituent materials and recycled. While recycling should be the last option, because it means the embedded value in products and components are lost, it is vitally important as the final step that allows materials to stay in the economy and NOT end up as waste [34]. Recycling involves the transformation of waste materials into new products or raw materials, which can then be used for various purposes. In the construction sector, recycling commonly refers to the process of converting CDW into reusable materials. This can involve crushing, grinding, or shredding waste materials like concrete, asphalt, metal, and wood to create recycled aggregates [60], crushed concrete, or other materials that can replace virgin materials in construction projects.

There are a lot of studies on the viability and performance of new recycled materials, resulting from CDW, such as cement [62], concrete [63], mortars [64], gypsums [65], plasters [66], plastics [67, 68], insulation materials [69], bricks [70, 71], soil reinforcement [72] and fire-resistant materials [73]. Besides CDW, there are other sources of waste being recycled and studied to be used in the construction sector and building environment, such as: concrete [74]; mortars [75]; plasters [66, 76]; gypsum [65]; thermal break strips made of recycled tyre rubber [77, 78] and cork-rubber composites [77, 78]; plastics [79]; insulation materials such as recycled tyre rubber and silica-aerogel composites [80, 81].

7.3.2 Collaborative Approaches and Business Models

In this section, some of the innovations in business models that are affecting the construction sector in favour of CE applied to its products are collected.

1. *Circular Supply Chains and Networks*

Currently, the conversion of traditional linear supply chains into circular ones to improve the management of natural resources and reduce the volume of waste produced is included as one of the goals for the transition of the construction sector towards CE [82]. The amount of material lost in demolition processes is equivalent to 40% of the total mass of raw materials extracted in production, making the construction industry one of the most polluting industries globally [9]. In this sense, one of the most ambitious targets included in CE is "closing the loop" in the flows of raw materials and resources used throughout the life cycle of construction products [42, 49, 83]. Figure 7.7 provides a schematic overview of the relationship between the stages within the supply chain and the stakeholders.

In this general overview, a transition towards CE in the building materials supply chain requires a joint effort of all participants included in the network [84]. Therefore, it is necessary to increase transparency, avoiding possible weaknesses in the chain and gaps in the agreements. This would generate opportunities for industrial symbiosis and the integration of reverse logistics in manufacturing processes, moving towards a redesign of current industrial processes and improving coordination between resources/inventories [49]. On the other hand, the creation of a well-defined market for CDW would make it possible to increase consumer demand for these recycled products, moving towards a green supply chain that integrates the environmental costs derived from the product distribution process [26]. In addition, for a transition towards circularity in the construction sector, it is necessary to recover the secondary raw materials generated in demolished buildings at the end of their useful life and, in turn, to analyse their viability for recycling, recovery or reincorporation

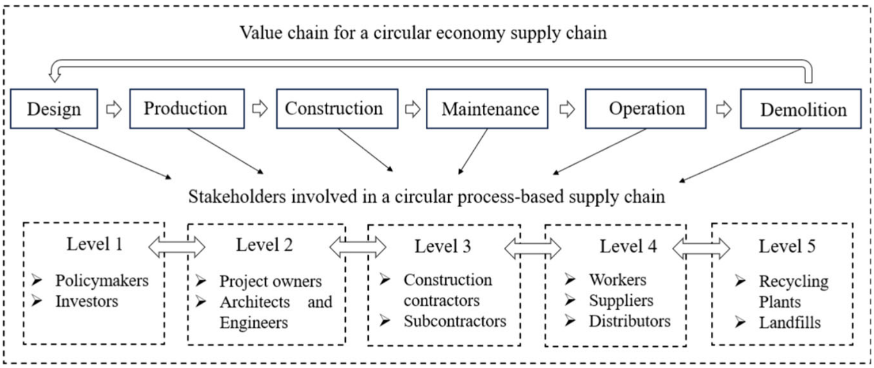

Fig. 7.7 Full supply chain cycle and stakeholders involved (*Source* own elaboration based on Cheng et al. [82])

in the production of new products [85]. At this point, several authors agree on the importance of reducing and separating CDW at source to improve its management process [86]. With this separation at the starting point, the logistical costs and environmental impact in terms of CO_2 equivalent emissions derived from transport to the processing plant would be reduced, so that both transport journeys and transported mass would be reduced.

2. *Sharing Economy and Product-as-a-Service Models*

Industrial strategies for value creation have changed radically in recent years as a consequence of globalisation and progressive technological development [87]. This evolution has affected the construction industry, which is evolving from product procurement-centred thinking towards product-service systems (PSS) [88]. In this way, building product manufacturers are forced to redesign their manufacturing processes and complexity increases in the early stages of development to accommodate this new business model [89]. By offering product-associated functionality, manufacturers are obliged to have a deep understanding of how their products behave after continuous use, which provides additional motivation to improve the skills associated with the engineering and product design stages through experience [90]. However, as in other industrial sectors, there must be a receptiveness on the part of consumers when it comes to accepting this product and service model. In this regard, Fig. 7.8 schematically shows the external and internal factors found in the literature that to a certain extent condition the acceptance of this business model in construction.

Several authors have worked with this business model trying to adapt different products to this "servitisation" process. Examples are linked to construction equipment [87], construction machinery [90], prefabricated building components [91] or building components [92]. Importantly, the product-as-a-service model brings

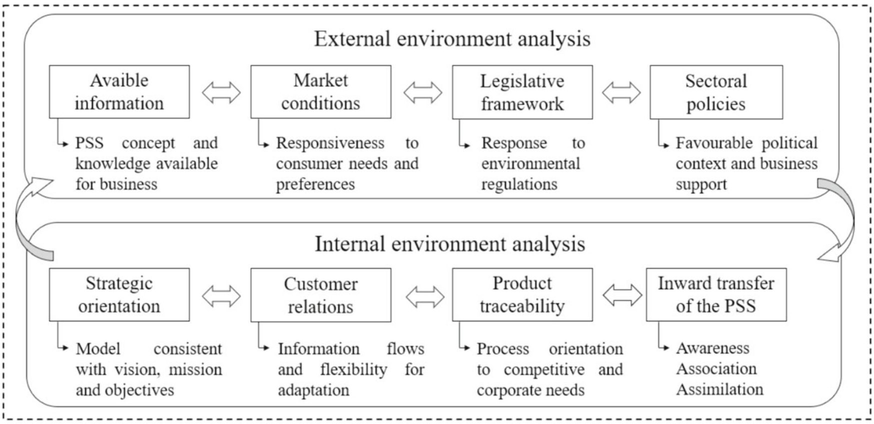

Fig. 7.8 Internal and external determinants of product-as-a-service models (*Source* own elaboration based on Cook et al. [89])

advantages from an environmental point of view, considering the full life cycle of the product and its subsequent recovery possibilities [93], as well as continuous improvement based on information sharing that boosts the sustainability of building products [88].

Finally, and in relation to the product-as-a-service business model, it is worth highlighting how in recent decades the collaborative economy has been encouraged to promote sustainability. This concept addresses the possibility of using high-priced physical assets without the need to buy them, reducing waste due to obsolescence or disuse [91]. Furthermore, thanks to the advancement of information and communication technologies, it is possible to promote a more democratic organization and reduce information asymmetries in favour of a CE in construction [94].

3. *Extended Product Responsibility*

Extended product responsibility (EPR) was first defined at the beginning of the century by Lindhqvist as a strategy to protect the environment and is intended to ensure that any product manufacturer takes responsibility for its entire life cycle, incorporating the stages of recovery, recycling, collection and disposal [95]. This approach would change the current production model affecting the construction industry by regularizing and setting the rules for the proper management of construction and demolition waste in line with the European Green Deal guidelines [1]. This approach is already being adapted for certain products around the world, such as European legislation for plastic products [96], or air conditioners and washing machines in Japan [97].

However, final construction products, understood as civil infrastructures or buildings, are complex and tailor-made entities in each design, which makes it difficult to standardize and trace the prototypes produced for the market [98]. In this sense, it is possible to think of an EPR localized to the main raw materials used in the elaboration of construction systems. However, the useful life of these is rarely less than 50 years and it is difficult to manage the final management of these products [98].

Therefore, as far as EPR is concerned, it is necessary to examine current initiatives, regulations and practices in the construction sector to understand their suitability and ability to address the issue of end-of-life management of CDW [99]. Only in this way, it will be possible to build a legislative framework for building and civil works, built on the “polluter pays” principle, encouraging producers to incorporate CE criteria in their manufacturing processes, promoting eco-design and supporting the recycling, recovery and final reuse of construction products [100, 101].

4. *Public–Private Partnerships and Policy Implications*

Public–private partnerships (PPPs) are a useful tool in the construction sector to leverage public resources and private management expertise in moving towards a circular and sustainable economy [102]. These partnerships are established based on a long-term relationship of trust, where resources, knowledge, skills and shared

Table 7.3 Advantages and disadvantages of public–private partnerships in the construction sector (*Source* Bao et al. [109])

Advantages	Disadvantages
✓ Public sectors can alleviate responsibility	✓ Long negotiation periods
✓ Private sectors can moderate investment	✓ Lack of flexibility
✓ Public sectors can draw on private sector expertise	✓ Inequality of risk and return
✓ Public–private partnership is strengthened in the long term	✓ Lack of transparency in Agreements

responsibility for decision-making are exchanged [103, 104]. However, these partnerships are not always favourable and have several advantages and disadvantages that can be seen in Table 7.3.

While it is true that PPPs are commonly accepted in the development of facilities, including design, financing and implementation [105], such as the supply of drinking water in large cities [106], in waste management for a CE there is still a long way to go. In the EU, progress is being made towards a policy framework to promote such an agreement to reduce the environmental impact of the construction sector [107]. However, this transition is slow and often not as efficient as desired and making infrastructure resilient will require a change of mindset on the part of private management and lasting support from governments [108].

7.3.3 Technological Innovations for Circular Material Usage

CE constitutes an impulse for improving the productivity of the construction sector with a need for investment in technology and digitalisation. According to Ferrer et al. [33], the scale and efficiency of networks of recycled, valued and recovered construction materials are fundamental to the following points outlined in Fig. 7.9.

Innovation ecosystems to boost re-industrialization and sustainability in the construction sector advocate the promotion and support of R + D + I (Research, Development and Innovation) and knowledge transfer instruments on: technologies 4.0; recycling and recovery of materials and components which are more complex to recycle (plastics, composites, waste); productivity improvements in component manufacturing and recovery (3D, robotics, Artificial Intelligence (AI), Internet of Things (IoT); new long-lasting materials; and materials traceability technologies (blockchain) [33].

1. *Advanced Recycling Technologies*

Resource recovery as business model and driver of CE focuses primarily on recovery of used materials or energy from waste—e.g., recycled steel and fibres, and recycled aggregates for their use in construction or in other sectors; being industrial and

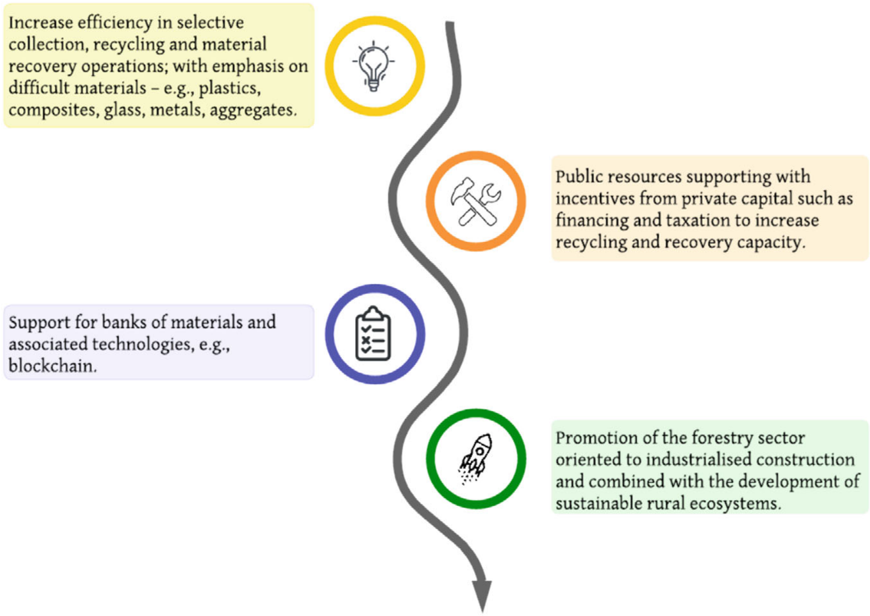

Fig. 7.9 Fundamentals in circular material usage (*Source* own elaboration based on Ferrer et al. [33])

energy symbiosis among complementary sectors essential for the adoption of the CE principles [33].

In the context of construction, disassembly and recycling best practices are employed to revalue the use of construction waste, which is often considered “low value” material. Testing methods for disassembly, treatment, and recycling would help to optimize the recovery and reuse of materials, contributing to the efficient use of resources in the production process [33]. By implementing these advanced recycling technologies, the construction industry can reduce waste, minimize the extraction of virgin resources, and promote a more sustainable approach to materials management. Furthermore, these technologies enable the transformation of waste into valuable resources, promoting the development of a CE. Recycled steel, fibres, and aggregates can be utilized in various sectors, including construction; creating a closed-loop system where materials are continuously reused and recycled. This not only reduces the environmental impact of resource extraction but also contributes to the development of a more resource-efficient and less wasteful economy [110]. Overall, advanced recycling technologies and resource recovery play a crucial role in driving the transition towards a CE by maximizing the value of waste materials and minimizing resource consumption. By adopting these technologies and principles, industries can contribute to a more sustainable and resource-efficient future.

2. *Intelligent Sorting and Separation Systems*

Intelligent sorting and separation systems are pivotal in advancing the principles of the CE by enhancing the efficiency and effectiveness of waste management and resource recovery processes. These systems leverage cutting-edge technologies such as AI, machine learning, computer vision, and robotics to accurately identify, sort, and segregate diverse materials. This enables their appropriate recycling, reuse, or recovery, thereby promoting sustainable practices. By automating the sorting process, these systems enhance the purity and quality of recovered materials, augmenting their value for subsequent reuse or recycling. Moreover, they optimize resource allocation by dynamically adjusting parameters, such as conveyor speed and sensor settings, thereby maximizing efficiency while minimizing waste. These systems also play a critical role in detecting and eliminating contaminants, thereby improving the quality of recovered materials and mitigating the risk of cross-contamination. With their exceptional accuracy and speed in sorting, they reduce manual labour requirements, increase throughput capacity, and enable the processing of larger volumes of waste. Furthermore, intelligent sorting systems generate valuable data pertaining to waste composition, quantity, and quality [33]. This data-driven approach facilitates informed decision-making, process optimization, and the development of novel recycling technologies. By integrating into circular supply chains, these systems facilitate the efficient recovery and reintroduction of recycled materials, thereby closing the loop in the CE. As technology continues to advance, these systems are poised to make significant contributions to resource efficiency, waste reduction, and sustainable material utilization.

3. *Digitalisation and Blockchain Applications*

The promotion of the guaranteed system for components and spare parts, digital traceability (European passport) and associated documentation are requirements for the delivery of sustainable and circular built environment [33]. Complementarily, financial aid for investments by industrialized and sustainable construction companies—e.g., modular design, BIM (Building Information Modelling), IoT digitalization, 3D printing, cutting robotics, …—, and support for components' banks and material passports, are proposed as drivers for offers in public–private collaboration [33].

Regarding circularity of materials, blockchain solution for materials passport embraces technology against the low transparency and traceability of the materials used—e.g., fibre plates, steels, coatings, facades. Collaborative design and manufacturing (BIM, IoT, …) benefit by the availability of new technologies which integrate design, with production and delivery systems—JIT (Just-In-Time) delivery—at the construction site.

4. *Robotic Deconstruction*

Technological innovations in deconstruction include advanced tools and techniques used to dismantle and repurpose buildings and structures in a more efficient, sustainable, and profitable manner. These innovations aim to reduce waste, minimize environmental impact, and improve safety during the deconstruction process. The use of robots for deconstruction is a promising approach that can improve efficiency and sustainability in the construction industry. Traditional demolition methods have significant risks and environmental impacts, especially in congested urban areas [111]. In Japan, alternative methods using Single-Task Construction Robots (STCRs) and semi-automated on-site factories have been developed to address legal, economic, and ecological needs. However, implementing traditional industrial robots in a deconstruction environment poses challenges, particularly in terms of human–robot interaction and collaboration. To overcome these challenges, efficient human–robot collaboration is considered in the design of deconstruction STCRs. Additionally, the application of the Robot-Oriented Design method can make the operation of the deconstruction system more efficient. Building components should be compatible with robotic applications, and connectors and joints between components should provide easy access for equipment during the disassembly phase. The use of robots for deconstruction can save energy, money, and time while minimizing casualties and disturbance to the economic environment [111]. A framework for the evaluation of robot-assisted, systemized deconstruction has been proposed, which includes performance indicators that can be adjusted based on stakeholder perspectives. Overall, the use of robots in deconstruction offers a scalable and sustainable solution for the industry.

5. *Emerging Materials and Sustainable Manufacturing Processes*

Innovation in materials, sustainable design, and the development of alternative technologies that require different materials can help mitigate supply risk. Solutions to reduce the ecological footprint and increase material recovery to improve the safety and competitiveness of production processes are within reach. However, global scenarios continue to present greater complexity and competition for natural resources [32]. The duration and footprints of carbon dioxide (CO_2), water and material consumption are lower in industrialized systems, being the environmental impact of circular and sustainable industrialized construction susceptible of different modelling scenarios of recycling percentage [33].

7.3.4 Barriers and Enablers of Circular Material Usage

Extensive literature has identified barriers and enablers to developing a circular economy in the construction sector. However, it is important to note that a circular economy is a multidimensional concept, and a closer inspection of existing literature reveals that barriers and enablers have primarily focused on the technical aspects of materials and products. According to a recent study by Charef et al. [112], barriers to the development of a circular economy in the construction sector can be categorized into six distinct types: economic (referring to market barriers), sociological (pertaining to cultural or psychological obstacles), political, organizational (involving stakeholders), technological, and environmental (concerning ecological impact). Similarly, Ababio and Lu [113] identified five categories of barriers: social and cultural, political and legislative, financial and economic, technological, and framework and theory related.

While research on barriers to circular economy development has been extensive, studies on enablers of the circular economy have yet to be conducted to the same extent. Ababio and Lu [113] have departed from classifying and listing enablers under specific categories and instead discussed them under broader themes. Generally, enablers are related to technology and innovation, policy, education and awareness, as well as financing and market creation. It is important to note that a comprehensive understanding of both barriers and enablers is critical for promoting a successful transition to a circular economy in the construction sector. This part of the report focuses on the material usage-related barriers to enablers addressed in the literature. They are discussed under four categories.

1. *Economic and Regulatory Barriers*

Numerous studies have identified insufficient and immature markets, as well as a lack of demand for reused and recycled materials, as the primary economic barriers to the implementation of circular economy practices in the construction sector [114–116]. These studies also suggest that the construction industry is often criticized for its poor flexibility in adopting innovative practices due to the perceived risk of losing profits [112, 115].

In the construction sector, adopting CE practices is met with a major challenge—the higher resource cost associated with deconstruction compared to demolition. Moreover, virgin materials tend to be less expensive than recycled materials, while recycling costs more than the disposal of CDW. Unfortunately, the recent COVID-19 pandemic has only worsened these challenges by stalling economic development and increasing the use of single-use materials. The implementation of CE practices in the construction industry requires significant investments, such as the renewal of equipment [116]. Moreover, outdated legislation and the lack of standardized guides regarding design and procurement procedures are major regulatory barriers to CE development [112, 117]. Additionally, a lack of government support and the absence of support from public institutions have been highlighted as critical barriers to CE adoption [112, 118].

In order to promote the integration of circular economy practices in the construction industry, it is necessary to adopt new business models and methods of evaluating assets that prioritize material value. For instance, long-term investments can be made to support the circular economy business case by utilizing whole-life costing. Another opportunity presented by the implementation of circular economy practices is the ability to transform the business model into a product-as-a-service contract (PSS), as noted by Rizos et al. [119]. Enablers that have been commonly identified include design-build-operate-maintain contracts and their variations, according to Ababio and Lu [113]. Furthermore, stakeholders in the construction industry have reported that implementing circular economy practices can offer more flexible working arrangements, as Torgautov et al. [117] reported.

2. *Cultural and Behavioural Challenges*

Cultural and behavioural changes can present significant obstacles to the adoption of innovative practices in the construction industry. This sector is known for its conservative nature and resistance to new ideas that challenge existing attitudes, customs, and beliefs. Some of the cultural issues that hinder the adoption of circular economy (CE) and sustainability practices among construction stakeholders include a lack of awareness, reluctance, and risk aversion. Moreover, there is a preference for virgin construction materials over reused and recycled products, which is reinforced by ingrained beliefs that circular economy practices are not feasible [112, 118].

Several studies have investigated stakeholders' perceptions of the adoption of CE practices in the construction industry. The literature reviewed in this section highlights that contractors are hesitant to use refurbished and recycled materials in their construction due to concerns about a potential decrease in the quality of their products [27, 112, 118]. Customers, on the other hand, may not prefer buildings constructed using old materials. Additionally, the quality of recovered materials is often perceived as inferior to virgin materials, further fuelling scepticism about the feasibility of CE practices [117].

3. *Stakeholder Engagement and Awareness*

In order to facilitate the widespread adoption of circular economy (CE) practices in the construction industry, it is important to address the existing cultural and behavioural barriers. This can be achieved through a variety of means, such as education, awareness-raising, and cultural change initiatives. By doing so, stakeholders can work towards creating a more sustainable and circular economy, which would not only benefit the industry but also the environment.

One effective enabling tool for increasing awareness, changing attitudes, and affecting behaviours is dialogue [113]. This can involve open and honest communication between different groups of stakeholders, including industry professionals, academics, and government officials. Through dialogue, stakeholders can gain a better understanding of each other's perspectives and work collaboratively towards finding solutions to industry challenges.

Academic curricula and professional workshops are also important enablers for capturing CE and its range of sustainable practices [113]. These educational opportunities provide stakeholders with the requisite ideas and knowledge to address industry challenges. Additionally, they help to ensure that industry professionals are equipped with the skills and expertise needed to implement sustainable practices in their work. By investing in education and training opportunities, stakeholders can work towards a more sustainable and circular economy in the construction industry.

4. *Governmental Support and Incentives*

The global construction industry is facing a significant challenge in embracing circular practices and business models due to the absence of adequate policies, laws, and frameworks. The lack of government support, such as financial aid or tax incentives, is making it less economically feasible to invest in circular models, and as a result, discouraging their adoption. The absence of regulatory pressure and strict laws also fails to establish the necessary urgency for circularity, and the required behavioural changes in the construction industry are not taking place. This is a pressing issue that needs to be addressed so that the construction industry can move towards a more sustainable and circular future [27]. Sustainable development is becoming increasingly essential, and as a result, circular buildings are gaining popularity. The main objective of circular buildings is to foster the idea of "building as a material bank" [115], where the materials used in the construction are stored and reused when the building's life comes to an end. However, this can only be achieved if there is a financial incentive to design buildings that can be easily deconstructed and reconstructed. It is worth noting that circular buildings are generally more costly than traditional buildings.

The circular economy in the construction industry is a complex issue that requires the involvement of all stakeholders, including governments, investors, designers, constructors, and users. The transition towards circular practices requires a significant change in mindset and approach, as well as the adoption of new technologies and systems. Nonetheless, the benefits of circularity in the construction industry are far-reaching, including reduced waste and carbon emissions, increased resource efficiency, and improved social and economic outcomes. Therefore, it is essential for all stakeholders to collaborate and work towards a more sustainable future for the construction industry.

7.4 Case Studies and Best Practices

7.4.1 Case Study 1—Gonsi Sócrates Bio-building (Barcelona, Spain)

Figure 7.10 shows the Gonsi Sócrates Bio-Building which was built by Construcía Company. They followed the Lean2Cradle® circular construction methodology [120]. Almost all the building materials (99%) were characterized and its components were reviewed, and up to 50 types of materials were inventoried. Among these materials, 89% (8,400 tons) will not become waste at their end-of-life but have a circular way to be reintroduced into the production process. Thus, when the useful life of the building ends, they can be reused, repaired or recycled in the way that is most convenient at that time, allowing them to preserve greater value for the next use [121].

Fig. 7.10 Gonsi Sócrates bio-building [122]

Another best practice used in this building was to have 'grey' finishes as a sustainable measure to avoid wasting possible materials in future adaptations required by new tenants. For example, laminated plasterboard partitions were removed to be recovered onsite. The plasterboards were temporarily stored in an available space in the same building. The three components of the laminated plasterboard partitions were separated: metal, plaster and rock wool and the following treatment was given to each of these materials [122, 123]:

– Metal: highly recyclable secondary material, which was easily reintroduced into the system as a material.
– Plasterboard: in the absence of a nearby recycling plant, a nearby construction building conducted by the same construction company was used to take the plasterboards. In that work, there was a shredding machine that allows the recycling of Cradle2Cradle laminated plasterboard.
– Rock wool: In this case, the remains of rock wool were concentrated to be recovered by Rockwool, which was the supplier responsible for recovering the work surplus.

7.4.2 Case Study 2—Urban Mining and Recycling (UMAR) Experimental Unit (Dübendorf, Switzerland)

The UMAR building (Fig. 7.11) was designed by Werner Sobek with Dirk E. Hebel and Felix Heisel and they considered a circular approach keeping a technological and advanced design and architectural form. Such an approach makes reusing and repurposing materials just as important as recycling and upcycling them. This conceptual emphasis means that UMAR works simultaneously as a material laboratory and a temporary material storage. The UMAR unit was designed and built as a prototype, showcase and demonstrator for a paradigm shift towards a circular building industry [124]. As such, the documentation of the materials, design, details and construction process are a crucial aspect of the process.

Several elements of this documentation have been implemented already: A material library within the unit offers samples of all materials used in construction. These samples are additionally linked to a digital material library with further information, data sheets and contact details on the project's website [125]. Some of the circular material used were [126]:

– StoneCycling® are waste-based bricks available in different colours and textures and are named according to their appearance for example "Wasabi" or "Salami" (Fig. 7.12). The construction material from rubble meets industry standards and can be used indoors and outdoors [127].
– Magna Glaskeramik is a very durable translucent material made with glass waste. Glass waste is first broken into pieces and then undergoes a complex sintering process without the addition of binders or the use of pressure, only utilising temperature and time. The colour of the material depends on the colour of the raw material used in production. It was used for the finishing material of the toilets [126, 128].
– ReWall® [129] consists of shredded and compressed beverage cartons to develop a floor-ceiling panel (Fig. 7.13). The board material is durable, moisture resistant

Fig. 7.11 Urban Mining and Recycling (UMAR) experimental unit [125]

Fig. 7.12 StoneCycling® [126]

Fig. 7.13 ReWall® NakedBoard [126, 129]

and contains no volatile organic compounds. It was used as interior partition, as alternative to gypsum boards. Similar research works have been conducted to ass the recyclability of beverage cartons [130].

– Ecor flatcor/Ecor brow. ECOR products are flexible, high density, compression moulded fibre board made from 100% waste cellulose. The plates are formed by water, heat and pressure, without any other additives [126].
– Ecobase carpet tiles gold. The tiles are equipped generally with a EcoBase™ backing, which contains recycled calcium carbonate from local drinking water companies through an upcycling process. Due to these recycling-oriented resources, the company now shifted to leasing concepts for their carpet tiles in order to be able to feed them back into the own production line after used [126].
– Natura 2. Water hyacinths or water lilies are free-swimming, perennial aquatic plants abundant in the Philippines. Cutting of the plants is required regularly to keep the waterways free for shipping and animals [126].

- Black Dapple sheets are made from recycled plastics, and available in different colour combinations. Depending on the raw material and its colour, the end product has a certain translucency. The material has a high hardness and density, good UV and weather resistance and a moderate scratch resistance. Dapple sheets are 100% waterproof. The massive material can be cut, drilled and milled [126].
- Ultratouch™ denim insulation. In the production process, cotton fabric from denim waste is shredded again into fibrous form and treated with a Boron salt solution. This gives the material mold and fungus repellent properties and ensures fire protection. The fibre mixture is then baked in a large oven and pressed to different thicknesses [126, 131].

7.4.3 Case Study 3—Open-Spaced Apartment (Prague, Czechia)

It is a small apartment renovated by Papundekl Architects, which the architects proposed to remove all the original prefabricated partitions (Fig. 7.14). All of these main elements are clad in recycled Packwall boards around their perimeter [132]. The coloured boards can also be used for the more operationally demanding parts of the furniture, such as the opening or sliding parts of the kitchen island or wardrobes. The PackWall [133] board is classified as semi-permeable, where water does not penetrate the surface, but the steam can travel through the material.

Recoma's recycled construction boards are versatile with infinites possibilities for application. Recoma's recycle 4,000,000 kg composite packaging per year which would otherwise go through waste streams where the majority of the material would have been incinerated. Material recycling instead incinerating this waste saves CO_2 emissions by 2700 tons per year. Recoma's products are also 100% recyclable without any waste, emissions or extra costs, since they can be made into new boards are RECOMA in a circular solution [134].

Fig. 7.14 Apartment designed by Papundekl Architects (left) and recovered construction board (right) [132, 134]

Fig. 7.15 *SKY techos ecosostenibles* [135]

*7.4.4 Case Study 4—"***Escuela Politécnica Superior***" (Burgos, Spain)*

Within the context of the Life Repolyuse European Project led by the University of Burgos, a new building product to reduce polyurethane waste was designed and implemented in three building case studies located in Coventry, Vitoria and Burgos (Fig. 7.15) [135]. The building product is named "*SKY techos ecosostenibles*" and is supplied by Yesyforma [136]. The panel consists of a new ceiling plate (plaster + polyurethane waste) which promotes the reuse of polyurethane waste by integrating it into new construction materials, thus prolonging the life cycle of this plastic material and avoiding its final disposal [137]. This material provides extra lightness and improves acoustic absorption compared to regular false ceiling plates, creating a more comfortable and conditioned environment.

The polyurethane foam waste comes from the refrigeration industry, specifically, it is generated from the manufacture of insulation slabs, they are those which are rejected at the production line or from those which are used for various manufacturing tests. The type of PU waste used in this research is a rigid polyurethane foam and is made out of two components which are polyol and isocyanate, this has an open cell structure.

7.5 Final Remarks

This chapter examines the primary challenges associated with using circular construction materials and suggests collaborative solutions to address them. Implementing circular principles in construction materials has the potential to transform sustainable building practices. Adopting this approach can significantly lessen the construction industry's environmental footprint, conserve natural resources, and create a more resilient built environment. Nevertheless, numerous obstacles need to be overcome to enable the broad adoption of circular construction materials.

This chapter provides specific recommendations for overcoming the challenges associated with the widespread adoption of circular construction materials and outlines future directions. The interdisciplinary study also examines strategies and principles for using circular materials in buildings, identifying various barriers, critical success factors, and enablers within this research area.

The construction sector is a major contributor to waste generation and resource consumption, yet it holds significant potential to lead the transition to a circular economy. By adopting design principles focused on circular material usage, the construction industry can reduce its environmental impact, conserve resources, and promote sustainable material practices. Key design principles for circular material usage include designing for circularity and managing material selection. Buildings should be designed to be durable, adaptable, and easy to disassemble, facilitating the reuse, recycling, and upcycling of materials at the end of their lifecycle. Construction materials should be chosen based on their environmental impact, recyclability, and durability, while construction waste should be minimized and managed to maximize material recovery. Implementing these principles requires collaboration among all stakeholders in the construction sector, including architects, engineers, contractors, and material suppliers. The benefits of a more circular construction sector are substantial: increased sustainability, resilience, competitiveness, cost reduction, innovation, and job creation.

Furthermore, it is highlighted the critical shift towards a circular economy (CE) in the building sector, emphasizing the need for collaborative business models and technological innovations. Key elements for sustainability include circular supply chains, product-as-a-service models, and extended product responsibility. While public–private partnerships show promise, they require careful management. Future efforts should concentrate on establishing robust regulatory frameworks, awareness programs, and international collaboration. Integrating technological advancements such as AI, robotics, and blockchain is essential for efficient waste management. Educating stakeholders on circular practices is crucial. Global collaboration can help standardize circular construction methods, leading to a more sustainable and resilient industry. This review advocates for a focus on resource efficiency, circular practices, innovation, stakeholder collaboration, and adaptive strategies to minimize environmental impact and enhance sustainability throughout the construction sector's operations.

Based on the conclusions drawn from this study, applying CE principles in the construction industry has significant and far-reaching implications. This research offers actionable steps for integrating these principles into practice, including design principles for circular material usage, stakeholder collaboration, technological integration, and the establishment of robust regulatory frameworks. These recommendations provide a roadmap for future implementations and a practical framework for policymakers, practitioners, and stakeholders to adopt and apply these principles. By embracing these recommendations, the construction industry can transition towards a more sustainable and resilient future, reducing environmental impact, conserving resources, and fostering innovation. Furthermore, integrating these principles supports the broader global sustainability agenda, significantly advancing CE practices beyond the construction sector.

This chapter related to implementing CE principles in the construction industry has revealed crucial insights for enhancing sustainability and reducing environmental impact. However, the slow adoption of these principles is due to industry-specific barriers such as limited knowledge and experience. Therefore, a collective effort to educate and disseminate information is essential to overcome these obstacles. Embracing innovation offers a promising path to promoting circularity. Successful case studies of circular practices can provide valuable insights for wider industry adoption. Developing robust regulatory frameworks can incentivize sustainable practices, and integrating advanced technologies can optimize waste management processes. Education on circular practices is vital, and global collaboration is essential for standardizing universally accepted approaches.

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