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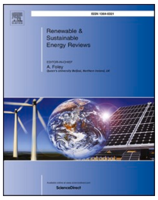

Mapping circular economy practices for steel, cement, glass, brick, insulation, and wood – A review for climate mitigation modeling

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ABSTRACT

Circular economy (CE) practices pave the way for the construction sector to become less material- and carbon-intensive. However, for CE quantification by climate mitigation models, one must first identify the CE practices along a product (or material) value chain. In this review, CE practices are mapped for the value chain of 6 construction materials to understand how these practices influence and can be considered in climate mitigation modelling. The main sub-categories of steel, cement, glass, clay-brick, insulation materials, and wood were used to identify which Rs are currently addressed at the lab and industrial scales: refuse, reduce, rethink, repair, reuse, remanufacture, refurbish, repurpose, recycle, and recover. The CE practices were reviewed using scientific repositories and grey literature, validated by European-wide stakeholders, and mapped across the life-cycle stages of the six materials – extraction, manufacturing, use, and end-of-life (EoL). The mapping was limited to the manufacturing and EoL stages because materials could be identified at these stages (the extraction phase pertains to resources, and the use phase to a product, for example, buildings). All reviewed CE practices identified at the industrial scale were quantified at the European level. For example, EoL reinforcement steel is 1–11 % reused and 70–95 % recycled; manufacturing CEM I is up to 60 % reduced; remanufacturing flat glass is 26 % remanufactured while less than 5 % EoL flat glass is recycled. A major barrier to closed-loop recycling is the need for sorting and separation technologies. Open-loop recycling synergies are found at the industrial scale between, for example, flat glass and glass wool value chains. Climate mitigation models are proposed to be augmented to include these practices requiring an explicit link between building use and the other construction materials' value chain stages.

1. Introduction

Circular economy (CE) and climate mitigation (CM) are two of society's main current challenges. CE has been listed as one of the avenues to achieve the ambitious carbon neutrality goal established by the Paris Agreement (2019). A concept first introduced in the 1970s [1], CE has become widespread with definitions and policies that support various stakeholders- [2]. Nevertheless, there are disagreements on how CE applications can achieve sustainability perspectives [3] since circularity is a vague term lacking clear targets and consensual definitions [2,4]. The ten Rs framework is widely accepted [5,6] – henceforth, the R framework – where the different waste management terms are combined and defined [7].

Quantification of the different Rs is nonetheless a challenge. Myriad studies list circularity indicators guidelines [8,9], but they often focus “on specific materials, substances, or products and are usually limited to applying relative indicators or rates” [10]. These metrics are frequently derived from other indicators, namely aggregated national, continental, or global economic data. Has et al. (2020) suggested that CE

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List of abbreviations

CE	Circular economy
CM	Climate mitigation
C&DW	Construction and demolition waste
EoL	End of Life
GHG	Greenhouse gas emissions
Lab	Laboratory
LCA	life cycle assessment
Mt	megatonnes
R framework	Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover

quantification should pursue a system-wide perspective to accurately quantify its contributions to emissions reduction and CM. Most notably, the claims that CE contributes – or may contribute – to climate mitigation are abundant [5,11–13]. Instead of reducing CE complexity into a single metric for circularity [14], CE can still be implemented from a system-wide perspective by embedding the R framework into CM models [15]. These models are vital for policy decision-support assessing pathways towards a carbon-neutral economy [16,17]. But they are not prepared to include CE practices and thus determine their role in meeting CM targets [15]. Currently, there are only two published studies in which CE has been considered in CM models: the recent EU impact assessment accompanying the 2040 CM target [18] and the other case in the Portuguese Carbon Neutrality Roadmap [19]. In both cases, CM was satisfied by modifying the exogenous CM model assumptions on primary material production (e.g., steel, cement, glass, etc.) or mobility needs (e.g., passenger·km). The lower needs are due to the adoption of CE practices, namely rethink, repair, reuse, refurbishing, and recycling, but there is no clear relation between the level of CE practices and the CM model inputs. In both cases, CM models are run with and without considering CE impacts on material and mobility demand, and results are compared to quantify the role of CE for CM. At the time of this review, no studies have included CE and the R framework in CM models. One of the motives for this is the inherent difference between the two domains. The R framework does not consider embodied energy (and greenhouse gas emissions – GHG) [20]. Some CE analytical tools, such as LCA, consider a certain moment in time, while CM models, by default, deal with time horizons of decades and account for technology improvement. Similarly, LCA tends to neglect the overall system impacts of decarbonization across the whole energy system, while CM models inherently need to consider all interconnected components of the energy system [20]. CM models have a relatively poor representation of all indirect (or embodied) GHG emissions due to the higher energy needed for manufacturing low-carbon technologies [20,21]. Current CE scenarios often include and focus on replacing energy sources, e.g., coal or petroleum, with natural gas or renewable energy sources but do not differentiate those measures from methods tackling materials themselves [13]. To capitalize on eventual synergies between CE and CM, it is necessary to bridge these two domains, better aligning their respective tools and analytical approaches [15].

Among all the CE and CM modelling integration areas, buildings (and construction materials) are gaining attention. Buildings in urban and industrial areas are one of the main culprits for carbon emissions and the main sink for construction materials [22]. Besides consuming the most carbon-intensive materials [11], the building industry consumes the largest fraction of mineral resources, possesses one of the highest carbon footprints, and produces the most waste [23,24].

Main GHG-saving CE practices use bio-based materials, sharing practices, urban farming, and recycling building facades [25]. Current regulations for CE implementation are scarce, but the European Committee for Standardization has released a preliminary standard that specifies circular principles and guidelines for the construction sector CEN/TC350/SC1 [26]. As circularity is established in the field, standardization is nascent, quantitative targets are skewed, and a holistic understanding of its impacts on CM needs to be included. This is because efforts to understand the effects of CE on climate mitigation in the building sector are recent [25,27] and are still based on micro-meso scale approaches such as life cycle assessment (LCA). LCA commonly disregards technology improvements over time and cross-sector/product effects of simultaneous decarbonization actions on the whole energy system [20]. These are two features required for CM modelling. Despite being a resource/material-centric activity, several authors claim CE will help the building industry achieve 38 % [28] or 61 % [29] carbon emission reductions. This is based on previous works that allocate most emissions to manufacturing construction materials [24].

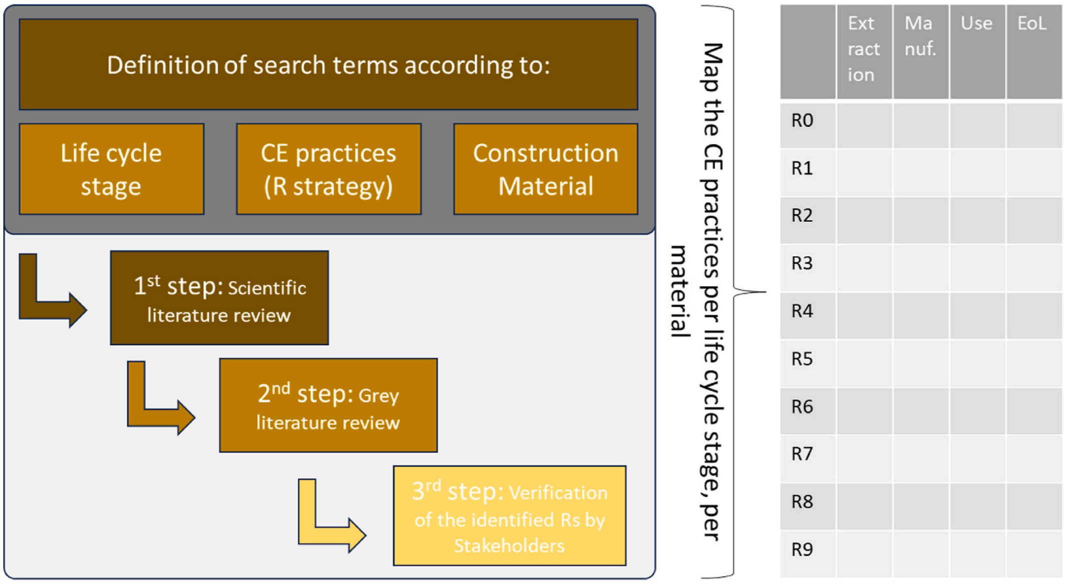


Fig. 1. Schematic representation of the review steps, from the definition of the keywords to the different steps carried out to identify the CE practices and map them according to the life-cycle stage. The table on the right exemplifies the conceptual framework (Fig. 2) skeleton and how the CE were mapped per material. CE – Circular Economy.

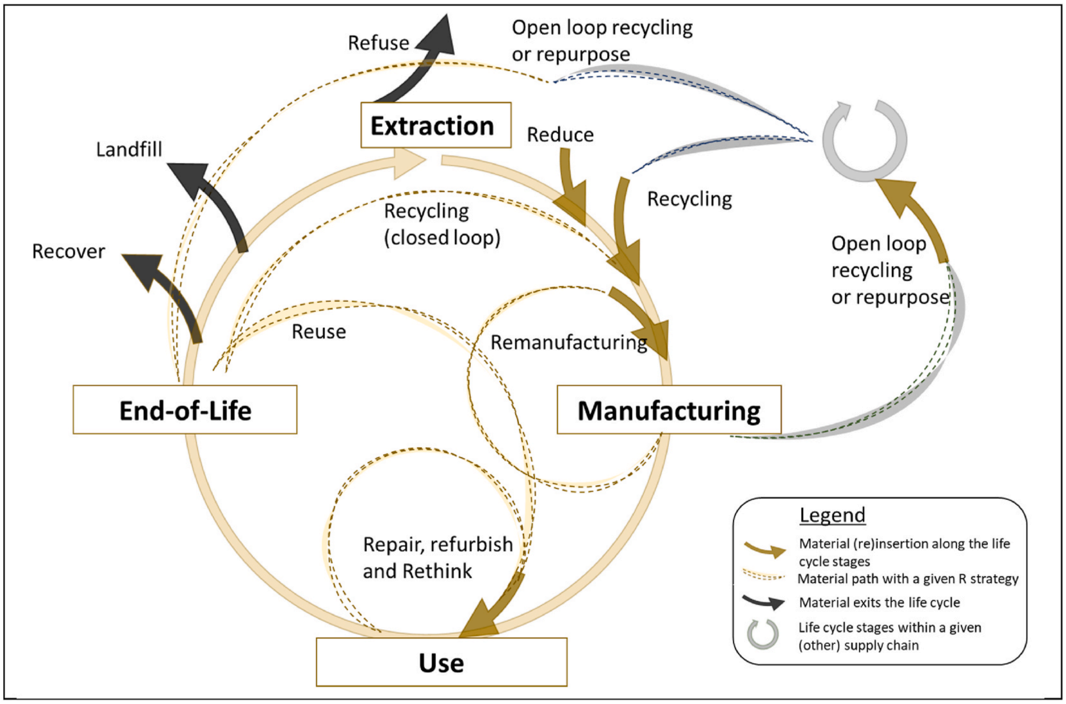


Fig. 2. Conceptualization of the R framework. The cycle graphically represents the dynamic movement of materials across life-cycle stages according to the implemented R strategy.

As the dynamics of CE are better understood, rebound effects can occur [30]. Downsides might be varied, such as (i) reduced quality of construction materials, (ii) reduced efficiency in lowering carbon emissions, (iii) challenging quantification of higher Rs, and (iv) higher overall transport needs [31]. To fully understand the role of CE for CM, it is thus necessary to include circularity in CM modelling, zooming in on the building's value chain. This, in turn, entails two main tasks: (1) systematic review and quantification of relevant CE practices along the construction materials value chain, and (2) modelling these explicitly in CM models, not forgetting associated transport needs. Only more integrated and circular CM models allow CE trade-offs and benefits towards carbon neutrality to be addressed [15]. The scope of this review is to provide a circular economy life-cycle-based framework to be used in climate mitigation modelling. CE practices will be mapped along the value chain for later integration in CM (and other) models. The framework is used to structure a detailed review of CE practices for 6 of the most used construction materials – steel, cement, glass, clay-based materials, insulation materials, and wood- and identifies the technological efficiency metrics of each material R. This review finalizes with a map of identified interactions across the value chains (open-loop recycling) and suggestions on how to couple CE practices to CM models. Some of the construction industry's European-wide stakeholders verified the practices.

This review is structured with a methodology section following the introduction. After that, the conceptual framework is presented, followed by the results from the CE practices review for each construction material. A discussion and conclusions ensue.

2. Methodology

The methodology for this review was loosely based on [32] and is schematically represented in Fig. 1. First, the terms used in the review are defined (3.1.), and then the review process is proceeded with (3.2). Once the scientific review was done (section 3.3.), a grey literature review was done using the exact search words as in the scientific review. Lastly, the R strategies were validated by engaging with stakeholders in the processing of these materials. The following sections describe the process in detail.

2.1. Definition of keyword

2.1.1. Life cycle stages

First, the life cycle stages were defined for each material's production. The stages in which most of the emissions of the construction industry are extraction, manufacturing, use, and end-of-life (EoL). Each step pertains to a stage of the material level of maturity.

At the **extraction phase**, raw materials or natural resources are extracted; therefore, there needs to be a higher level of processing. This phase is equivalent to mining/quarrying.

Different raw materials come together in the manufacturing phase to produce a construction material. At the manufacturing phase, the materials are produced and used downstream as building blocks for products (in this case, buildings). These materials are steel, cement, glass, clay-based materials, insulation materials, and wood.

The **use phase** of construction materials intrinsically needs an object or product, where different materials are combined and take the form of a product. Construction materials can be used in many products –buildings, and infrastructure.

Lastly, there is the **EoL phase**, the end-of-life phase. The construction sector EoL has two types of demolition: conventional demolition and selective demolition. Conventional demolition has minimal selection and sorting of materials. Selective demolition has in mind the reuse of materials for the same end. End-of-life includes demolition and waste management.

2.1.2. CE practices

In this section, the R10 framework was adopted [7]. To adapt the terms to the construction sector – specifically construction materials –Table 1 definitions were developed, where CE strategies/practices are described and adapted from Potting et al. [7]. The search keywords may vary from a combination of these ten words with the addition of "circular economy" as a keyword. The *R* keywords used are listed in Table 1 and are refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover.

Table 1
Construction materials and their sub-category considered in this review. The material sub-categories selected for this study are also identified, and a justification for their selection is given.

Construction material	Identified sub-category	Selected sub-class for this study	Justification for material sub-classification selection
Steel	Structural steel Reinforcement bar	Reinforcement bar	Over half (52 %) of all steel will be used in the construction sector in 2022 [33], and reinforcement bars contribute around 30 % of construction steel [34]. This is arguably one of the most steel products, as structural steel represents 17 % [35].
Cement	CEM I – CEM VI	CEM I	The most used binder materials are of the Portland cement family (EN 197-1). The cement clinker is the reactive component that activates supplementary materials of different chemical compositions (such as CEM II) cements. Clinker phases need to be produced from demolition waste to make circular cementitious binders. Hence, Portland cement (CEM I) type binders were adopted, allowing for the highest recovery rate.
Glass	Flat glass Glass fiber	Flat glass	Flat glass is the main glass product produced in Europe. Data retrieved from [36]
Clay-based materials	Brick	Brick	Non-refractory building bricks, clay blocks for walls, and bricks for masonry [37].
Insulation materials	Glass wool Stone wool EPS/XPS PUR/PIR Bio-based	Glass wool	Top 1 insulation material by volume on the European market, accounts for 1/3 of the total volume (IAL Consultants, 2022)
Wood	Sawn wood Particle board Fibre board	Sawn wood	Sawn wood is the main wood product manufactured in the EU [38]. In addition, sawn wood marks the start of cascade utilization.

2.1.3. Construction materials

The search was limited to 6 construction materials: steel, cement, glass, clay-based materials, insulation materials, and wood. Within each material, only 1 sub-classification of materials was considered to simplify this review. These sub-classifications of materials and the justification for the selection are presented in Table 2. Finally, reinforcement bars, Portland cement (CEM I), flat glass, brick, glass wool, and sawn wood were used as keywords for the review.

2.2. Literature review

For the literature review, efforts were split into three successive phases: (i) Scientific research-based literature, (ii) Grey literature with industrial current practices, and (iii) Workshop/interview with knowledge experts/stakeholders.

While phases (i) and (ii) serve as catalogues and information gathering of CE practices, phase (iii) – the stakeholder workshop – serves to validate/refine the identified practices. This last phase also gathers expertise from practitioners and the industry.

2.2.1. Scientific literature review

A series of keywords were selected to undertake the research-based literature, and used different sources to develop a final database. This was done systematically per material, noting the number of publications found per search combination. Table 3 summarizes the search terms and search findings per material, while the full literature review protocol can be found in Table S1 in the supplementary information. A short note on the source used for the literature research – DTU Findit was used as an engine as an alternative to Scopus or ScienceDirect in some cases. The reason is that DTU Findit uses ScienceDirect and other engines as described here (https://findit.dtu.dk/en/about/providers). The reasons for excluding documents are also summarized in Table 3, but generally, they refer to these three main reasons.

- Eliminated duplicate papers, counted in the different criteria;
- Transferred the papers that were not related to the topic to the corresponding materials (e.g., papers that did not mention glass but mentioned bricks);
- Eliminated the papers that did not pertain to the materials at hand (e.g., container glass waste when referring to flat glass waste).

2.2.2. Grey literature

The grey literature review was done using the freely available search engines Google and DuckDuckGo.com during April and May 2023. Grey literature materials and research are documents produced by organizations outside of traditional commercial or academic publishing, such as reports developed by industries and institutions. The procedure for each construction material is described in Table 4; the criteria varied according to the material. Some materials presented more options, so the search was more extensive. Nevertheless, grey literature provided between 8 and 42 extra references (Table 4).

2.2.3. Stakeholder engagement

After selecting the main CE practices for each of the materials, an online workshop was organized on the 15th of June of 2023 with interested stakeholders associated with the six value chains under study. The workshop showed and discussed the practices identified and, finally, validated the practices reviewed. The sessions were split per material reviewed, where each stakeholder was engaged in their expert area. An illustration of the presentation for flat glass can be seen in section S2 of the supplementary material, as well as questions asked to the stakeholders. The stakeholders present in the workshop are European institutions and European-wide industries, and their entity names will not be disclosed for privacy reasons. The information provided by the industry can be found in greater detail in Section 4, labeled as personal communication, followed by the date of the 15th of June. All information relates to the identified CE practices, their estimates, decision criteria, and other relevant information.

2.3. Conceptual framework

To derive guidelines that allow the adaptation of the existing R framework to CM modelling (and other meso-to-macro) models, the R concepts across the four stages of a life cycle were described: (i) extraction, (ii) manufacturing, (iii) use phase and (iv) EoL. These stages are common to most models, independent of their level of complexity, from high-to low-resolution models [40].

The R strategies framework establishes a hierarchical set of strategies that aligns well with the waste hierarchy of the EU Waste Framework Directive (2008/98/EC), particularly in preventing waste generation [7,

Table 2
Summary of keywords and number of publications found per material.

Approach details	Steel	Cement	Glass	Clay-based	Insulation Materials	Wood
	Reinforcement bars (steel)	CEM I	Flat glass	Brick	Glass Wool	Sawn wood
Source:	DTU FindIt	DTU FindIt	DTU FindIt	DTU FindIt	Scopus	Researchgate, ScienceDirect
Search terms (more details, see Table S1)	Circular, economy, recycling, reinforcement, bar, rebar, steel, manufacturing, construction, demolition	Recycling, cement, demolition, circular economy, concrete, manufacturing, clinker, slag	CE, flat glass, manufacturing, construction, demolition, recycling, extraction	Circular, economy, brick, manufacturing, extraction, construction, demolition, recycling	Glass wool, fibreglass (fiberglass), reuse, recycling, repurpose, manufacturing, construction, demolition, CE	Wood, building material, construction, circular economy, eoL strategies,
Reason for excluding studies	Excluded studies on concrete aggregate, steel slag, and glass concrete. Repeated articles were deleted.	Excluded aggregate recycling (lightweight, sand and gravel), soil stabilization, small scale of material volume, investigation on clinker diluted binders without circularity	Excluded glass from other end uses besides flat glass, such as PV, LCD, ceramics. Repeated articles were deleted.	Excluded unfired bricks, earth construction, and ceramics for purposes other than construction. Repeated articles were deleted.	Excluded papers with a focus on stone wool and glass fiber. Two relevant papers, but information is not available.	Excluded networks, consumer perceptions, furniture wood, paper, wood plastic composites, chemistry, agriculture
Review date	May 16, 2023	May 23, 2023	March 13, 2023	April 27, 2023	19/05/23	April 28, 2023, May 02, 2023
Total # articles	454	169	209	118	175	445
# after selection	*25*	*56*	*71*	*25*	*14*	*57*

41]. To avoid waste, the framework prioritizes minimization of resource extraction by recycling, reusing, repairing, etc., and keeping materials longer in the value chain. In the case of construction materials, a material can also be a product (e.g., glass is a construction material but also a product that could be used without being combined with other materials to create, for instance, a window). This agrees with the latest European Commission CE plan [42], where substantial material savings are predicted through value chains and production processes. In contrast, extra value can be generated, and economic opportunities can be unlocked [5]. Determining the quantity and quality of these savings is key to achieving a truly sustainable framework. The R framework was then adapted to a given life cycle stage (Fig. 1). The concepts used in this study are adapted from the extensive current body of work available on CE, e.g. Refs. [6,7,39], and described in Table 1.

Once the Rs were allocated to a given life cycle stage, the R framework can be conceptualized in terms of life-cycle stages (Fig. 2). It is worth noting that some studies have already attempted this conceptualization, e.g. Refs. [43,44], but to couple it to life cycle assessment (LCA) methodology. This review uses Fig. 2 framework to allocate the reviewed CE practices.

A consideration regarding the allocation of Rs to the four considered life cycle stages should be expanded. For most reviewed practices, it was not possible to distinguish between them while using the keywords "extraction", "manufacturing", "use" and "EoL". Instead, the CE strategies for construction materials are allocated mostly at the manufacturing and EoL stages. Fig. 3 (left) represents the Rs allocation based on conceptual definitions in the framework (Table 1, Fig. 2) and compares it with what was found in reviewed CE practices in the literature (Fig. 3, right). At the extraction phase, the keywords apply to resources (or raw materials) like sand, iron ore, etc. The R strategies at the use phase are repair and refurbish since this phase refers to a product – in the construction sector, a building, or composite aspects of components. This is exemplified by, for example, windows, where the window itself is composed of aluminum, polymer, and flat glass or wood, polymer, and flat glass. This is to mention the 6 considered materials, where the complexity of buildings increases exponentially with recent constructions. Quantitating the repair or refurbishment of individual materials is challenging, as the components are normally refurbished in tandem. Returning to the example of flat glass, if the glass is broken, flat glass is seldom repaired – the window is replaced, and flat glass is then taken for recycling. Here, the EoL stage is being addressed again. Another example would be the refurbishment of walls with new insulation. For this, the wall is deconstructed (or demolished), and the bricks would be reused in the optimum case. For refurbishment, new insulation material and new mortar are needed, which would be new materials for the mortar (cement and aggregates). The old insulation material would be recycled – but most likely landfilled – and the former mortar would be added to CD&W. In this case, individual materials are again addressed at the EoL phase. For simplicity, the flow of materials was chosen as the unit of analysis. Thus, the extraction and use phases were addressed separately, while this study focuses on the manufacturing and EoL stages (see Fig. 3 for a summary).

3. Results from CE practices review

Construction materials production has been rising in recent years, and with the rise in output, an increase in waste at the EoL of these materials can be expected. CE strategies reduce the total waste produced and are expected to minimize the resource extraction burden. The following sections present the main results regarding CE practices found along the life cycle of CEM I, reinforcement bars, flat glass, brick, glass wool, and sawn wood. These six materials were found to be both full industrial-scale CE practices implemented along the different stages of their life cycle and emerging practices currently still at the lab scale. Table 5 summarizes the CE practices identified in the manufacturing and EoL stages, offering an overview and classifying them at a full industrial or laboratory scale. For the full industrial scale, the practices adopted by the industry were considered – all other practices are considered here at the laboratory level. Some emerging practices exist beyond the lab scale, but for simplicity scale will not be further discriminated.

Except for sawn wood, a primary biomaterial, CEM I, reinforcement bars, flat glass, brick, and glass wool, they consist of a blend of different raw materials, which might vary in weight for their contribution to CM. For example, fossil fuel-based materials are more expressive regarding CM but do not impact CE practices much. Next, the individual materials CE practices and their potential (positive or negative) effect on some of the resources used are described for each considered construction material.

Table 3
Summary of search engine, keywords, and number of publications found per search performed.

Material - sub-material	Search strategy(s), including how items were selected	# of items selected
Steel - Reinforcement bar	Search keywords: 1 “circular economy” "rebar" "manufacturing" 2 “recycling” "rebar" "manufacturing"	12
Cement – CEM I	Search keywords: 1) recycling AND cement* AND demolition 2) circular AND economy AND concrete AND manufacturing 3) recycling AND concrete AND manufacturing *Selection: Items were selected by scanning the first 5 pages (50 results) from each search*	42
Glass – Flat glass	Search keywords: 1 circular economy flat glass manufacturing 2 "circular economy "flat glass" "manufacturing" 3 "circular economy "flat glass" "manufacturing" "reuse" *Selection: Items were selected by scanning the first 5 pages (50 results) from each search*	8
Clay-based material – Brick	Search keywords: 1) "circular economy" "brick" "manufacturing" *Selection: Items were selected by scanning the search's first five pages (50 results). Sponsored sources and sources from outside of the EU were excluded*	8
Insulation Materials – Glass wool	Search keywords: 1) "circular economÿ"glass wool" "manufacturing" *Selection: Items were selected by scanning the search's first ten pages (100 results).*	11
Wood – Sawn wood	Search keywords: 1) "circular economy" "sawn wood" "manufacturing" 2) "recycling" "sawn wood" "manufacturing" 3) "circular economy" "sawn wood" "demolition" *Selection: Items were selected by scanning the search's first five pages (50 results).*	11

3.1. Steel – reinforcement bars

Steel is the most used metal in modern society, but its production is energy- and carbon-intensive [45]. Global crude steel production has increased from 1350 million tons (Mt) in 2007 to 1962 Mt in 2021, with a marginal decline to 1885 Mt in 2022 [33]. A substantial portion of steel, approximately 52 % (or 918 Mt), was employed in the construction sector in 2022 [33]. Notably, reinforcement bars contributed nearly 30 % to the overall usage of construction steel [34].

3.1.1. Manufacturing

CE practices are identified at the industrial and lab scales during reinforcement bar manufacturing, where the R strategies are identified as refuse, rethink, reduce, and recycle.

Refuse aims to substitute the reinforcement bar with bamboo [46, 47] and fiber-reinforced polymer (e.g., glass, carbon, aramid, and natural fiber such as bamboo, wood, and hemp) [48] as reinforcement in buidlings. The low stiffness, ductility, and price of fiber-reinforced polymer may challenge the substitution of rebar. **Rethink** is another CE option, where the reinforcement bar is manufactured by designing de-constructible concrete beams [49] and advocating using corrosion inhibitors to prevent moisture damage [48,50] These are currently lab practices of circular economy to improve future rebar recovery and extend rebar lifetime.

As **reduce**, 14 % and 24 % weight savings per m^3 concrete can be achieved by upgrading from 335 MPa (MPa) reinforcement bars to 400 MPa and 500 MPa, respectively [51]. However, the authors did not assess environmental impacts. To derive the sustainability of this reduction, life-cycle environmental impacts should also be calculated [52]. Using nopal mucilage and ixtle (Tampico) fibers as additives could enhance concrete mechanical properties and thus reduce the mass of rebar used in concrete [48,53].

Lastly, **recycling** reinforcement bars is very forgiving in terms of material quality, as rebars can tolerate much higher levels of contamination (e.g., 0.4 % versus 0.07 % of maximum copper tolerance in rebar and fine wire) than other steel grades, offering a potential sink for recycling steel scraps contaminated with other metals, such as steel scraps from automobiles, tube, and wire [54–58]. The source of steel scraps for reinforcement bar production remains less studied.

3.1.2. End-of-life

Reinforcement bars are mostly used in reinforced concrete. As one of the most utilized construction metal materials (43 % of metal in UK construction [59]), reinforcement bars could ideally be recycled without quantity loss. However, subsurface reinforcement bars in foundations are left in the ground at EoL and cannot be collected [60,61]. At the EoL phase, CE practices of reuse and recycling are distinguished.

Reusing EoL reinforcement bars is frequently observed in reusing concrete beams [49,62] and blocks [63] directly at the EoL where rebars are embedded. A low reuse potential rate of steel rebar is identified [64], with 1 % in the UK in 2001 [51] and an average of 11 % in several German cases [65]. Barriers to the reuse of demolished reinforcement bars in the UK vary across issues related to cost, availability, less client demand, traceability, and value chain [66].

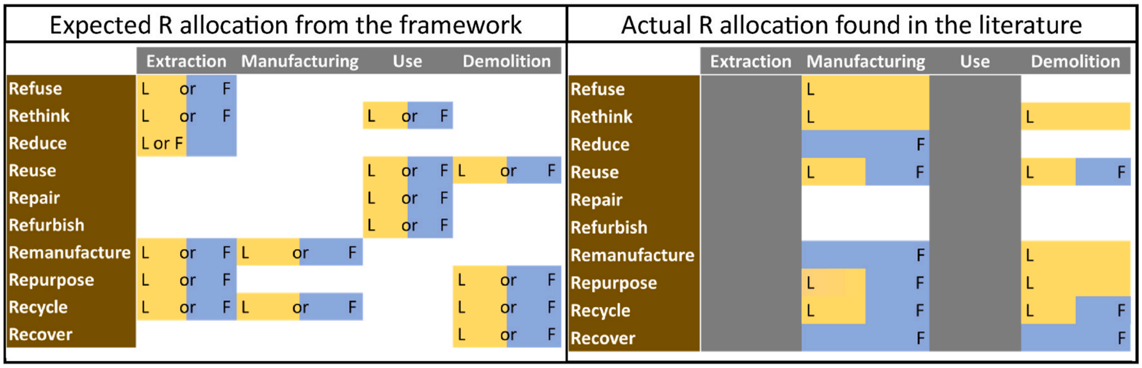
Reinforcement bars are embedded in concrete, and up to 99 % of bars can be retained in concrete. 88 % undergo a **closed-loop recycling** process to produce new reinforcement bars [65]. Recycling practices of EoL reinforcement bars are closed loops. Reinforced concrete must be crushed to allow the collection and recycling of steel rebars [67]. In some German demolition cases, the collection rate of EoL reinforcement bars ranges from 97% to 99 % [65], and this rate drops to 92 % in 2001 in the UK [51] and 71 % in 2023 in the US [68]. The chloride-attacked rebars should be recycled through electrochemical treatment to remove impurities and improve scrap quality [69]. At the lab scale, scrap rebars are cut into cylindrical pieces to produce fiber-reinforced polymer needles [50]. In practice, according to the Environmental Product Declaration (EPD) reports, the recycling rates are 95 % in Finnish [64] and Turkish steel companies [65] and 98 % in Norwegian steel companies [70]. In Jordan, the entrepreneurs collect the used steel reinforcement bars, manually strain them, and market them at half the price of new rebars [71]. In principle, metals are infinitely recyclable from the remelting process [72]. The manufacturers of rebars prioritize cheap old scrap input, avoiding pig iron, direct-reduced iron, and new scrap consumption when impurity content is below the tolerance level [73]. Because reinforcement bars are so resilient to quality losses, steel scraps from automobiles, tubes, and wire ware can be used in reinforcement bar production. Repeated steel recycled over time results in the accumulation of tramp elements (such as copper, tin, chromium, nickel, and molybdenum), and primary steel or less contaminated scraps need to be added [74]. Therefore, caution should be given to the material quality when applying CE measures to steel.

3.2. Cement – CEM I

Cement is a key functional component in urban infrastructure, but no specific product (a specific concrete, etc.) can be singled out in the CE discussion. Cement can contain many supplementary cementitious materials in various quantities other than the cement clinker produced in cement kilns, such as fly ash, other industrial byproducts, or natural materials; details can be found in the harmonized European standard EN

Table 4
– *Definitions of the R10 framework adapted from* Refs. [6,7,39] and its adaptation to a life cycle stage. EoL – end of life.

CE strategy	Description (adapted from Refs. [6,7,39])	Life cycle stage	Allocation to the Life-cycle stage (this study)
R0 Refuse	Abandons the function of the material/product or replace it with a radically different material/product.	Extraction	Achieves resource and material savings by rejecting the use of a material.
R1 Rethink	Elongates the lifespan of the material/product.	Use	Elongates the use phase of a product by using strategies to prolong its use.
R2 Reduce	Reduces the number and volumes of resources used in manufacturing products/materials.	Extraction-Manufacturing	Reduces the amount of resources/material used in manufacturing by applying updated technologies/techniques.
R3 Reuse	Describes a new consumer use a product/material discarded or abandoned by another consumer but still functional.	EoL-use	Brings a product from EoL to the use phase again, with the same end-use. The product needs to be at EoL to be “reused”.
R4 Repair	Repairs and maintains a defective product/material to be used again for its original function.	Use	Uses strategies to elongate the use phase of a product.
R5 Refurbish	Restores an old product/material to its original state and modernize it.	Use	Uses strategies to elongate the use phase of a product.
R6 Remanufacture	Uses parts of a discarded or abandoned product/material in a new product with the same function.	Manufacturing	Uses the pre-consumer waste of product manufacturing in the manufacturing process again of the same value chain. When the manufacturing waste of one value chain is transferred to another, this practice would then be recycled in an open loop.
R7 Repurpose	Uses a discarded or abandoned product/material or parts with a different function in a new product/material. Incorporate wastes from or to other value chains; the main difference from recycling is that repurposing requires less energy.	EoL-manufacturing phases of other value chains	Assumes a different use of an EoL product as open-loop recycling and the service of materials in a different value chain.
R8 Recycle (closed loop)	Processes a product/material to manufacture the same product/material with the same or lower quality.	EoL-manufacturing	Keeps materials in the product’s value chain, bypassing the Extraction phase of resources and going directly to Manufacturing, reducing the loss of quality in the materials and their dissipation into other value chains.
R8 Recycle (open loop)		EoL-manufacturing phases of other value chains	Transfers EoL materials into the products/materials manufacturing stage of other value chains, exiting the original product/material value chain. The main distinction between open and closed loops pertains to the value chain.
R9 Recover	Processes a product/material to obtain energy.	EoL	Represents a material loss from the value chain since the material is incinerated to produce energy. Equivalent to landfill in terms of circularity in Fig. 2.



Expected R allocation from the framework

	Extraction	Manufacturing	Use	Demolition
Refuse	L or F			
Rethink	L or F		L or F	
Reduce	L or F			
Reuse			L or F	L or F
Repair			L or F	
Refurbish			L or F	
Remanufacture	L or F	L or F		
Repurpose	L or F			L or F
Recycle	L or F	L or F		L or F
Recover				L or F

Actual R allocation found in the literature

	Extraction	Manufacturing	Use	Demolition
Refuse	▨	L	▨	
Rethink	▨	L	▨	L
Reduce	▨	F	▨	
Reuse	▨	L F	▨	L F
Repair	▨		▨	
Refurbish	▨		▨	
Remanufacture	▨	F	▨	L
Repurpose	▨	L F	▨	L
Recycle	▨	L F	▨	L F
Recover	▨	F	▨	F

Fig. 3. Expected R allocation per life cycle stage according to literature definitions and concepts – as presented in Fig. 2 -and Actual R allocation after review (right). Legend: grey –not identified at the material level;L (yellow)/F (blue) – identified practices in the six materials’ value chains where L (yellow) refers to practices identified at the lab scale while F (blue) refers to full industrial scale practices.

197-1. Cement clinker represents the most reactive component in most common cement types and has a relatively narrow range of chemical composition. All cement types can produce various cementitious construction materials, such as pre-cast or ready-mix concrete, cement mortar, cement render, and concrete flooring. Concrete is the most used material in this category, and the cement content and compressive strength of the designed concrete are the key properties of its application.

Cementitious composite materials require separation before the crushed cement paste can be fed into cement kilns again. Hence, the actual quantity of cement clinker is not reported in waste statistics and can only be estimated based on average cement contents and cement type. Today, cement clinker contents are being reduced in most European countries, for example, by replacing cement with coal fly ash to reduce the embodied CO_2 footprint of the cement, which also alters its chemical composition. Cement, independent of the sales container, has a limited shelf life as it may absorb water from the environment, which may limit transport (export/import) [75].

3.2.1. *Manufacturing*

Several R’s from the R-strategies have been identified for the manufacturing process, ranging from **Refuse**, which represents the change of **cement** type towards other compositions produced at, e.g., lower temperature (belite-rich clinker, etc.), alternative CaO production [76] or using alternative chemical binding mechanisms such as alkali activation [77]. Most of these materials have not been utilized on a day-to-day basis on an industrial scale.

The most common approach is to **reduce** the cement **clinker content** by replacing clinker with supplementary cementitious materials and other byproducts (these represent cement types CEM II, CEM III, etc.) [78]. This avenue is also used to reduce clinker and replace it with other industrial waste materials, but this may cause recycling issues

Table 5
Overview of the CE practices identified in this review explored in sections 3.1-3.6. The percentages illustrate the given R strategy implementation at a Europe-wide scale retrieved from the literature and verified by stakeholders. Legend: M: Manufacturing phase; EoL: End-of-life phase. In addition, the letter **F** represents the (full) industrial scale, while **L** refers to the lab scale. * - internal waste. NA – not applicable.

Circular options	**Reinforcement bars**		**CEM I**		**Flat glass**		**Brick**		**Glass wool**		**Sawn wood**	
Stage	***M***	***EoL***	***M***	***EoL***	***M***	***EoL***	***M***	***EoL***	***M***	***EoL***	***M***	***EoL***
Refuse	L		L				L					
Rethink	L					L						
Reduce	L		F 60%				F (30-70 %)		F (NA)			
Reuse		F (1%-11%)				L		L			L	
Repair												
Refurbish												
Remanufacture			F < 1%		F (26%)		F (100%) *	L	F (10-15%), (100%) *			
Repurpose					F(NA)	L		L	L	L	L	L
Recycle Close loop	F (NA)	F (70-95%)		L	L F (NA)	F (0-5%)			F (65-70%)	L		
Recycle Open loop			F < 1%		L	L	F (6 %)	L			F (39-45%)	F (1.4-24%)
Recover			F < 1%								F (NA)	F (62%)

when problematic impurities (heavy metals, etc.) are introduced and will limit recycling options when these impurities may be leached. With some limitations, the cement quantity in concrete can be reduced through concrete technology [78] for comparable strength or the concrete quantity itself through structural design optimization. It is possible to **remanufacture** cement from, e.g., unused cement bags that have, for example, surpassed their shelf life. However, no reported values have been found to indicate the scale of this possibility. **Recycling** materials from cement plant processes, such as limestone dust, is used in industry (as well as in remanufacturing). Concrete demolition fines may be treated to bind CO2 and used in concrete as SCM or other functions [79].

Manufacturing cement clinker from concrete fines (construction and demolition waste – C&DW) represents closed-loop recycling for CEM I clinker, done in pilot scale tests [80–82]. Additionally, the **recovery** of heat or cooling from production and mining processes for other users (symbiotic manufacturing) is possible [83,84]. In contrast, the recovery of byproducts of other industries as fuels in cement kilns is widespread [85,86].

3.2.2. *End-of-life*

As cement clinker is an intermittent material that does not persist in the structure of a product, as the functional material is concrete, etc., the discussion on cement demolition is complex and requires several processes and functions. **Rethinking** the design for disassembling concrete structures or elongating service life refers to using concrete, not cement (clinker). In any case, to close this loop, the sand, and gravel -together called aggregates-need to be separated from the cement paste, which could be used as secondary raw material for clinker production [80–82]. In contrast, the aggregates may be used in recycling concrete or as base layers in roads [79,87].

3.3. *Glass – flat glass*

In 2007, global flat glass production reached 44 million tonnes, of which 70%—or almost 31 million tonnes—was architectural flat glass [88]. The number doubled to 63 million tonnes in 2014, considering windows were in construction [89]. This number drops to 8.9 million tonnes for Europe [90], and in the same year of 2013, 1.5 million tonnes of flat glass waste were produced (1.27 Mt from renovation + 0.26 Mt demolition) [91].

3.3.1. *Manufacturing*

The industrial process of producing glass, precisely flat glass, has been perfected for decades. Today, numerous CE practices are implemented at the industrial and lab scales during flat glass manufacturing - reduce, remanufacture, and recycle were identified as R strategies for flat glass.

Reduce of heat/energy used in flat glass manufacturing is a common practice by, for example, adding additives like soda ash to the sand mixture to lower flat glass melting point [92]. No evidence for material reduction is given; therefore, CE needs to account for this practice. **Remanufacture,** or the waste produced from pre-consumer waste reintroduced into manufacturing, pertains to the cullet and wastes induced during flat glass production [93–95]**.** In the EU, pre- and post-consumer cullet accounts for 26 % of raw materials used in flat glass manufacturing. Of these 26 %, 75–80 % is internal cullet from the process, 20–25 % pre-consumer cullet from fabrication offcuts before it reaches the consumer, and 0–5% EoL flat glass [91]. In the flat glass industry, reducing and remanufacturing have the benefit of lowering furnace temperatures during manufacturing. Using [96]cullet decreases the furnace energy consumption by about 2.5–3.0 % with every 10 % increase of cullet input to the melting process [90] – and a simple calculation would result in 25–30 % furnace energy saving if all virgin feedstock was replaced with cullet.

Some of the pre-consumer cullet can be used in other applications. 85–90 % of pre-consumer glass waste is consumed internally for flat glass production, where the remaining might be transferred to, e.g., glass wool production (personal communication, June 15, 2023). This means that 10–15 % of pre-consumer cullet leaves the flat glass value chain into another value chain – a circular practice of **recycling** in an open loop [97,98].The use of pre-consumer glass cullet in soil stabilization [91] and glass-ceramic glass with ternary-quaternary glass [92] has been reported. Some pre-consumer glass may also produce glass wool (personal communication, June 15, 2023). Recycling of wastes from other value chains in flat glass has also been reported: (i) ornamental stone wastes as an alternative raw material during soda-lime glass manufacturing [96]; and (ii) blast furnace sludges and pure graphite were used as reducing agent in the vitrification process [92].

3.3.2. End-of-life

According to some sources, glass is a permanent material that can be recycled indefinitely without losing quality [97]. Therefore, 100 % of glass can be recycled, but this number differs from reality. Authors from Sweden report that only 1 % is handled in circular or closed-loop value chains [98]; Flanders state that post-consumer flat glass is split into 1 % landfill, 27 % open-loop recycling, and 72 % downcycle [88]. *Glass for Europe* states that currently, most C&DW waste flat glass is not recycled in any glass furnace and goes to landfill [94], but different practices were observed. At the EoL stage, rethink, reuse, repurpose, and recycle were identified as flat glass CE practices.

Temporary storage of flat glass was identified as a **rethinking** CE practice. Rethink pertains to actions that increase the use phase of a product and elongate its lifespan (adapted from Ref. [6]). Mustafela et al. [99] recommended temporarily storing glass waste (mainly heavy metal-containing glass) in storage cells instead of mixing it with C&DW to prevent contamination of other materials. The authors suggested that remediation techniques will likely be developed to recover some materials. This practice might induce a loss of capital/material, as a stock of (nonhazardous) waste is created that would remain stored indefinitely. **Reusing** EoL flat glass is discussed widely in grey literature, with a high willingness to practice it, but existing demand for the reuse of façade products is low, according to Hartwell and Overend [100]. In the same study, the authors consider re-use as less favourable over longer lifetimes due to the lack of performance assurance of the window, even considering a typical service life of <15 years. A study shows that the flat glass sheet that covers solar cells in EoL photovoltaic (PV) panels is still of high quality and performance for reuse in other PV panels or façade buildings [101]. Nevertheless, it is a common understanding that, to achieve both reuses, mechanical separation from the encasing needs to be improved to guarantee the integrity of the glass for reuse.

Repurposing is less energy-intensive than recycling, primarily by mechanically treating EoL products. The repurpose examples of EoL glass cullet are all open loops. In concrete, cullet is used as (i) aggregate replacement [102–111] (ii) cement replacement [112–120], (iii) geopolymer [121], and gypsum substitute [122]. Other open-loop options for cullet were found to replace sand in geotechnical applications [123].

As mentioned, **closed-loop recycling** practices for EoL flat glass cullet amount to 0–5% [91]. Nowadays, recycling in a closed loop is challenging primarily due to the costs of transporting and treating EoL flat glass and impurities and the need for appropriate equipment for handling and selection (personal communication, June 15, 2023). To improve this performance, separating glass from the remaining C&DW would have to be significantly improved, which currently is still costly and logistically challenging. Although not a circular option, optimizing the mechanical treatment before repurposing or recycling any EoL material can improve R strategies immensely, with many material gains achieved by optimizing these techniques. One study sheds light on improving the optical-electronic sorting system [124]. As for **open-loop recycling**, the ceramic industry can be listed as mutually beneficial since flat glass cullet lowers the temperature and energy of ceramic sintering [125,126]. Examples of emerging ceramic products are (i) glass-ceramic foams [127], (ii) soda-lime glass waste in weakly alkaline solutions [128,129], (iii) tiles [130,131], and (iv) clay-fired bricks [132,133]. Among industrial-scale recycling, cullet applications are seen in the glass wool value chain, where up to 75 % of raw materials are constituted by EoL flat glass cullet (personal communication, June 15, 2023) and asphalt production [134].

3.4. Brick – clay-based brick

Ceramic manufacturers from the EU-27 account for 23 % of global ceramics production, from which 21 % are bricks, roof tiles, and clay pipes [135]. [136]Europe's annual brick production value is 5.5 billion euro, covering 1300 production sites [137]. Production sites are typically close to the market, with different product requirements in every country and region. In 2012, the distribution of European brick production was 38 % in Northern Europe, 35 % in Central Europe, and 27 % in Southern Europe; Germany, France, Italy, and the UK were 68 % [138]. Fired bricks are considered one of the most durable construction materials, with a long lifetime, and the production costs shares are energy 30%–35 %; labour 25%–30 %; raw materials 20–25 %; other production costs 15%–20 % [138].

3.4.1. Manufacturing

Great effort has been made to reduce energy consumption in manufacturing, as large amounts of heat are needed to dry and fire the bricks. CE practices were identified at the industrial and laboratory scales during brick manufacturing, mainly the R strategies refuse, reduce, remanufacture, and recycle.

Refuse covers replacing fired clay bricks with other brick-shaped products that do not require firing to lower the associated CO_2 emissions compared to conventional fired bricks. A commercially available non-fired brick is the K-Briq [139], made from 90 % of demolition and construction waste, including concrete, rubble, old bricks, and plasterboard. Geopolymer bricks with [125] and without clay [126] are also tested on a laboratory scale. **Reducing** the clay content in bricks is driven by lowering the energy consumption in the production and, thus, costs. The structure and dimensions of the bricks are continuously improved by reducing the thickness or adding non-visual holes in the bricks, also with the aid of computer simulations [136]. For instance, the dimensions of Dutch-facing bricks can be reduced from 10 to 6.5–8 cm in depth [140], reducing material consumption by up to 35 %. Another approach is to replace the traditional facing bricks with brick strips/slips 1.5 cm thick, reducing the raw material consumption by 70 % [140], implying a loss of function from structural to ornamental. This has the additional advantage of having the brick strips/slips on hanging systems, which are easily detachable and reusable [37] compared to brick-and-mortar masonry.

Closed loop **remanufacture is a common practice in the industry, and it uses** internally fired discarded production residues to substitute raw materials, mainly sand. Overall, this practice generates no waste in brick manufacturing [37]. **Recycling** of other wastes into brick production is around 6 % (Brick Development Association, 2021), mainly by adding sawdust/waste cellulose fibres to bricks before firing, which improves the insulation properties of the fired brick [141]. Wastes from other value chains that have been investigated for reducing the clay content are sewage sludge [142], sewage sludge ash [143], rice hush ash [144], biomass bottom ash [145], mining waste [146–148], construction waste [147], red mud [149], quarry sludge [150], MSWI fly ash [151], wet pomace [152], bottom ash [153] into bricks by substituting clay material in brick. Depending on the waste material, up to 100 % replacement of clay is possible in laboratory studies. Limitations of these practices are the consistent availability of the materials and environmental concerns by introducing raw materials containing higher amounts of heavy metals into production.

3.4.2. End-of-life

The reuse potential for bricks is nearly 100 %, but when used in construction, bricks are combined with mortars to make masonry. Lime mortar can easily be reclaimed from old bricks [154–156], whereas cement mortar can be much more difficult to remove due to its higher strength [157]. A saw-cutting method can salvage up to 97.8 % of the old brick from masonry with cement mortar [154,156]. Reusing bricks is identified as a **repair** strategy, as the mortar must be removed. The EoL phase is essential in not damaging the bricks in the masonry, and by taking precautions of not driving heavy machinery onto demolished masonry and when loading the masonry onto trucks, the percentage of repairable bricks can increase from 25-30 % to 80–85 % [158]. For each reused Danish brick, 0.5 kg of CO_2 can be saved in emissions [158]. The reuse of old bricks is essential for the renovation of historic buildings [141].

Remanufacturing in closed loop covers uses up to 15 % recycled brick after removing cement and concrete residues from the rubble to produce new bricks [141]. Open loop remanufacturing turns used bricks into thinner brick slips by saw-cutting [154].

Repurposing assumes a different use of an EoL product and the service of materials in a different value chain, where EoL bricks (and masonry) are crushed and downcycled as road filler and aggregates [159,160], backfilling in pits and quarries [37], cover layer [37], wetland fillers [161], aggregates [37] or tennis courts/sports fields [37,162].

Several open loop **recycling** options were identified for EoL bricks after crushing, such as us precursor in geopolymer and alkali-activated materials [163,164], concrete aggregates [165], cement replacement and SCM [165,166], in soil-cement bricks [167] and substrates [37].

3.5. *Insulation materials – glass wool*

In the European market, insulation products amounted to 9.8 million tons in a volume of 265.8 million m3 in 2020, and 89 % of these insulation products are applied to the building sector [168]. Among these insulation materials, glass and stone wool are the most popular, accounting for 55 % of the total volume [168]. The annual mineral wool waste from the EU's construction and demolition sector is estimated at 250 million tons, of which 160000 to 480000 are from production [169]. Glass wool alone makes up one-third of the total volume [168] and currently 800000 tons of waste are generated in EU per year [170]. Landfilling is the standard practice for most glass wool waste [171]. A desire for circular solutions from industry and academia has been shown, and circular practices have increased [172].

3.5.1. *Manufacturing*

Glass wool production is an energy- and carbon-intensive process at the industrial level, and a large amount of energy is consumed during the melting of raw materials and the curing of glass wool products due to the high temperature required for both processes. It is competitive compared with other insulation materials regarding energy and carbon performance at a functional level benchmarked with the same thermal resistance [173].

In practice, increased CE practices, including reducing, remanufacturing, repurpose, and recycling, have been visible for approaching energy and resource efficiency in industry and lab during glass wool production.

Reduce aims to achieve the same product performance but at a lower resource intensity. It has been applied at an industrial scale as optimized fiberizing but to limited density ranges (personal communication, June 15, 2023). The density of glass wool products Isover Saint-Gobain produces ranges between 10 and 125 kg/m^3 (personal communication, June 15, 2023).

Remanufacture aims to reduce raw material and energy consumption for glass wool production by introducing recycled glass cullet and glass wool from pre-consumer waste, like internal waste from production. According to Krijgsman & Marsidi [174], an increase of 1–3% in energy efficiency could be achieved by increasing the use of recycled cullet by 10 %. However, cullet quality must be ensured. Otherwise, it may lead to increased energy consumption due to rising production losses [174] quality of glass wool production is much higher (personal communication, June 15, 2023). Currently, glass wool production incorporates up to 80 % of glass cullet in practice (personal communication, June 15, 2023) [175] and this figure can rise to 95 % at maximum, as is done in Japan (personal communication, June 15, 2023). About 10–15 % of the input is from internal glass wool waste through remanufacturing in a closed loop [176]. This comprises 75–100 % of the internal waste [177]. The remaining recycled glass cullet input originates from external fractions such as containers and flat glasses.

No remanufacture of glass wool waste from construction sites into insulation products - such as new glass wool products, blowing wool, insulating bricks, and ceiling tiles - has been in prevailing practice. Still, it is emerging (personal communication, June 15, 2023) [172,177–179]. In France, take-back schemes for collecting, sorting, and reprocessing waste have been established in practice by Isover, aiming at closing the loop for glass wool waste [177]. In addition, the lab's remanufacturing of waste glass wool produces thermal insulation composites by incorporating waste glass and other materials [180–182]. In an experiment producing foam glass insulation [180,181], 40 % of glass wool waste is directed from landfilling to new insulation products on the product level. An emerging recycling example found to address waste and environmental concerns is introducing a biobased binding agent, ammonium sulfate, generated from biowaste in an industrial symbiosis case for glass wool production by Saint-Gobain Finland [183].

Repurpose of pre-consumer glass wool waste, after collection and sorting, consists of, e.g., Isover to make bricks and winter mats (personal communication, June 15, 2023). More repurpose practices identified are from the laboratory scale. Glass wool waste is either used as raw material or additive to produce cement-based mortar and concrete [184–190], building ceramics [191], geopolymer [192,193], and gypsum products [194]. One promising waste application among these lab trials, using glass wool waste as a precursor in the production of geopolymer that could replace energy and carbon-intensive cement in concrete, has been demonstrated at an industrial scale [195].

3.5.2. *End-of-life*

Glass wool can be infinitely recycled, regardless of the quality, age, density, or properties of glass wool. They can be remelted as many times as necessary to enter the composition of new insulation products without impacting the final quality [177]. Waste is a significant issue for post-consumer glass wool. The CE strategies identified are recycling and repurposing, which are concerned with finding new routes for them instead of landfilling. The recycling and repurposing practices for pre-consumer waste found in the lab apply to them. In industrial practice, attempts at closed-loop waste recycling into new products have been going on (personal communication, June 15, 2023) [177,178]. Repurposing waste into partition walls and ceiling tile (with a short lifetime) for acoustic insulation in office buildings is rising (personal communication, June 15, 2023).

3.6. *Wood*

The global production of sawn wood in 2022 amounts to approximately 489 million m^3. Coniferous wood accounts for 345 million m^3, while the remaining 144 million m^3 are attributable to other woods. EU production of sawn wood is about 101 million m^3 from coniferous wood and approximately 8.6 million m^3 from non-coniferous wood [196]. Softwood is essential for construction due to its mechanical properties, availability, processability, and, usually, price. The cost of softwood pertains to many factors, e.g., type of use, its source trees, and production volume. Global sawn wood production has been increasing steadily, yet at a cyclical rate, over the last few decades. According to Ramage MH et al. [197], about 38.1 % of the wood used worldwide is used in construction. About two-thirds are sawn wood, while the remaining share comprises wood-based panels. Besides softwood being the primary material used in construction and other industries, most hardwood is used for energy production. In 2022, around 172 million cubic meters were processed energetically [196].

Table 6
Proposal to include the R10 framework in CM models. CE – Circular Economy; CM – climate mitigation.

CE strategy	Description	How they can be considered in CM models
R0 Refuse	Abandons the function of the material/product or replace it with a radically different material/product.	New and alternatively, products can be explicitly modeled, including quantitative replacement coefficients (e.g., using wood for structural building components instead of steel or cement).
R1 Rethink	Elongates the lifespan of the material/product.	Sharing products can be considered here. In CM models, building occupancy is explicitly considered to impact demand for heating and cooling, among others. It is proposed to include scenarios on different levels of space sharing that will lead to differences in demand for energy use in buildings.
R2 Reduce	Reduces the number and volumes of resources used in manufacturing products/materials.	Product manufacturing processes are explicitly modeled in CM models with mass balances detailing energy, materials, and GHG emissions. Efficiency increases for all inputs can be modeled by replacing productive technologies and/or material inputs with more efficient ones (e.g., replacing glass furnaces or clinker kilns).
R3 Reuse	Describes a new consumer use a product/material discarded or abandoned by another consumer but still functional.	It is proposed to consider this similarly to R1 by including in CM models' assumptions on modification of new building construction rates due to extending the lifetime of existing buildings and by refurbishing office buildings to housing and vice versa.
R4 Repair	Repairs and maintains a defective product/material to be used again for its original function.	Detail the material, energy & water flows associated with building repair & renovation in CM models. Building renovation is critical for energy savings, ensuring thermal comfort with GHG emissions with substantially less (or even negative) emissions. Detailed energy use in different types of buildings is a key part of most CM models. Both full building retrofit and partial renovation should be considered.
R5 Refurbish	Restores an old product/material to its original state and modernize it.	
R6 Remanufacture	Uses parts of a discarded or abandoned product/material in a new product with the same function.	Re-structure value chains in the CM models to include relevant feedback loops for the construction materials (e.g., reusing bricks in a new building). New processes and commodities need to be added to the CM model, characterized by costs, efficiencies, and mass balances.
R7 Repurpose	Uses a discarded or abandoned product/material or parts with a different function in a new product/material. Incorporate wastes from or to other value chains; the main difference from recycling is that repurposing requires less energy.	This is similar to the previous CE strategy. Here, feedback loops will focus on loops across the different materials value chains (e.g., using brick waste for cement production).
R8 Recycle (closed loop)	Processes a product/material to manufacture the same product/material with the same or lower quality.	The previously mentioned redesigned value chains inside the CM model should include recycling feedback loops across the energy system for each material (e.g., recycling steel scrap for new steel products, recycling bricks from C&D waste). This entails a detailed representation of recycling processes in the CM model and waste collection and transport steps.
R8 Recycle (open loop)		
R9 Recover	Processes a product/material to obtain energy.	CM models explicitly consider waste incineration for electricity and heat production (via CHP plants, boilers, and/or dedicated district heating facilities)

Although the literature review focused on the keyword sawn wood, the building materials fiberboard and oriented strand board (OSB) are also included since considering only sawn wood without addressing the cascade utilization is not applicable. Even today, byproducts from the primary production of sawn wood and, to a certain extent, reclaimed wood is used in wood panel production as an actual case of cascade utilization.

3.6.1. *Manufacturing*

Considering wood as a building material, a purely circular approach must be regarded as practicing cascade utilization. Cascade utilization may be well understood as part of the CE approach due to its objective and the integration of R strategies [198]. The initially high-quality wood product is successively passed on to less demanding product stages along its life cycle. Thus, wood products are rarely used for identical recycling; instead, the purpose of the product changes after each life stage. Several approaches have been established during the manufacturing phase at the industrial and laboratory scale. The manufacturing phase describes processes in which a new wood product is being produced and, concurrently, processes in which waste materials from production, for instance sawdust, are being used to manufacture new products. Approaches for reuse, repurpose, recycling, and recovery were identified.

The bark is removed during the initial processing of sawn wood, and the logs are sized accordingly. Various sawdust residues are obtained during this process and used to produce further objects, mostly used differently in functional terms. Likewise, the residual waste is recovered and utilized for thermal or energetic production in the sawmills. **Reusing** waste materials from the manufacturing process allows the production of smaller pieces of furniture [199] or the manufacturing of wood fiber insulation [200]. Besides, wood waste and epoxy-based adhesives can be produced from manufacturing residues to minimize conventional adhesives in wood-based panel manufacturing and simultaneously provide more easily reusable and recyclable products. Satisfactory mechanical and physical properties are observed using 30–40 % of wood waste and epoxy-based adhesives rather than conventional adhesives [201]. Furthermore, sawdust is reused in wood production to manufacture wood plastic composite [202,203]. Raw material savings result from including reused secondary materials, depending on the degree of hardness and the specifications demanded. Following the concept of **Repurpose**, wooden planks and byproducts from production are functionally applied in different ways in building installations. Suitable planks can be repurposed as facade cladding, flooring, and other building applications [204]. Large-scale implementation is unlikely, as different approaches seem more feasible and purposeful—the key approach for cascade utilization centers around **Recycle**, mostly in open loops. 38.6 % and 44.6 % of sawmill byproducts, such as sawdust or wood chips, are typically processed into particle board and fiberboard [205,206]. As the final step in the cascade utilization, wood products are thermally recovered when they are no longer used in any other functional state or when energy production becomes economically viable. As an option for the **Recovery** of byproducts occurring within manufacturing processes, utilization is frequently used for direct thermal recovery at processing facilities described above (personal communication, June 15, 2023).

3.6.2. *End-of-life*

The EoL phase of wood products requires a differentiated perspective. Final EoL consideration results at the end of the cascade utilization with thermal recovery. Along the cascade utilization, at each stage and with each new quality, an EoL phase of its own exists, initiating the passage to the subsequent level. Keeping this in mind, reuse, recycling, and recovery approaches were determined.

Waste wood is suitable for **repurpose**. For this purpose, wood that has been demolished serves as an additive for various composite products. As a wood-plastic product, acoustic panels, garden furniture, indoor-use bricks, or playground surfaces can be manufactured [207]. Similarly, producing cement-wood composite products such as wood-wool-cement boards is feasible [208]. Besides repurposing wood products, wood might be used directly in the **Recycling** phase. A theoretical recycling factor of about 25 % exists for buildings with wood as a load-bearing structure. Besides, about 21 % of the recovered wood could be used to manufacture fiberboard and OSB. Including waste wood from engineering wood fractions, around 44 % of the total quantity of wood recovered can even be used to produce particle boards, as the requirements are less demanding, particularly in terms of toxicity and absence of pollution [209]. For the suitability of waste wood as structurally relevant components, damage-free test options often need to be improved to verify the properties of the building products efficiently. In addition, some EU countries restrict direct use by classifying waste grades. Waste wood is used to manufacture particleboard and fiber boards. The mechanical properties are not a concern since the product passes to a different quality stage and is finally chipped and further processed. Between 1.4 % and 24.5 % of the required raw materials are from waste wood [205]. **Recover** of wood products accounts for about 51.6 % of global wood use [210]. In practice, however, this value refers to the primary use and not the final utilization of wood products, most of which would eventually have to be thermally recovered in analogy to the cascade utilization. Based on a survey by Mantau [211], about 62.5 % of the total wood used in the EU is thermally utilized for energy production. Here, the cascade utilization approaches are included, and the final recovery applies to the factual EoL scenario of the wood products.

4. Discussion

4.1. CE implications for climate mitigation

From a holistic carbon mitigation point of view, reducing the production volume reduces GHG emissions. This aligns with the principle of sufficiency – one of the actions recommended by the IPCC [212] – but also with the higher R strategies such as Refuse, Reduce, or Rethink [7]. All these practices share the principle of avoiding the demand for energy, materials, land use, and water. In the manufacturing of construction materials, production reduction has not been observed. On the contrary, production has steadily increased for all the considered materials here – cement, reinforcement steel, bricks, flat glass, glass wool, and sawn wood [213]. Higher R strategies such as Refuse and Rethink were identified at the lab scale value chains of cement, steel, and glass (Fig. 3). Notice that the action of refusing the use of reinforcement bars (steel) relies on, for example, the use of sawn wood (or laminated wood) as a replacement [214] – i.e., the reduction of one material use increases the material use of another. In this case, the increase of wood. No higher Rs are identified in wood because bio-based materials are considered low-carbon construction materials [215]. To capture the (impacts) implications of displacing one material in favor of another, large-scale models that encompass several economic sectors, like CM models, should be used to evaluate the systemic effect of concurrent CE practices instead of considering single CE practices individually.

An approach to integrate the R10 framework into CM models is presented in Table 6 for the specific case of steel, cement, glass, brick, insulation, and wood construction materials. The approaches vary per R strategy and can entail different modification levels in the model structure. Including CE strategies R6, R7, and R8 into CM models implies substantial model changes by adding new sectors (each with new processes and inputs/outputs) and new linkages between sectors.

Reduce as a practice is widespread - all reviewed materials' have tried to reduce the number of raw materials in their production process, except for sawn wood. As a side note, the practices identified in the flat glass value chain minimize energy consumption, not material consumption. These impacts of CE measures can be more easily included in CM models, as they intrinsically consider energy inputs and efficiencies of detailed industry manufacturing processes. While still looking at Reduce, wood and other bio-based materials are being prioritized to replace mineral-based construction materials (such as cement, steel, and glass). Solid timber walls (CLT) used as structural (and filler) material in buildings can be given as an example. This trend is greatly supported by the low-carbon profile wood products provide for LCA accounting. Therefore, wood and bio-based materials should see their consumption/demand increase in the coming years [215]. Studies show that CLT construction is material-efficient since other materials used (e.g., plaster) can be reduced and that the EoL reuse of timber, and thus the possibility of cascading use of the wood products is increased, which decreases the raw material used for low-quality products in the cascade [216]. To include these considerations in CM models, it is necessary to establish a quantitative relationship – feedback loops – between lower demand for mineral-based carbon-intensive materials and wood (bio-based) materials. With this information, it is then straightforward to consider a lower demand, e.g., cement, and a higher demand for wood as exogenous model inputs. The CM model will compute GHG, energy, and cost trade-offs as part of its solution.

R strategies to keep materials in the use phase longer are Reuse, Repair, and Refurbish (renovations). Extending products' lifetimes disincentivizes primary production of materials, lowering GHG emissions. The materials, energy, and water needed to perform renovations and the associated Rs differ from material to material and the type of repair/refurbishment for reuse. For example, repairing a flat glass is straightforward but rare, while repairing a window implies repairing the wood or stainless-steel frame; repairing a brick wall requires new bricks and mortar, and some parts of the wall can be reused in the new wall. Repairing the whole building (and its embedded materials) at a different scale can avoid building a new one and subsequently lower manufacturing and extraction, not considering rebound effects or reduced demolition wastes as input for CE practices. As for the case of Reduce, once a quantitative relationship is established between higher repair rates and lower material demand, it can then be introduced in CM models.

The lower R practices, such as repurposing, recycling, and recovery, essentially dismantle and shred products into smaller pieces that can be used as resources to produce new materials, except for recovery, which implies a material loss for its energy conversion. Recovery usually refers to bio-based materials generally with an intrinsic calorific value. For repurposing and recycling, products are separated into their components for use again in materials manufacturing. This process is beneficial for materials manufacturing, as it enables the industry to continue to produce its materials but now use secondary resources instead of virgin materials. Although very useful from a resource "protection" point of view, this process still consumes energy and consequently emits carbon (depending on the energy source). Additional processes might add to the energy demand of the manufacturing process, which allows for the minimization of undesirable contaminants, separation, and transport. While repurposing has its place in this chain, material manufacturers do not necessarily explore this practice to maintain consistent material characteristics (personal communication, June 15, 2023). Recycling is essential to mitigate the environmental impacts and use of material and water resources of the ever-increasing production and use of commodity materials [217]. Regarding CM modelling, all the lower R practices can be explicitly modeled as processes that consume energy and waste (and generate GHG emissions) at a specific cost. Their outputs will be materials (or commodities in CM modelling jargon) that can be input into other economic sectors, such as the material manufacturing industry.

Table 7
Summary of the main challenges for current closed-loop recycling of CEM I, Reinforcement bars, flat glass, brick, glass wool, and sawn woods. A strategy to improve closed-loop recycling is given as a solution. These conclusions were derived after interviews with stakeholders. EoL – end of life.

	Reinforcement bars	CEM I	Flat glass	Brick	Glass wool	Sawn wood
Main current challenge	Separation of reinforcement bars from concrete	Extraction of materials from EoL concrete that can replace raw meal to produce cement (clinker).	Transportation and handling, cleaning of impurities, etc. are too costly. Technology for separation does not exist.	Separation of mortar from bricks. Transportation costs from a demolition site to brick manufacturing, which extracts raw materials in close vicinity	Establishment of an economically viable business model, proper sorting process, and infrastructure.	Preference of thermal recovery rather than material recycling and reusing wood products for economic reasons.
Closed-loop recycling strategy	Improvement of extraction. Caution for steel quality, as too many impurities stall the process	Improvement of technologies to extract concrete fines for carbonation/limestone filler replacement/supplementary cementitious material in CEM II type cement. Recycling of materials from the process in the process (limestone dust, etc., replacing chalk/ limestone)	Improvement of collection, separation, and handling of EoL flat glass.	Improvement of technologies for separation. With technological development, the aim should be on reuse of bricks rather than recycling	Source separation and collection are in place, and the industry is developing sorting and closed-loop recycling. Forecasting legislation changes, e.g., mandatory recycling, high tax for landfills, and landfill ban, offer incentive	Use of materials for longer in the use phase and promoting cascade utilization. Biogenic materials only offer limited potential for closed-loop concepts.

Many CM models are already considering, for example, cullet and scrap recycling. Identifying the costs of these lower R practices and their maximum potential applicability in a long-term scenario is difficult. Can 100 % of glass be recycled by 2050? To what extent will scrap availability limit secondary steel production? Next, the challenges and opportunities of recycling in closed and open loops are discussed for each of the six materials currently being used.

4.2. *Closed-loop recycling*

The EU Environmental Action Programme states that "barriers facing recycling activities in the Union internal market should be removed and existing prevention, re-use, recycling, recovery, and landfill diversion targets reviewed to move towards a lifecycle-driven 'circular' economy, with a cascading use of resources and residual waste that is close to zero" [218]. Materials (and products) should then be kept on the market for as long as possible, and for materials to maintain their value and integrity without losing quality. The practice of closed-loop recycling aligns with this goal more than open-loop recycling since, in closed loops, the material is recycled without significant changes. In contrast, open-loop recycling may change the inherent properties of the recycled material [219]. In theory, keeping materials and resources within a closed value chain prevents the quality degradation and dissipation of the raw materials used. This may be more applicable for relatively pure glass or steel-based products than for composite materials like cement-based materials (concrete, mortar, etc.), whose demolition wastes more severely deviate from the chemical composition and mineralogy of the initial raw materials.

The challenges nowadays to recycle resources in a closed loop regard mainly two limitations: (i) lack of current technology, strongly allied to (ii) economic unfeasibility. The two reasons are intrinsically connected, as there are no current technologies that separate resources/materials in an end-product (e.g., cement fines are difficult to isolate from concrete; reinforcement bars are difficult to segregate from concrete; glass from window frames: brick from mortar, etc.), and it thus becomes economically impracticable to utilize these materials directly as raw materials again. The costs are high in terms of human resources, transportation, cleaning of debris, etc. Strategies to improve current conditions involve mainly (i) better separation of products at the end of their life, (ii) development of technologies that enable this separation, and (iii) improvements in collection/transportation routes. The long service life of houses or infrastructure adds another complexity when compared with shorter recycling systems, as demolition wastes may not be available in the desired quality and volume as demolition occurs hopefully many decades of the use phase, creating a mismatch between waste generation and production demands [220]. Table 7 summarizes the main challenges in the selected six construction materials value chains for closed-loop recycling and the best-identified strategies to mitigate these challenges. Generally, the main impediment to closed-loop recycling lies in technological limitations and/or difficulties separating waste. A recent study by Companero et al. [221] brings forward the issue of scrap quality for steel recycling, namely how producers and manufacturers are faced with opposing financial and sustainability incentives in using scrap as feedstock because regular sorting and scrap-preparation infrastructure cannot deal with the increasing complexity of steel scrap [222] even state that metal scrap is challenging to separate unless done manually. There is then a trade-off between technology and costs, since manual labour can increase recycling costs exponentially (depending on the country). Another example from cement production highlights limits for using different construction and demolition wastes as raw materials in cement production [81].

5. Open-loop recycling

Recycling in an open loop is a term widely used in replacement of downcycling (see International Organization for Standardization (ISO)

Table 8
Identification of industrial symbiosis between cement, glass, brick, insulation, wood, and others. "Others" value chains were identified as the other detected value chains that were identified. Grey-shaded lines/columns highlight the absence of symbiosis. EoL – end of life.

Manufacture *Waste*	**Steel**	**Cement**	**Glass**	**Brick**	**Insulation**	**Wood**	**Others**
Steel							
Cement				Cement or lime may be used to improve adobe/rammed earth-type materials.			Industrial scale: **concrete demolition waste** repurposed as recycled aggregates in new concrete, road base, or backfill material. Waste heat may be used in communal heating systems, etc. Other waste materials are used as alternative fuels.
Glass		At the lab scale, EoL cullet used in concrete as supplementary cementitious material		At the lab scale EoL and pre-consumer flat glass used in brick and ceramics	Industrial scale: EoL and pre-consumer flat glass used to make glass wool		Industrial scale: Consumer glass used in asphalt At the lab scale: EoL flat glass cullet used a sand substitute in concrete
Brick		At the lab scale, brick used as cement replacement in concrete					Industrial scale: brick used as road filler, aggregates cover layer, backfilling material At lab scale: used as geopolymer
Insulation		At the lab scale, glass wool used as a geopolymer precursor		At the lab scale: glass wool used in building ceramics			At the lab scale, glass woold used as gypsum composite, aggregate to replace sand in cement-based concrete/cement mortar and winter mats
Wood		Lab scale: Concrete and wood composite structures are being investigated. Bio ashes are being tested on the lab scale as supplementary cementitious materials.			Lab scale: Glass wool produced using biobased binder (binding agent) produced from bio-waste (through biogas production)		Industrial scale: Wood residues from manufacturing are processed for thermal recovery for heating production
Others		Coal fly ash, slag, etc used as cement replacement	Lab scale: cullet used as ornamental stone wastes, blast furnace sludges, and pure graphite				

Standard on LCA, paragraph 4.3.4.3 in ISO 14044), i.e., the recycled material is of lower quality and functionality than the original material [223]. According to ISO 14044, a loop is closed when “material from a product system is recycled in the same product system,” and downcycling manifests as changes in the inherent properties of the recycled material [219]. Once a material exits its value chain, it will start to be mixed and dissipated into other materials, often losing its initial properties and reducing the quality for which it was initially synthesized. While closed-loop recycling can restrict waste quality, recycling in an open loop offers producers/manufacturers many benefits and synergies. In the six investigated materials’ value chains, many synergies were identified at the lab scale and some at the industrial scale. Table 8 identifies these practices, mentioning their scale as well.

Even though many stakeholders see recycling in a positive light, this review would only be complete by acknowledging that recycling has drawn some skepticism. Besides thermodynamic limitations and energy intensive, several authors [30,219] point out one of the significant pitfalls of recycling: the idea that recycled material displaces primary production. Indeed, recycling is about avoiding waste production and saving natural resources. Still, there are other production qualities, value chains, and/or market criteria at play that can hinder this principle. Even though open-loop recycling attenuates the quality criteria, it benefits cross-sector cooperation and results in positive market relationships (possibly avoiding competition and lowering natural resource consumption). This is the case, e.g., between the flat glass and glass wool value chains, flat glass and asphalt, brick, and road filling (Table 8).

6. Conclusion

The applied R-framework and reviewed CE practices allow a first step toward more circular CM model development, which is currently largely missing. This is particularly relevant as the framework is applied for construction materials whose manufacture is modeled in CM models with particular emphasis on cement, steel, glass, and bricks. These mineral-based materials are among the hardest to abate industries in the current economy due to their intrinsic combustion production processes and carbon stoichiometry. This review describes the current CE strategies adopted by the more traditional construction materials and provides circularity percentages when the CE practice is performed at the industrial scale. For example, EoL steel reinforcement bars are closed-loop recycled 70–95 % and reused 1–11 % in Europe. It is common practice to reduce up to 60 % CEM I content by adding wastes from other industries at the manufacturing stage; remanufacturing of flat glass goes up to 26 %; raw materials use is reduced by 30–70 % in manufacturing bricks; and 65–70 % of glass wool manufacturing is recycled in a closed-loop. The most common practice for wood is recovery – 62 % - but a considerable amount is recycled in an open loop 39–45 %. The quantification of these practices allows to quantify explicit feedback loops in CM models, particularly when models are augmented to describe these added flows of energy and materials. This aspect is key to increment the way CM models express CE today, which focuses on replacing energy sources, e.g., coal or petroleum, with natural gas or renewable energy sources but does not differentiate those measures from methods tackling materials CE.

The review also allows us to verify that recycling is the preferred method by construction materials producers/manufacturers. Still, it comes with trade-offs for quality in a closed loop. Recycling in an open loop (industrial symbiosis) presents a market benefit here since it does not offer competition for the producers. This might depend highly on “by-products” or waste from the upstream industry, creating supply chain bottlenecks and other rebound effects. The premise that the waste of one producer can be used as a resource for other producers can minimize the resources extracted from nature. Still, more holistic market studies are needed to avoid the rebound effects of the circular economy. This should be established so certification processes in the building industry (such as DGNB, LEED, and BREEAM) can emphasize CE as a criterion for sustainability without risks.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

All authors report financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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