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Links between circular economy and climate change mitigation in the built environment

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Abstract

The construction sector represents one of the most significant sources of waste generation in the European Union (EU), with nearly one billion tonnes of construction and demolition waste annually. This sector also determines a third of the annual EU greenhouse gas (GHG) emissions. Accordingly, construction represents one priority area for intervention within the EU Action Plan for the Circular Economy. Increasing resource efficiency through slowing, closing, and narrowing material and energy loops, is a key line of action to mitigate climate change. However, this review paper demonstrates that the analysis of links between circular economy solutions and climate change mitigation has been scarce, despite a recent sharp increase in related literature, with 20 articles (83%) published in 2018-2019. Slowing resource solutions have been the focus of the research and could bring up to 99% savings in GHG emissions per functional unit, where material reuse stands out as the most promising alternative. Closing resource solutions can reduce emissions by 30-50% per functional unit, but results are highly dependent on recycling efficiencies and transportation distances to recovery facilities. Solutions for narrowing resource loops can bring additional GHG savings, but they remain understudied. Despite the promising results for mitigating GHG emissions, this article argues that the circular economy solutions do not always result by default in emission reductions and that a case-by-case quantification is crucial. This should be accompanied with further methodological development, such as proper allocation procedures, accurate definition of the system boundaries and integration of forecasts, among other relevant aspects.

Keywords: greenhouse gases; slowing resource loops; narrowing resource loops; closing resource loops; construction; resource efficiency.

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1. Introduction

The resource inefficiency of the predominant "take-make-use-dispose" economy model can no longer be sustained in the long-term. Instead, a circular economy (CE) based on reusing biological and technological resources for as long as possible in closed-loop systems should be deployed (Mendoza et al., 2017). Growing demand for resources with the corresponding environmental disruptions is one of the critical drivers for this necessary shift (Hoornweg et al., 2013). For instance, the annual global extraction of primary material is set to triple by 2050, with 90% of biodiversity loss caused by resource extraction and processing (UNEP, 2019). From an economic perspective, the increasing volatility of raw materials prices has been highlighted as one of the main reasons to adopt CE principles (Heyes et al., 2018). As an example, the price of cement and construction metals in the United Kingdom (UK) increased by 9.4% and 7.2%, respectively, between 2014 and 2018 (Defra and NS, 2019).

The CE model can be defined as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops" (Geissdoerfer et al., 2017). Slowing resource loops entail prolonging and intensifying the use of products to retain their value over time, whereas closing resource loops facilitate upcycling to restore or create new value from used materials (Bocken et al., 2016). Finally, narrowing resource loops imply eco-efficient solutions that reduce resource intensity and environmental impacts per unit of product or service (Mendoza et al., 2019).

There are many challenges to deploying a fully CE model. For instance, one estimate suggests that the world is just 9% "circular", meaning that 8.4 Gt of materials are cycled input, whereas 84.4 Gt are newly extracted virgin resources (Circle Economy, 2019). Accumulated material stocks (mostly minerals and metals in buildings, infrastructure and capital equipment) are almost ten times larger than annual material throughput (890 Gt versus 92.8 Gt, respectively) (Circle Economy 2019). The construction and maintenance of houses, offices, roads and other infrastructure represent the largest resource footprint with 42.4 Gt consumed annually, equivalent to almost 50% of global material consumption and 20% (> 9 Gt of CO_2 eq.) of global greenhouse gas (GHG) emissions (Circle Economy, 2019). According to Hertwich et al. (2019), the most important uses of materials in terms of embodied GHG emissions in the construction sector are cement, lime and plaster (2.9 Gt CO_2 eq.). Indeed, materials contribute more than 50% of the carbon footprint of buildings and infrastructure, and around 40% of GHG emissions from total material manufacturing derive from the production of materials used in construction (Hertwich et al., 2019). As the urban built environment is expected to grow 60% by 2050 to satisfy the needs of the future urban population (UNEP, 2013), the construction sector is key to achieving the climate change mitigation goals set in the Paris Agreement (United Nations, 2015a).

Europe has 95 Gt of construction stocks (buildings and infrastructure), which is increasing at a rate of 1% per year on average, with more than 50% of the materials used for maintenance and renovation (Circle Economy, 2019). By 2050, the construction stock in Europe is expected to grow by around 12 Gt (13%) compared to 2015, although

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75% of the buildings that will shape the housing stock in 2050 already exist (URBACT, 2013). Importantly, around 10-15% of building materials are wasted during construction, 20-40% of energy in existing buildings can be profitably conserved, and 54% of demolition materials are landfilled because they are unsuitable for reuse due to their toxicity (EMF, 2015). Likewise, more than a billion tonnes of construction and demolition waste, with half of it being excavation material, is expected to be produced annually from 2020 onwards at the European Union (EU) level (Jiménez-Rivero and García-Navarro, 2017). Accordingly, urgent action is needed to substantially improve the resource efficiency and environmental sustainability of urban developments in line with the 2030 United Nations Sustainable Development Goal 11 aiming to make cities and human settlements inclusive, safe, resilient and sustainable (United Nations, 2015b).

By 2050, the EU aims to reduce GHG emissions by 80–95% compared to the 1990 levels (European Commission, 2018). The building sector currently accounts for more than a third of the EU's total GHG emissions (European Commission, 2019a). The EU Directive on the energy performance of buildings (European Parliament and Council, 2010) and the energy efficiency Directive (European Parliament and Council, 2012) have focused on the reduction of operational emissions related to the use and maintenance of buildings. However, these regulations do not consider the embodied emissions associated with the construction and demolition of structures (Giesekam et al., 2014). For instance, Scott et al. (2018) highlight that out of the 773 Mt CO_2 eq. emissions embodied in construction materials in the EU, more than half are outside the reach of the energy performance of buildings directive (European Parliament and Council, 2010) and the GHG emissions trading scheme (European Parliament and Council, 2003). This lack of focus on embodied emissions comes from the traditional environmental impact assessments focusing on operational emissions as the major contribution of the total building-related emissions (Ng et al., 2013; HM Government, 2010). However, operational emissions have gradually fallen due to improved energy performance and energy efficiency regulations and the growth in databases and environmental quantification methods. Accordingly, the relative contribution of buildings-embodied emissions is increasingly significant (Ibn-Mohammed et al., 2013; Giesekam et al., 2018; Ingrao et al., 2019). For example, the NHBC Foundation (2012) calculated that embodied emissions represent between 31% to 44% of the total emissions for buildings with a 60-year life expectancy. Strategies and regulations focused on the improvement of only operational performance of buildings would fail to achieve the EU GHG-reduction target and should be accompanied by the reduction of embodied emissions (Szalay, 2007; Drummond and Ekins, 2017.; Scott et al., 2018).

The embodied emissions mainly arise while extracting resources and processing construction materials (Giesekam et al., 2014; BIS, 2010; Ingrao et al., 2018). For materials processing, the production efficiencies are already near the practical thermodynamic limits, due to the high cost of energy (Müller et al., 2012). The widespread use of carbon capture and storage (CCS) or other negative emission technologies is unlikely to occur within the timeframe needed (Li et al., 2013). Therefore, a significant reduction in embodied emissions in the EU construction sector will require a focus on the consumption side, going well beyond improvements in production efficiencies and negative emission technologies. Reducing the consumption of high-impact construction materials is crucial for the EU to achieve the legally binding emission-reduction target. A synthesis of existing research in this area is necessary to identify the most suitable solutions and inform construction stakeholders and policymakers (Giesekam et al., 2014).

The main aim of this article is to analyse, through a systematic literature review, the potential effects of implementing CE strategies on the GHG emissions in the EU construction sector. debajo de presents the methodology applied to perform the systematic literature review. This is followed by a frequency analysis of the reviewed literature (debajo de), grouping the findings by slowing, closing, and narrowing resource loops. Finally, a discussion of the results is presented in debajo de, and key conclusions and recommendations for future research are provided in debajo de.

2. Methodology for the literature review

The literature review drew on the SCOPUS database, using the following search strings: “circular economy” AND “CE solution” (different keywords) AND construction OR buil*. The 26 keywords related to CE solutions considered were: durability, remanufacturing, refurbishment, product service systems, servitisation, sharing, closed-loop, material circularity, reuse, upcycling, maintenance, repair, upgrade, upgrading, circular supplies, reverse supply chains, reverse logistics, take back systems, cascading, by-product exchange, repurpose, recover, extended producer responsibility, cycling and industrial symbiosis. These CE keywords were gathered from relevant literature review papers on CE, including Kirchherr et al. (2017), Kalmykova et al. (2018) and Merli et al. (2018), where the concepts are described. Broader keywords, such as material or resource efficiency, eco-design or sustainability, were not used to limit the literature search to the papers explicitly developed within the context of the ongoing and emerging research on CE.

From the total of 689 matches identified until November 2019, only peer-reviewed papers and contributions to conferences were considered (Table S1 in the Supplementary Information file). Likewise, only articles in English referring to EU countries or countries from the European Free Trade Association (Iceland, Liechtenstein, Norway, and Switzerland) were included. The timeframe was restricted to 2006 up to the present (November 2019).

A screening of the original 689 matches was performed directly during the searching activity by reading the abstracts and discarding those articles where CE was not the main topic of the research (e.g. not explicitly mentioned), and/or where the CE strategies and solutions related to construction processes and products were not linked to quantitative data on GHGs and to actions for mitigating climate change. The literature selected for comprehensive analysis (24 papers) was categorised into three main CE strategies: i) slowing resource loops (Table 1), ii) closing resource loops (Table 2), and iii) narrowing resource loops (Table 3); each of them grouping a number of CE solutions that demonstrate how each CE strategy can be implemented in practice.

Table 1. Articles analysing solutions for slowing resource loops.

Article	**Construct. element**	**Circular economy solution**	**Variation in greenhouse emissions (circular versus linear)[a]**
Barret and Scott (2012)	Construction sector	Refurbishment	Between -35 & -166 kt CO_2 eq. (year 2050)
Brambilla et al. (2019)	Steel-concrete composite systems	Reuse	-27% (-80 kg CO_2 eq./m^2) to -35% (-120 kg CO_2 eq./m^2)
Brütting et al. (2019a)	Cantilever truss	Reuse	-46% (-76 kg CO_2 eq./infrastructure)
Brütting et al. (2019b)	Train station roof	Reuse	-56% (-2.3 t CO_2 eq./infrastructure).
Buyle et al. (2019)	Wall assemblies	Reuse	-14% to -37% CO_2 eq. savings per wall assembly unit
Campbell (2019)	Mass timber (buildings)	Durability	Mass timber in buildings represents -1.2 Mt CO_2 eq. sequestration per year at EU scale (0.03% of the EU + Iceland total annual emissions)
Castro and Pasanen (2019)	Building	Refurbishment	Change of building envelope (20 years): +6.1% in total embodied carbon; major changes (10 years): +66.6% in total embodied carbon
Cooper et al. (2017)	Construction sector UK & EU-27	Reuse	Embodied energy use: -13% (-95.2 PJ in the UK) & -14% (-1011.6 PJ in EU-27)[b]
Eberhardt et al. (2019a)[c]	Office building	Reuse, elements optimisation & material substitution	Reuse (concrete structure): -15% to -21% (-35 to -50 kg CO_2 eq./m^2); reuse & optimisation: -26% (- 60 kg CO_2 eq./m^2); material substitution: -59% (-140 kg CO_2 eq./m^2); reuse (concrete-based floor slabs, core walls, roof slabs, columns & beam): -25% to -60% material-related carbon emission savings
Eberhardt et al. (2019b)[c]	Concrete column, window & roof felt	Reuse & recycling	Concrete-based column: -36% (-180 kg CO_2 eq./column); window: -92% (-32 kg CO_2 eq./window); roof felt: -99% (-3.2 kg CO_2 eq./roof felt)
Eberhardt et al. (2019c)[c]	Concrete structure, façade & columns	Reuse, durability and material substitution	Reuse of the prefabricated concrete structure: -40% CO_2 savings (two reuses) & -55% CO_2 savings (three reuses); reuse glass facade with wooden columns: -80% CO_2 savings (three reuses) & -73% CO_2 savings

			(two reuses); reuse beams: - 33% CO_2 savings (three reuses); reuse roof: -41% CO_2 savings (three reuses); reuse core walls: -50% CO_2 savings (three reuses); substitution of wood columns by steel (+101% CO_2 emissions) & by concrete (+239% CO_2 emissions) in glass facade.
Ghisellini et al. (2018)[c]	Different building structures and materials	Reuse, recycling and refurbishment	Material reuse and recycling: -5% global warming potential; 95% recycling: -77% of material-related global warming potential; refurbishment: -13% global warming potential[d].
Hertwich et al. (2019)	Buildings	Reuse and intensive use	CO_2 emissions of intensively-used buildings: -50% compared to baseline; reuse of energy-intensive components (e.g. steel): - 0.36 kg CO_2/kg compared to recycling; secondary materials: -40% of the impact of virgin aggregates.
Hopkinson et al. (2019)	Steel structures, concrete and bricks	Reuse	Steel structures: -30% C emissions; steel frame: -38% C emissions; brick: -0.5 kg CO_2 per brick; concrete: -97% C emissions[e].
Nußholz et al. (2019)	Wood-plastic composite (WPC), concrete & bricks	Reuse	-56% to -64% (-0.95 to -1.42 kg CO_2 eq./kg WPC; -12,400 to -18,400 t CO_2 eq./year for the Scandinavian market.); -67% (-0.008 kg CO_2 eq./kg secondary concrete; -7,300 t CO_2 eq./year in Denmark); -99% (-0.025 kg CO_2 eq./kg brick; -25,300 t CO_2 eq./year in Denmark).
Ros-Dosda et al. (2019)	Floor coverings	Durability	Between +8.1 and +38.9 CO_2 eq./m^2 in additional emissions for more intensive use, repair, maintenance and replacement, over a 50-year lifecycle.
Sanchez and Hass (2018)	Building frame structure	Reuse	Variations of +77% with different disassembly plans for the same building frame structure (from 209 kg CO_2 eq. to 897 kg CO_2 eq.).
Scott et al. (2019)	Construction sector in the UK	Reuse	-0.49 to -3.69 Mt CO_2 eq. (years 2023-2027) & -0.70 to -5.23 Mt CO_2 eq. (years 2028-2032).

[a] Negative values (-) represent emissions savings with the implementation of the circular economy compare with linear solutions; positive values (+) represent an increase
[b] Reduction values are not disaggregated and include the implementation of reuse, lightweighting, substitution and efficiency increase
[c] Article studying solutions from several circular economy approaches, but with main focus on slowing resource loops.
[d] Material reuse and recycling (UK) (Cuellar-Franca and Azapagic, 2012); 95% recycling (Portugal) (Coehlo and De Brito, 2012); Refurbishment (Portugal): (Ferreira et al., 2015).
[e] Steel structures (Italy) (Pongiglione and Calderini, 2014); steel frame (UK) (Segro, 2013); reused brick (Denmark, Germany and Italy)(Rebrick, 2013); concrete (The Netherlands) (Glias, 2013)

Table 2. Articles analysing solutions for closing loop approaches.

Article	Construct. element	Circular economy solution	Variation in greenhouse emissions (circular versus linear)[a]
Antunes et al., 2019	Reclaimed Asphalt Pavement (RAP)	Upcycling	Hot mix asphalt containing 100% RAP: -35% (-18 kg CO_2 eq./t)[b]
Hertwich et al. (2019)	Buildings	Upcycling	Recycle hydrated cement waste into new cement: - 30% greenhouse gas emission savings
Jiménez-Rivero and García-Navarro (2016)	Gypsum	Upcycling	The recycling process itself produces fewer greenhouse savings compared with the combination of landfilling and natural extraction, but these benefits can be significantly reduced by transport
Migliore et al. (2018)	Brick	Upcycling	Brick with 50% composition waste from marble quarries: -50% GHG emissions compared with a 100% virgin brick (2.6 and 5.2 kg CO_2 eq. per t)
Nasir et al. (2017)	Insulation	Upcycling	-39% (from 1.51 kg CO_2 eq./kg virgin stone wool to 0.92 kg CO_2 eq./kg recycled textile).
Rasmussen et al. (2019)	Building	Upcycling and design for disassembly (DfD)	Innovative upcycling of a building: -0.7 kg CO_2 eq./m^2/year compared to DfD building and -1.1 kg CO_2 eq./m^2/year compared to only common material recycling of a building

[a] Negative values (-) represent emissions savings with the implementation of the circular economy compare with linear solutions; positive values (+) represent an increase
[b] Zaumanis et al. (2014)

Table 3. Articles analysing solutions for narrowing loop approaches.

Article	Construct. element	Circular economy solution	Variation in greenhouse emissions (circular versus linear)[a]
Andrade et al. (2019)	Two-bedroom house (buildings)	Efficiency increase	Passive house measures: -69 kWh/m^2 yr; passive house & more efficient but conventional building system: -118 kWh/m^2 yr; passive house & more efficiency & heat pump: -127 kWh/m^2 per year
Barret and Scott (2012)	Construction sector	Substitution & modular building	Substitution of cement: Between -298 and -1240 kt CO_2 eq. (year 2050); Modular building: Between -27 and -165 kt CO_2 eq. (year 2050)
Cooper et al., (2017)	Construction sector UK and EU-27	Lightweighting, substitution and efficiency increase	Embodied energy use: -13% (-95.2 PJ in the UK) & -14% (-1011.6 PJ in EU-27)[b]
Hertwich et al. (2019	Buildings	Light-weighting and material substitution	Timber compared to the use of concrete and/or steel: from -100 to -400 kg CO_2 eq./m^3
Ros-Dosda et al. (2019)	Floor coverings	Material substitution	Emissions savings from having ceramic tiles instead of: synthetic carpet over a 50-year lifecycle: -89.9 kg CO_2 eq./m^2; parquet: -28.8 kg CO_2 eq./m^2; PVC -26.4 kg CO_2 eq./m^2; laminate: -19.9 kg CO_2 eq./m^2; natural stone: -9.7 kg CO_2 eq./m^2.
Scott et al. (2019)	Construction sector	Design optimisation to reduce material inputs and substitution	Optimization design: between -0.52 & -9.23 Mt CO_2 eq. (years 2023-2027) and - 0.73 & -13.07 Mt CO_2 eq. (years 2028-2032); substitution: between -1.79 & -19.82 Mt CO_2 eq. (years 2023-2027) and -2.53 & -28.08 Mt CO_2 eq. (years 2028-2032).

[a] Negative values (-) represent emissions savings with the implementation of the circular economy compare with linear solutions; positive values (+) represent an increase

[b] Reduction values are not disaggregated and include the implementation of reuse, lightweighting, substitution and efficiency increase

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3. Results

3.1. Frequency analysis

The sample of studies reviewed includes 24 publications: 16 peer-reviewed journal papers and 8 conference papers. Literature suggests that while CE is an expansive area for research, its application to the construction sector has been limited (Campbell, 2019). The small size of the sample here is constrained by focusing on trade-offs between CE measures and climate change mitigation measures in the construction sector – an important discussion that is yet to be developed by researchers in any detail. According to several systematic literature reviews on CE (e.g. Geissdoerfer et al., 2017; Merli et al., 2018), an interest in this topic has been growing since 2006. However, EU-focused research on CE took off only in 2012, perhaps with the emergence of the Ellen MacArthur Foundation's work in this area. Accordingly, even though the keyword search was set to start in 2006, 96% of papers in this analysis were published between 2016 and 2019. The number of publications per year grew from one paper in 2012 to 16 papers in 2019 at the time of writing, although no articles in the sample were published between 2013 and 2015 (see Figure 1).

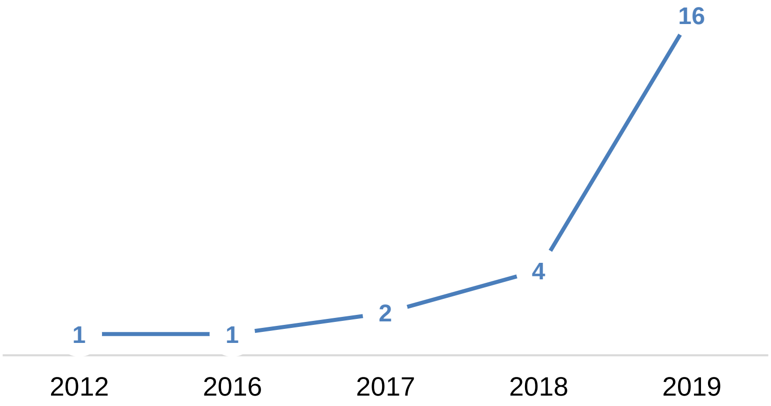

Figure 1. Number of publications per year.

The reviewed papers are dispersed across a variety of journals, showing that research on CE in construction has not yet found a natural 'home' where a critical mass of papers would be published. The IOP Conference Series (Earth and Environmental Sciences) and Journal of Cleaner Production are the top two publishers for this sample of papers, having published five and four papers respectively. Resources, Conservation & Recycling and Proceedings of the Institution of Civil Engineers (Engineering Sustainability) are the next most popular tier of publishers, with two papers each thus far. The remaining journals have each yielded one paper from the reviewed sample and fit into a diverse range of disciplines, including construction, economics, materials, environment and management. A third of the papers were published in conference proceedings, which can be an indicator of a new, growing area, with researchers first testing their ideas in a conference setting before publishing them as journal articles.

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Geographically, half of the reviewed publications focused on a single country as a case study, with the rest exploring two or more countries or the EU as a region. The case study locations were dominated by the wealthier European nations (see Figure 2), and the UK was the most frequent case study appearing in 7 out of 24 studies, likely due to the sample being published in English. The second most frequent location, Denmark, appeared in 6 studies (e.g. Eberhardt et al., 2019a, 2019b, 2019c), potentially thanks to its active research on CE and sustainability. Eastern European countries did not feature in the reviewed publications, showing a potential geographical gap in applying CE to the construction sector. One of the publications did not apply its findings to a specific geographical location as a case study (Sánchez and Hass, 2018), although it did mention Europe, which is why it complied with the selection criteria.

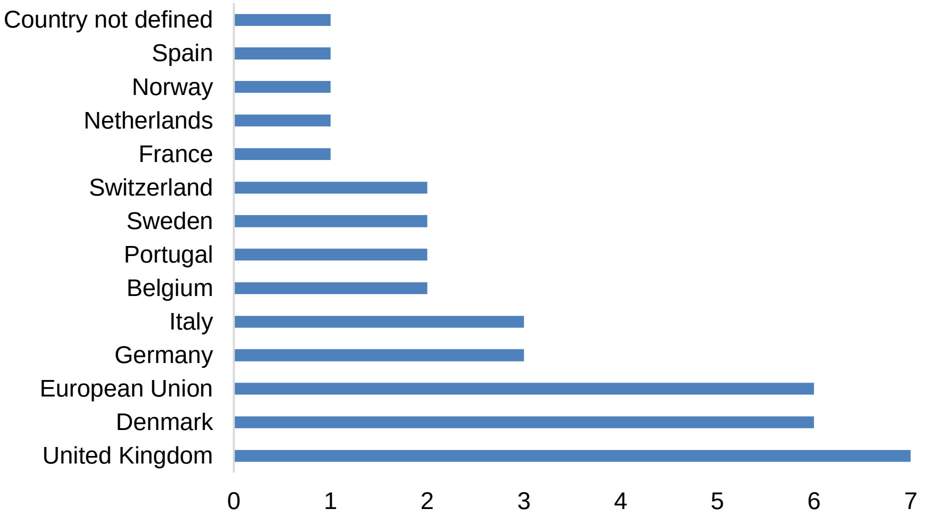

Figure 2. The number of publications by country or region.

The scope of the reviewed studies ranged from narrowly focusing on a specific material (21% of the studies), to expanding the focus to an entire building (the majority of the studies at 67%), to an even more general perspective on the construction sector (the remaining 12% of the studies in the sample), as Figure 3 shows. Examples of specific construction materials in the reviewed publications include gypsum (Jiménez-Rivero and García-Navarro, 2016), asphalt (Antunes et al., 2019) and bricks (Migliore et al., 2018) – we have interpreted these as 'materials' to contrast them with more complex structures, for example, steel-concrete systems. Such structures were analysed as parts of buildings, in addition to wall assemblies, windows and facades, unlike the specific materials that were a single focus. The publications analysing the construction sector as a whole (e.g. Cooper et al., 2017) all had the UK or EU as a case study. The construction sector dominated as the focus of the studies exploring a combination of narrowing resource loop and slowing resource loop strategies to CE, while specific materials were prevalent among the closing resource loop studies. The studies focused on buildings mainly mapped onto slowing resource loop strategies.

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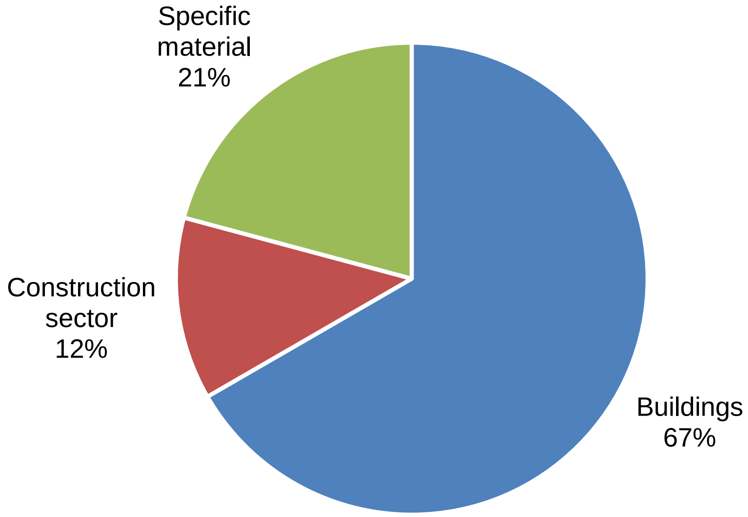

Figure 3. The percentage share of publications by construction element.

Finally, Figure 4 shows the studies grouped by the three main CE strategies investigated: slowing, closing and narrowing resource loops. The sample of reviewed studies was dominated by the CE solutions aligned with slowing resource loops (Table 1), with 13 out of 24 publications falling into this category and four more publications focusing on both slowing and narrowing the loops. Reuse was the CE solution most represented in the slowing-loops literature, with 14 publications including this CE solution. Only four studies analysed durability (e.g. Campbell, 2019), and three analysed refurbishment (e.g. Ghisellini et al., 2018). There were no studies in the sample about servitisation or sharing to slow the resource loops. Among the closing resource loop CE solutions (Table 2), upcycling was considered in six studies. Among the narrowing CE solutions (Table 3), the focus was on increasing efficiency and encouraging material substitution. The present article is thereafter structured following the three CE strategies – slowing, closing and narrowing resource loops – and the specific solutions associated with each strategy.

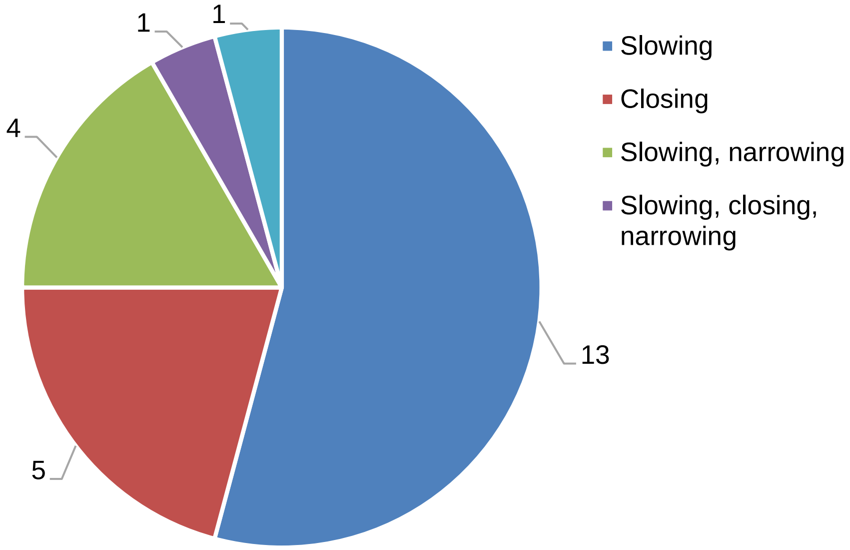

Figure 4. The number of publications by circular economy strategy.

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3.2. Literature review findings

3.2.1 Slowing resource loops

3.2.1.1. Reuse at the product level

Some researchers focus on design for disassembly (DfD) as a key solution to facilitate material reuse, including the development of methods to quantify the resulting potential GHG emission savings. For instance, as shown in Table 1, Eberhardt et al. (2019a) propose a Life Cycle Assessment (LCA) method for quantifying the potential environmental savings of applying DfD to concrete structures to optimise material choices combinations, extend the service life of buildings and facilitate reuse of construction materials. The effectiveness of the method is demonstrated through its application to a Danish office building. The results show that the reuse of the internal concrete structure for two and three cycles thanks to DfD can lead to 15% (-35 kg CO_2 eq./m^2) and 21% (-50 kg CO_2 eq./m^2) of CO_2 eq. emissions savings, respectively, compared with traditional buildings where material replacements take place over the 50 to 80-year building´s lifespan. On the other hand, the optimisation of load-bearing concrete columns at the facade (assumed for reuse through DfD) could reduce carbon emissions by 26% (-60 kg CO_2 eq./m^2). A combination of DfD with material optimisation is, therefore, suitable to reach higher environmental savings. At the material level, the reuse of concrete-based floor slabs, core walls, roof slabs, columns and beams for two and three cycles over the building’s lifespan can generate from 25% to 60% material-related carbon emission savings compared with primary materials, providing also reasonable economic savings. However, the substitution of concrete with different material choices such as steel, wood and glass can lead to higher CO_2 emissions saving potentials compared with DfD and material reuse choices. For instance, the implementation of recyclable load-bearing timber columns at the facade (instead of concrete) can reduce by 59% (-140 kg CO_2 eq./m^2) the accumulated embodied CO_2 emissions over an 80-year building lifespan (Eberhardt et al., 2019a). Therefore, carbon saving potential driven by material substitution can be up to 300% higher (+105 kg CO_2 eq. m^2 more savings) than the savings driven by DfD for material reuse. Accordingly, material substitution can represent a more suitable solution for the mitigation of GHG compared to reusing some materials.

Complementary to the above study, Eberhardt et al. (2019b) demonstrate (using temporal considerations) the potential variations in the material flows and environmental burden of three common building components (a concrete column, a window and roof felt) when they are designed by applying linear economy approaches versus a prospective CE-approach based on DfD. The results suggest that a DfD concrete-based column, window and roof felt can reduce GHG emissions by 36% (-180 kg CO_2 eq./component), 92% (-32 kg CO_2 eq./component) and 99% (-3.2 kg CO_2 eq./component), respectively, compared to conventional designs implemented in Denmark. Nevertheless, the potential carbon benefits of reusing construction materials are not gained immediately but at the point of future retrieval (e.g. 80 years ahead). Thus, long lifespans of buildings increase uncertainty in determining future practices and the quality of materials. Furthermore, material loops cannot be 100% circular as additional materials are needed to uphold the material loop due to system losses between product cycles.

Considering a whole building perspective, Sánchez and Haas (2018) describe a user-friendly novel disassembly planning method to find efficient selective disassembly sequences for retrieving target components from buildings. The approach is based on the combination of environmental-impact, building-cost, and rule-based analysis, and it is performed for one component at a time and by considering a given disassembly/deconstruction method per component. The method is validated through the analysis of different disassembly sequences for a typical building frame structure. The environmental sustainability of different disassembly sequences was calculated using LCA but considering only production, construction, and end-of-life phases. The results show that the global warming potential (GWP) of different disassembly plans applied to the same building frame structure can range from 209 kg CO_2 eq. to 897 kg CO_2 eq. (+77%). This article demonstrates the relevance of applying selective disassembly thinking to reduce the disassembly steps and time dramatically, hence reducing environmental impacts and costs.

Other examples of the use of DfD are provided by Brütting et al. (2019a,b). The authors describe optimisation and disassembly techniques to design truss structures that maximise the direct reuse of structural components over multiple service lives. The final objective is to significantly reduce the resource intensity, superfluous waste generation and environmental impact of building structures. Two case studies are analysed: i) a cantilever of simple layout and ii) a train station roof structure of complex layout made from reused elements from disassembled electric pylons. LCA is applied to analyse the environmental savings of reusing steel elements rather than adopting new weight-optimised solutions made from primary steel. The reuse of steel elements in the cantilever truss can reduce the embodied carbon up to 46% (-76 kg CO_2 eq./infrastructure), whereas the carbon savings related to the reuse of materials in the train station roof correspond to 56% (-2.3 t CO_2 eq./infrastructure). Accordingly, reusing structural elements can result in a significant reduction of embodied carbon, even though the reused solutions may have a higher mass and lower mean capacity utilisation. According to the authors, reuse is also a more environmentally sustainable option and implies further emission savings than recycling to manage construction products when they reach the end-of-life. Whereas material recycling demands energy to reprocess materials and often results in a loss of quality leading to downcycling, reuse implies only minimal physical transformations, including the use of already embedded technology.

Complementarily, Brambrilla et al. (2019) focus on steel-concrete composite floor systems, which represent the most efficient structural solution for buildings and bridges because the composite action combines and optimises the structural properties of the two most used and high-impact building materials (steel and concrete). The authors compare the life cycle environmental impacts between a demountable composite floor system (ReuseStru) using pretensioned high-strength friction grip bolts as shear connectors to facilitate disassembly and reuse, and three conventional composite floor systems (composite slabs, precast hollow core slab and precast solid) that employ welded shear studs as shear connectors (conventional demolition and recycling). The geographical context and time frame considered were the UK and 100 years, respectively. The findings demonstrate that the ReuseStru system can reduce carbon emissions from 27% (-80 kg CO_2 eq./m^2) to over 35% (-120 kg CO_2 eq./m^2) compared to the conventional steel-concrete composite structures. Considering a building with a total surface of 2232 m^2 effectively covered by the composite floor system, the carbon savings arising from the implementation of the ReuseStru could range from 180 to 270 t CO_2 eq. For the ReuseStru to contribute higher climate change impact than the conventional composite systems, the transportation distance for material reuse by heavy trucks should be greater than 1000 km.

Nevertheless, other studies suggest that construction products with good reusable and recycling properties do not guarantee lower GHG emissions unless the entire life cycle is considered. The lowest climate change impact is achieved with reusable or easy to recycle assemblies if they are actually reused or recycled at the end-of-life. Otherwise, construction products with no possibilities for direct reuse, but having a low manufacturing impact can be the best alternative for climate change mitigation. For instance, Buyle et al. (2019) studied the environmental impacts of seven alternative wall assemblies with five different end-of-life scenarios in Belgium: i) current practice (actual Belgium percentages of landfilling, incineration with energy recovery and recycling), ii) maximised energy recovery, iii) improved recycling (higher rates than in current practice), iv) optimised recycling (much higher recycling rates and off-site reuse) and v) reuse in the same building without any additional treatment. Four of the wall assemblies represent conventional practice (linear construction model). The other three assemblies are demountable and reusable. The three reusable models have, on average, 37% less climate change impact when the reuse scenario is applied compared to the four conventional with the current practice waste treatment. However, the improvement is reduced to only 14% when both groups are analysed considering current end-of-life waste management practices. Actually, one of the conventional assemblies becomes the best alternative within the present end-of-life scenario due to lower GHG emissions during the production process.

Focusing on end-of-life management, Hopkinson et al. (2019) performed a literature review of CE-solutions for the most common building products for load-bearing structures: i) structural concrete components from reinforced-concrete structures, ii) steel from steel-concrete composite structures, and iii) bricks from masonry walls bonded by cement-based mortar. Although findings confirm the limited attention to innovation and research focused on the reuse of the building stocks (from a technical, economic and environmental standpoint), the authors provide a few examples of CE case studies. For instance, the reuse of steel structures without melting in Italy could generate 30% savings in energy and carbon emissions (Pongiglione and Calderini, 2014). The authors also mention a study demonstrating the technical feasibility of a complete 3250 m^2 steel frame warehouse relocation and reassembly in the UK leading to 38% carbon reductions compared to a benchmark building (Segro, 2013). The research from Rebrick project (Nielsen, 2013) is also mentioned, where it was estimated that each reused brick could save 0.5 kg of CO_2 emissions compared to building with new bricks in Denmark, Germany and Italy. Finally, concrete reuse can generate 97% lower carbon emissions than concrete recycling in The Netherlands (Glias, 2013). Nevertheless, Hopkinson et al. (2019) conclude that the creation of CE building systems requires an ability to couple closely the recovery and reuse of products from the end-of-life of buildings to stock replacement and maintenance.

Another interesting review is the one provided by Hertwich et al. (2019), who evaluate the product-level carbon emission savings related to material efficiency solutions applied to buildings. According to the authors, the reuse of energy-intensive building materials, such as steel, could result in 0.36 kg CO_2 saved per kg compared to recycling given the energy requirements of remelting in an electric arc furnace, which is much less than replacing virgin steel (1.78 kg CO_2/kg) but still not negligible (Hertwich et al. 2019; Dunant et al., 2017).

3.2.1.2. Reuse at the sector level

The potential environmental savings of material reuse has also been analysed from a broader market perspective, including business model and policy considerations. For example, Nußholz et al. (2019) investigate the relevance of secondary material for decarbonisation of the building sector, including the interplay of business model innovation and policy instruments. The authors estimate the carbon saving potential of three Danish and Swedish companies producing building materials with secondary material inputs, including i) wood-plastic composite (WPC) for plank products, ii) constructed assets based on secondary concrete, and iii) reused bricks. At the product level, the reuse of secondary materials can contribute to reducing i) 56% to 64% (0.95–1.42 kg CO_2 eq.) the manufacturing carbon emissions per kg WPC produced, ii) 67% (0.008 kg CO_2 eq.) the manufacturing carbon emissions per kg aggregate prepared for concrete production, and iii) 99% (0.025 kg CO_2 eq.) the manufacturing carbon emissions per kg of brick produced. At the industry level, the production of bricks using secondary material inputs shows the highest carbon saving potential, with estimated annual savings of 25,300 t CO_2 eq. in Denmark, being the yearly carbon saving potential for concrete production around 7,300 t CO_2 eq. The annual carbon saving potential of WPC production is estimated at 12,400 to 18,400 t CO_2 eq. for the Scandinavian market. The results demonstrate that all three case studies can offer relevant carbon savings, although such savings can vary significantly depending on the affected processes in production and the market dynamics and readiness to supply (and accept) secondary products.

Following this market perspective, other studies have analysed the influence of reusing construction materials in the reduction of embodied GHG emissions at a country or region level. For instance, Scott et al. (2019) calculated the savings associated with the reduction of material inputs through design optimisation, material substitution and material reuse in the UK construction sector. To do so, the authors considered three different scenarios based on the level of implementation of each CE solution: high (100% implementation), medium (66%) and low (33%). For the reuse solutions, the range in the potential reduction in the consumption of virgin materials for each scenario corresponds to 10-35% for steel, 3-18% for timber, 2-30% for brick and 1-5% for other construction materials. The implementation of these levels of reuse implies GHG savings equivalent to 0.49-3.69 Mt CO_2 eq. and 0.70-5.23 Mt CO_2 eq. for the fourth and fifth carbon budget periods established by the UK government (years 2023-2027 and 2028-2032, respectively).

Similarly, Cooper et al. (2017) consider the consequences in embodied primary energy consumption and exergy from the implementation of different types of CE solutions for the year 2007 in the UK and EU, and compare them with more conventional energy-saving measures. The authors propose 22 CE solutions applicable in the construction sector, nine of them associated with reusing (e.g. reuse of foundations, bricks or structures) accompanied with three levels of implementation: “intermediate” (30% implementation), “advanced” (60%) and “maximum technical potential” (100%). The results were calculated globally, and therefore, the individual effect of reuse solutions cannot be presented. Applying the 22 CE solutions in the intermediate scenario would imply savings of 13% (95.2 PJ) and 14% (1011.6 PJ) in the total energy use embodied in construction materials in the UK and EU, respectively.

Finally, Ghisellini et al. (2018) reviewed the recent literature on CE solutions (reduce, reuse, and recycle) with applicability to the management of construction and demolition waste with the purpose of determining if the adoption of the CE framework is environmentally sustainable. According to the review, material reuse and recycling (after a selective deconstruction) can generate 5% reduction in the overall building´s GWP in conventional passive houses in the UK (Cuellar-Franca and Azapagic, 2012). On the material level, Coehlo and De Brito (2012) demonstrate a relevant reduction of the environmental impacts when shifting from no recycling to a 95% recycling of waste materials for reuse into new constructions. Such a shift can drop material-related GWP by 77% within the Portuguese context. However, this implies the need to ensure the availability of high quantity and well-maintained salvaged materials from deconstruction activities, which must be carried out by experienced deconstruction workers. Accordingly, Ghisellini et al. (2018) concluded that the environmental (and economic) sustainability of CE solutions applied in construction depends on several factors, including: i) the adoption of selective demolition; ii) the type of building and building elements to be designed or managed; iii) the type of materials to be reused and/or recycled; iv) the building location; v) the scale of the recycling plants; vi) the presence of a market for salvaged goods from deconstruction; and vii) the economic and political context. Consequently, the climate change impacts associated with material reuse and/or recycling is a site-specific outcome and the hierarchical importance of reuse and recycling as well as of incineration over landfilling cannot be predefined.

3.2.1.3. Durability

Campbell (2019) analysed the application of different CE approaches to mass timber[1]: i) modify less (avoid the need to adapt timber, increase production efficiency and reduce

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[1] Mass timber are large timber products like panels or beams made by connecting together smaller timber elements

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the use of non-renewable resources like glues); ii) hold (increase adaptability and durability); iii) loop (increase inner cycles, particularly reuse); and iv) new business models like selling a product as a service. From the climate change perspective, the authors assessed the dual benefit of timber mass for both reducing the GHG embodied emissions of buildings and locking up CO_2 until their end-of-life. Regarding the embodied emissions, Campbell (2019) highlighted that they represent between 30-50% of the total lifetime emissions of UK buildings (UKGBC, 2017) and therefore, the increase in the use, reuse and durability of mass timber can play a crucial role in the reduction of the emissions of the sector. The measurement of these embodied emissions should be consistent and comprise all life cycle stages, including the often neglected end-of-life, where the benefits of some circular economy approaches (e.g. increasing reuse instead of landfilling) should be quantified. Regarding the current CO_2 sequestration per year in mass timber used in buildings, Campbell (2019) considered that it only represents around 0.03% of the EU + Iceland total annual emissions (1.2 versus 4317 Mt CO_2 eq./yr) and this ratio is not expected to increase in the near future.

Eberhardt et al. (2019c) linked durability to the reuse of building components, with more durable components able to withstand a larger number of reuses. They also argued that the economic and environmental value, as well as the durability of reused components, increase with the scale of a component, moving from crushed building materials to building elements (e.g. bricks), to building modules (e.g. walls), and finally to entire prefabricated building structures. To test this hypothesis, the authors included in their scenarios, first, the scale of reused components and, second, the number of reuses. The authors estimate that emissions savings from reusing (thrice) smaller components such as beams (33% in CO_2 savings), roof (41% in CO_2 savings), and core walls (50% in CO_2 savings) were usually lower than those from reusing the building's prefabricated concrete structure (55% in CO_2 savings). The reuse of a prefabricated concrete structure leads to only 40% in CO_2 savings if reused twice. A glass facade with wooden columns reused three times resulted in 80% in CO_2 savings, as opposed to 73% in CO_2 savings if reused twice. The substitution of wood by steel or concrete for the columns would increase CO_2 emissions by 101% and 239% respectively. These percentages are at the component (i.e., in this case, column) level, and hence, in absolute terms, they would be smaller than the numbers at the level of an entire building. This study is an example of interwoven slowing loops and narrowing loops, with durability, reuse and material substitution combined into a set of CE measures. Similarly, Ros-Dosda et al. (2019) analysed durability and material substitution by comparing six types of indoor floor coverings, including ceramic tiles, natural stone, laminates and carpeting. Related to the durability aspect, the authors concluded that the number of replacements and repairs is a critical factor in affecting GHG emissions. In particular, more intensive use, repair, maintenance and replacement can increase emissions by 8.1-38.9 CO_2 eq./m^2.

3.1.2.4. Refurbishment

Potential reductions in resource consumption and GHG emissions can be achieved by extending building lifespans through refurbishments, which directly reduce upstream energy demands (Hertwich et al., 2019). Nevertheless, time- and space-related

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decisions involved in the refurbishment of a building have a significant impact on the building's lifecycle GHG emissions (Castro and Pasanen 2019). For example, changing the building envelope, such as roof tiles, external insulation and cladding, every 20 years (an assumed typical timeframe for periodic refurbishments) can lead to a 6.1% increase in total embodied carbon. Major refurbishment, such as changes to floor finishes, ceiling finishes and internal walls, every ten years can result in a 66.6% increase in total embodied carbon. The authors argue that both the time component, i.e. the frequency of refurbishments, and the spatial layout of such refurbishments require in-depth research. For example, the spatial planning of internal partitions, finishes, and service systems can hinder or facilitate the efficiency and 'circularity' of refurbishments. Ultimately, decision-makers need to consider whether a refurbishment can be avoided altogether if it adds to the carbon footprint of the building.

While the refurbishment process is clearly not zero-carbon, it can have relative environmental benefits, when compared to demolishing a building and constructing a new one in its place. Based on Ferreira et al. (2015), Ghisellini et al. (2018) highlight that the refurbishment of buildings in Portugal by reusing materials can reduce the building's GWP by 13% compared to demolition and new construction activities. From a sector perspective, Barret and Scott (2012) concluded that retrofitting most the houses demolished or vacant in 2004 in the UK (7% of the stock) and therefore, reducing the amount of materials used in new construction building, could reduce GHG emissions up to 166 kt CO_2 eq. in year 2050. To achieve the maximum carbon emission reductions from refurbishment, Castro and Pasanen (2019) advocate designing resource-efficient buildings using low-carbon materials and having future refurbishment requirements in mind to develop benchmarks for embodied carbon.

3.2.2. Closing resource loops

Upcycling, in contraposition to downcycling, has been defined as a recycling process in which used materials are converted into something of the same or higher value and/or quality in their second life (Sung, 2015). The direct comparison of emissions of closing-loop technologies (e.g. upcycling) with linear waste treatments (e.g. landfilling) for construction materials without considering other essential aspects of the process (e.g. transport to treatment facilities or energy consumed in demolition versus deconstruction) can lead to wrong conclusions. As an example shown in Table 2, Jimenez-Rivero and Garcia-Navarro (2016) propose several indicators, including GHG emissions, to measure the management performance of end-of-life for gypsum if upcycled (recycled gypsum with the same quality that avoids natural extraction) or landfilled in five pilot plans in Belgium, France, Germany and the UK. The upcycling process itself produces GHG savings compared with the combination of landfilling and natural extraction, but these benefits can be significantly reduced by transport when there are longer distances to the recycling facilities. For example, in one of the pilot plants the further distance for the recycling facility implied 1037 kg CO_2 eq./t gypsum waste associated only to the transport, a significant amount if compared with the 2033 kg CO_2 eq./t emissions of the whole extraction process of natural gypsum. Other factors that can affect the efficiency of transportation and, therefore, the emissions are poor optimisation of roundtrips due to the shape and size of the waste, type of skips and how waste is placed in the trucks.

Focusing on the cement used in construction, Hertwich et al. (2019) highlight that methods to upcycle hydrated cement waste into new cement have been developed, which could help reduce of CO_2 emissions by to 30% (Diliberto et al., 2017; Gastaldi et al., 2015). Indeed, technologies to recycle all components of cement are under development and could lead to substantial reductions in GHG emissions, which have yet to be comprehensibly analysed (Nusselder et al., 2015). Regarding the recycling of other construction materials, Antunes et al. (2019) conducted a systematic review of the incorporation of RAP (Reclaimed Asphalt Pavement) in new bituminous mixtures (RAP recycling) considering design requirements, limitations and performance at European level. For example, Zaumanis et al. (2014) reported significant environmental benefits of RAP recycling in France, with carbon emission savings of 35% (-18 kg CO_2 eq./t RAP bituminous mixtures) and of 20% in energy per t when comparing a virgin Hot Mix Asphalt (HMA) with an HMA containing 100% RAP. The key challenge is the quality assurance as the specification criteria should be equal to both RAP and virgin aggregates. Likewise, the durability performance of 100% RAP requires further investigations.

Rasmussen et al. (2019) proposed an innovative upcycling solution by constructing a building from primarily upcycled materials, including shipping containers, concrete strip foundations, expanded polystyrene, construction wood, windows and facing tiles and gypsum boards. The authors compared the environmental impacts of this solution with the construction of the same building following DfD principles and with common material recycling, such as aluminium or oriented strand boards. It was found that the innovative upcycling solution results in reductions of 0.7 kg CO_2 eq./m^2/year when compared with the DfD and can save 1.1 kg CO_2 eq./m^2/year compared with common material recycling. The results indicated the importance of the 100:0 EN standards' allocation approach where a system's use of recycling/reuse is merited (e.g. upcycling solution), rather than meriting a system providing recyclable/reusable materials (e.g. through the adoption of DfD principles).

In the same line of open loop upcycling, Migliore et al. (2018) assessed the carbon footprint of one brick with large quantities of waste from localised marble quarries in the Apuan district (Italy). The brick is manufactured by pressing and not by firing to reduce energy consumption and with a maximum 50% marble waste composition. The GHG emissions can be reduced up to 50% compared to a brick from virgin materials (2.6 and 5.2 kg CO_2 eq. per t, respectively). This case study shows that it is possible to promote GHG savings in a systematic manner by reusing waste from different processes in the construction sector.

Regarding construction insulation products, Nasir et al. (2017) compared the carbon emission of using recycled textile materials as insulators (P1) with traditional insulation materials as stone wool (P2). The authors concluded that the emissions of the production with virgin stone wool were 64% higher than with recycled textile (1.51 kg CO_2 eq./kg versus 0.92 kg CO_2 eq./kg). Supply chain carbon mapping showed that the use of chemicals in the treatment of both types of insulation products contributed significantly to the total life cycle carbon emissions. The results also show that transport elements dominate a larger percentage of the total emissions of the circular supply chain

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compared to the linear. The authors concluded that future research should consider adopting a more closed-loop end-of-life for P2 insulation materials via recycling.

Finally, Hertwich et al. (2019) conclude that the recovery of steel, aluminium, and copper from construction and demolition waste results in the recycling of base metals, which achieves significant emission reductions. Nevertheless, higher collection rates and sorting efficiencies, while avoiding the contamination of base metals, are essential steps to minimise emissions further.

3.2.3. Narrowing loops

Approaches for narrowing resource loops are only represented in six of the reviewed articles, which focus on material optimisation and material substitution in combination with other CE solutions. Articles analysing solutions related to material substitution have been considered to narrow resource loops, assuming that the new material choices are less material- and/or energy-intensive. For example, Hertwich et al. (2019) highlight that the GHG emissions of new buildings can be reduced either through product-lightweighting, such as using lighter structures, or using less carbon-intensive materials, such as replacing steel and concrete with wood where appropriate.

As shown in Table 3, Ros-Dosda et al. (2019) compare six types of indoor floor coverings, including ceramic tiles, natural stone, laminates and carpeting. There are significant differences in emission savings of different flooring systems, intended to last for 50 years. Ceramic tiles can save 89.9 kg CO_2 eq./m^2 compared to synthetic carpets, 28.8 kg CO_2 eq./m^2 compared to parquet, and 9.7 kg CO_2 eq./m^2 compared to natural stone. Inorganic floor covering (ceramics and natural stone) gave the highest emissions savings across the life cycle due to low maintenance requirements, despite being emission-intensive during the manufacturing stage. This finding emphasises the importance of analysing the entire life cycle.

Findings for Norway and Sweden also show that avoided GHG emissions from using timber, instead of concrete and/or steel, typically lie between 100 and 400 kg CO_2 eq./m^3 timber, although the entire range spans from minus 310 to plus 1060 kg CO_2 eq./m^3 (Hertwich et al., 2019 based on Petersen et al., 2005). Nevertheless, increasing the demand for wood is controversial due to the current unsustainably high harvest rates in some regions, which leads to environmental burden shifting. Considering the limited global availability of timber, it is important to focus its use in structures where carbon benefits are the largest (Hertwich et al., 2019).

Narrowing energy consumption by implementing technological improvements and architectural passive-house measures can help to reduce the lifecycle carbon footprint of a building significantly. A case study of a two-bedroom house in Portugal's capital (Andrade et al., 2019) shows that combining an optimised heating-cooling system with passive-house measures and a heat pump can cut energy use, and hence emissions, substantially. Passive-house measures include, in this case, thermal insulation and double glazing and would alone lead to energy savings of 69 kWh/m^2 per year per building. These passive-house measures combined with a more efficient but conventional building system, which includes an air conditioner for heating and cooling and a gas condensing heater for hot water, would imply reductions of 118 kWh/m^2 per year. With an added heat pump, the annual energy savings can be brought up to 127 kWh/m^2.

Focusing on the country-level, Scott et al. (2019) studied GHG embodied emissions savings in the UK through the reduction of material inputs thanks to design optimisation. The conjunction of the proposed design measures (e.g. optimised roll-out reinforcement steel meshes or optimal building information modelling) can generate up to 9.23 Mt CO_2 eq. and 13.07 Mt CO_2 eq. savings for the period 2023-2027 and 2028-2032, respectively. Likewise, material substitution (e.g. increase the use of hybrid timber-steel, cross-laminated timber/glulam or of other biotic materials (e.g. straw bale)) would reduce the emissions by up to 19.82.Mt CO_2 eq. and 28.08 Mt CO_2 eq. within the same periods.

Cooper et al. (2017) analysed the reduction in the embodied energy and associated GHG emissions achieved through 13 different lightweighting, material substitution and efficiency improvements for the EU and UK. Pipeline lightweighting, a more efficient use of beams or the substitution of steel and bricks by wood were among the solutions considered. The individual effect of narrowing loop approaches is not available from the study because the energy savings are aggregated for the 22 CE economy measures associated with the construction sector. However, global results are discussed in section 3.2.1.2. *Reuse at the sector level*

Also with a geographic focus on the UK, Barret and Scott (2012), expanding on the report by Scott et al. (2009), analysed the climate change mitigation potential associated with three CE scenarios for material efficiency with different levels of implementation (quick win, best practice and beyond best practice). The authors compared these scenarios for the year 2050 with a “business as usual” scenario, based on historical trends and expert judgments for a plausible future for the UK economy. Two of the CE approaches focused on narrowing loops in the construction sector: modular building (2% implementation by 2020 and 5%-10% by 2050) and substitution of cement by lower carbon intensive materials (10% implementation by 2020 & 20%- 40% by 2050). The application of modular building and off-site construction can reduce the emissions by 27-165 kt CO_2 eq. The best CE approach is the substitution of cement by low carbon materials with emission savings of 298-1240 kt CO_2 by 2050. However, these figures should be considered as an approximation, because the substitution rates are not material-specific and the authors use plastic as a proxy for a low carbon material.

4. Discussion

The findings of this literature review suggest that the implementation of CE approaches (slowing, closing and narrowing loops) in construction projects can help mitigate climate change significantly. Studies focused on slowing resource loops have demonstrated that substantial GHG savings can be achieved (up to 99%) per functional unit. Material reuse stands as the most promising CE solution for reducing GHG, where DfD plays a key role in achieving the separation of material streams for further reuse, and for recycling when the materials can no longer be reused in construction. Reuse is also linked to an increase in the durability of buildings and constructed assets because it leads to product-life extension (e.g. through refurbishment) making products more durable. Accordingly, reuse can be considered a key CE solution that can be applied in combination with other CE solutions adding more value (e.g. environmental and cost savings) to building systems. The dominance of reuse might be related to being one of the most direct CE solutions that can be implemented in the construction sector. While downcycling (e.g. concrete used for aggregates) can also be applied directly, they are considered the last resort in a CE model, where upcycling and reuse should be prioritised.

The six studies focussed on closing loop solutions were selected considering CE principles and, therefore, avoiding downcycling. With this premise in mind, the reviewed articles show significant reductions (between 30% and 50%) in GHG emissions for some recycled construction materials compared with virgin materials. However, several studies agree that the level of emission reductions is influenced by the logistics of the materials, and that the virgin materials could become the best option if transportation is emission-intensive (e.g. if the distance to the recycling facilities is significant).

Narrowing loop solutions are represented in this review by only six articles that in most cases, consider multiple CE solutions and therefore go beyond narrowing. The articles show a significant impact, at the construction level, of solutions such as design optimisation (e.g. reductions of up to 9.23 Mt CO_2 eq. for years 2023-2027 in the UK) or material substitution (e.g. reductions of up to 19.82 Mt CO_2 eq. for the same period). However, there are still several barriers to such CE solutions, including high initial costs, limited information and public awareness about costs and benefits, and lack of political support for CE. These barriers explain why some optimisation solutions, such as modular buildings and off-site construction, are not expected to be implemented on a large scale in the short term (Barrett and Scott, 2012). For substitution solutions, some studies point out that the durability and reuse options associated with certain substitutes like mass timber remain understudied (Campbell, 2019; CIB, 2014).

At the product level, the reviewed studies demonstrate that, in most cases, emission reductions can be achieved. GHG emissions can drop by 5% up to 99%, depending on the solution and functional unit considered (e.g. building square meter, a component, a product or an entire infrastructure). With Europe´s level of urbanization expected to grow from today’s 74% to 84% by 2050 (European Commission, 2019b), even small improvements in the resource efficiency of the built environment by encouraging circular economy practices, such as reuse, refurbishment and materials upcycling can lead to significant GHG and environmental savings. The demand for construction materials and related emissions can be reduced through more intensive use of buildings (reducing per capita floor area), extending the lifetime of buildings, using lighter constructions and less carbon-intensive building materials (e.g. wood-based construction instead of steel and cement), reducing construction waste (e.g. through pre-fabrication), reusing structural elements, and recycling building materials (Hertwich et al., 2019). However, it is essential to first rigorously quantify and then select appropriate CE solutions, to prioritise those reducing emissions, as demonstrated by Barrett and Scott (2012) and Buyle et al. (2019).

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Some studies highlight that the emission quantification from CE solutions remains poorly understood, owing in part to the multitude of material uses and diversity of contexts and in part to limited research (Hertwich et al., 2019). This quantification is necessary because the implementation of CE principles in the construction sector is not always beneficial to the climate, as it can increase emissions. For example, manufacturing more reusable or recyclable versions of construction products can lead to higher emissions compared to non-reusable or non-recyclable versions of the same products, particularly if the more circular versions are not reused and recycled at the end-of-life (Buyle et al., 2019; Ros-Dosda et al., 2019). Zink and Geyer (2019) have also demonstrated that thanks to direct and indirect rebound effects, using construction waste as a resource for other production processes does not guarantee lower environmental impacts. Similarly, Nußholz et al. (2019) have concluded that CE solutions do not result in carbon savings by default but depend on businesses overcoming the many barriers to closing material loops, including unclear financial cases, low amount and quality of materials at the end-of-life, and lack of mechanisms for materials recovery. Hertwich et al. (2019) highlight that the emission-reduction potential of some CE solutions depends on a region’s stage of development, its local material resources, and its existing building stock. In particular, measures targeting new buildings are more critical in developing countries, whereas measures related to lifetime extensions, reuse and recycling are more pertinent to countries with a large existing stock (Hertwich et al., 2019).

The CE case studies showing an increase in GHG emissions justify the need for tools that consider global and cross-sectoral effects (e.g. consequential LCA) and reflect multiple scenarios (e.g. different end-of-life treatments or life expectancy of the materials), combined with uncertainty analysis to assess the consequences of construction decisions accurately. Accordingly, despite the research efforts reviewed in this article, the assessment of potential environmental benefits and, particularly, the implementation of CE thinking in the construction sector, is still in its infancy. Nowadays, the recovery of resources in the construction sector is mostly limited to minimising waste and maximising downcycling (Esa et al., 2017; Guo et al., 2017; Haneef et al., 2017; Jimenez-Rivero and García-Navarro, 2017). The reuse, refurbishment, maintenance, remanufacturing, cascading, multi-recycling, multi-reuse or upcycling of building materials at scale requires significant changes to the industry practices, particularly in relation to construction methods and management of construction wastes. During this transition to CE, it is crucial to consider the context of a building project, the diverse nature of its supply chain, and the balance between short-term profits and long-term environmental goals (Eberhardt et al., 2019b).

In particular, it is important to facilitate business model innovation (Heyes et al., 2018), which can help align a construction company’s business priorities with CE strategies and potentially reduce the company’s GHG emissions. However, while companies can address some of the barriers (such as outdated ownership arrangements or customers’ limited awareness of CE benefits) by adopting novel business models, additional policy interventions are crucial to remove remaining barriers (Tingley et al., 2017).

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The need to use appropriate qualitative tools is a recurring conclusion across the reviewed literature. Environmental analytical tools often support ‘linear’ assessments, focused on primary functions of buildings and materials. Such assessments can miss the impacts of multiple product life cycles (e.g. product-life extension through DfD and reuse) or upcycling of construction materials. Thus, it is not obvious the future circumstances (e.g. context-related recycling scenarios) to consider as well as for how long material quality can be maintained over time. Furthermore, material loops cannot be 100% circular as additional materials are needed to uphold the loops due to system losses between product cycles (Eberhardt et al., 2019a). Cooper et al. (2017) highlight that studies considering only direct energy and emissions savings during the use stage of construction materials are likely to underestimate the benefits of CE approaches. Therefore, a cradle-to-grave life cycle perspective considering the embodied emissions of the materials is crucial for analysing the effects of CE approaches that change the way construction materials are designed, sold, used and treated at the end of life (Campbell 2019; Scott et al., 2019). Analytical tools should pay careful attention to transportation and end-of-life treatment required for material reuse and upcycling, as some of these operations may offset potential environmental benefits (Brambrilla et al., 2019). Further research and investment in closed-loop processes can improve the quality of the final product and the number of treatment facilities and, therefore, reduce life-cycle indirect emissions associated, for example, with long-distance transport from the demolition site to the treatment facility (Jiménez-Rivero and García-Navarro, 2016)

5. Conclusions, challenges and future research

Research and policy on climate change mitigation have mostly focused on technologies for low carbon energy and energy efficiency (Pauliuk et al., 2017). However, uncertainty and the time lag associated to the technologies’ deployment makes additional short-term measures crucial, given the extremely limited carbon budget remaining before exceeding the 2°C ‘dangerous climate change’ threshold (IPCC,2014). In this sense, circular economy (CE) solutions reducing the use of virgin materials and energy in a resource intensive sector like construction have been suggested as a potential solution on the way to achieving the ambitious GHG reduction targets set at the EU level (Scott et al., 2019). To examine the issue in depth, this article has reviewed 24 studies that analyse the link between CE and climate mitigation in the EU construction sector. Most studies show a positive association between CE solutions and GHG emission reductions. However, other studies show an increase in emissions arising from energy- or material-intensive CE solutions, direct and indirect rebound effects, or the barriers to creating value from these solutions. Based on the reviewed literature, the following aspects should be addressed to overcome those barriers and ensure savings both in materials and in GHG emissions in the built environment:

- Apply new CE-oriented structural design (e.g. design for disassembly, modularity, flexibility, and reuse).
- Adapt construction processes to the mechanical and geometric properties of the available materials, and avoid finishes that make materials no longer suitable for reuse or upcycling.

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- Establish circularity design standards, including the application of selective and sequential disassembly planning and minimum durability requirements.
- Develop and get access to databases providing information about material stocks, waste and the markets for reused and recycled materials.
- Tag materials and use building information modelling to track components and assemblies, and import them into building design software at the design stage.
- Implement online marketplaces, stock control systems and product tracking and monitoring protocols.
- Develop innovative technologies and machinery in manufacturing, construction and demolition processes to assist with CE approaches (e.g. by using 3D printing for remanufacturing),
- Develop business and financial cases demonstrating potential economic benefits associated with the adoption of CE principles, particularly if the cost of negative externalities is included.
- Define new ownership arrangements, such as leasing major structural components (e.g. roofs), which could make sense in commercial and industrial facilities with short anticipated lifespans and standardised designs.
- Introduce market mechanisms and CE-related infrastructure (e.g. facilities for collection and recovery).
- Revise and rearrange construction-related policies to facilitate waste management practices for material reuse and upcycling (e.g. by incorporating reuse of higher material value in construction and demolition waste targets).
- Develop new insurance policies that balance better risk, quality assurance and safety to avoid the tendency to over-specification and over-design.
- Develop financial incentives to encourage circularity (e.g. by taxing the use of material without a minimum level of recycled content).
- Provide incentives to enhance cooperation or competition between actors in secondary materials markets and increase supply and diversity in offers.
- Target customer segments that value lower GHG emissions and consider circularity approaches as marketing opportunities (e.g. by highlighting higher flexibility or durability of the buildings).
- Develop technical guidance and education to improve confidence and skills in designing and building with reused and recycled materials.
- Research potential synergies between CE measures and climate change mitigation worldwide. Most reductions in GHG emissions associated with the CE approaches in the EU construction sector could occur outside the EU (e.g. through production in South-East Asian countries).
- Assess the social challenges of implementing CE measures (e.g. whether consumers are prepared to select higher cost, longer lasting construction products over a new non-reusable and cheaper construction products).

The importance of tools and methods for quantifying emissions is discussed in most of the reviewed articles. To adequately quantify the link between CE approaches and climate change mitigation in the built environment, this paper suggests that future research should concentrate on the following aspects:

- Use standard, consistent and geographically adapted data and allocation methods to provide key stakeholders with a reliable basis for decision-making.
- Better understand the relevant processes, inherent properties (e.g. composition, geometry and topology) and interdependences between construction materials and markets to identify and evaluate trade-offs.
- Define the service life of materials and buildings, the number of reuse and upcycling cycles, and how long the material quality can be maintained.
- Develop a material hierarchy based on the GHG footprint and different CE solutions.
- Investigate the differences between, and priorities of, each region/country in terms of climate change strategies from a top-down level. Then apply CE solutions on a case-by-case and regional basis to understand the barriers and enablers, and to optimise the CE approaches by region.
- Integrate forecasts to determine the time- and space-related climate change implications of future scenarios when material reuse or upcycling would take place (e.g. with time horizons of 20 to 80 years).
- Analyse potential direct and indirect rebound effects and burden shifting of climate change impacts.
- Examine through consequential LCAs the indirect effects of CE solutions at the sectoral level to determine whether emission savings at product level might be offset through changes occurring at the sectoral level.
- Evaluate the implications of transportation as it can offset the inherent GHG savings from CE solutions, and affect other environmental impacts, such as local air quality.

Despite the demonstrated savings in resource and emissions from material reuse in construction, while the recycling of construction materials has increased, material reuse in some EU countries has declined substantially in the last decade (Giesekam et al., 2014). Importantly, opportunities exist to improve material reuse through new ownership arrangements, such as leasing major structural components (e.g. roofs). Such arrangements could be applied to commercial and industrial facilities with short anticipated lifespans and standardised designs (Giesekam et al., 2014).

Nevertheless, focusing just on improving resource efficiency through material reuse or recycling (for instance) to reduce GHG emissions may not be necessarily beneficial in the long-term (Robèrt et al., 2013). Product-life extension is not always feasible and may not improve environmental sustainability. For instance, Camilleri (2018) highlights that many technical long-lasting products lead to more energy consumption and release more entropy than nature-based products that can be easily reintroduced back into the environment (closing resource loops effectively). In some cases, shorter-lived products accompanied by continuous innovation might have an environmental advantage over reusable longer-lived products (Allwood et al., 2013).

The findings of this paper are of particular interest to policy-makers designing policies in the areas of climate change and circular economy, and for stakeholders from the construction sector, including architects, product designers, builders, and construction and demolition waste companies. The geographical focus of this paper has been on the EU due to the importance of the construction sector and the legally binding climate change compromises in this region. However, the conclusions obtained and challenges identified are applicable worldwide.

Author contributions

Alejandro Gallego-Schmid: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project administration. **Han-Mei Chen**: Investigation, Writing- Original draft preparation, Reviewing and Editing. **Maria Sharmina**: Conceptualization, Formal analysis, Writing – Original Draft, Writing – Review & Editing, Visualization, Funding acquisition. **Joan Manuel F. Mendoza**: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writting - Review & Editing, Visualization.

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