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

Alejandro Gallego-Schmida, Han-Mei Chenb,c, Maria Sharminaa, Joan Manuel F. Mendozad,e

a Tyndall Centre for Climate Change Research, School of Engineering, The University of Manchester, Pariser Building, Sackville Street, M13 9PL Manchester, United Kingdom.

b Civil Engineering Division, School of Engineering, The University of Manchester, Pariser Building, Sackville Street, M13 9PL Manchester, United Kingdom.

c School of Architecture, University of Liverpool, Abercromby Square, Liverpool L69 7ZN, United Kingdom.

d Industrial Organisation and Management, Faculty of Engineering, University of Mondragon, 20500 Arrasate-Mondragon, Gipuzkoa, Spain.

e IKERBASQUE, Basque Foundation for Science, Bilbao, Spain.

Corresponding author: alejandro.gallegoschmid@manchester.ac.uk; jmfernandez@mondragon.edu.

**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 contributes 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 key to mitigating 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. The implementation of these solutions should be accompanied with further methodological development, such as proper allocation procedures, accurate definition of the system boundaries and integration of forecasts.

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

# 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 CO2 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 CO2 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 originate in 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 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. Although the deployment of a CE is considered to have a direct impact on the 2030 United Nations Sustainable Development Goal 12 (responsible production and consumption), CE strategies can also play a key role in achieving the Goal 11 to make cities and human settlements inclusive, safe, resilient and sustainable, as well as Goal 13 on climate change mitigation, among others (United Nations, 2015b). For this reason, the CE is considered instrumental to achieving sustainable development (Mendoza et al., 2017).

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 CO2 eq. emissions embodied in construction materials in the EU, more than half are not covered by 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 (Giesekam et al., 2018; Ibn-Mohammed et al., 2013; Ingrao et al., 2019). For example, the NHBC Foundation (2012) calculated that embodied emissions represent between 31% and 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 (Drummond and Ekins, 2017.; Scott et al., 2018; Szalay, 2007).

The embodied emissions mainly arise while extracting resources and processing construction materials (BIS, 2010; Giesekam et al., 2014; 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 its legally binding emission-reduction target by 2050. 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. Section 2 presents the methodology applied to perform the systematic literature review. This is followed by a frequency analysis of the reviewed literature (section 3.), grouping the findings by slowing, closing, and narrowing resource loops. Finally, a discussion of the results and main challenges is presented in section 4, and key conclusions are provided in section 5.

# 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 up to 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.

# 3. Results

## 3.1. Frequency analysis

The sample of studies reviewed includes 24 publications: 16 peer-reviewed journal papers and eight 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.

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 either a potential geographical gap in applying CE to the construction sector, or a lack of documenting such practices in this region. 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).. 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.

Finally, Figure 3 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 3. The number of publications by circular economy strategy.

## 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 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 CO2 eq./m2) and 21% (-50 kg CO2 eq./m2) of CO2 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 CO2 eq./m2). Combining DfD with material optimisation can, therefore, 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 other materials such as steel, wood and glass can lead to higher CO2 emissions saving potentials compared with DfD and material reuse. For instance, the implementation of recyclable load-bearing timber columns at the facade (instead of concrete) can reduce the accumulated embodied CO2 emissions by 59% (-140 kg CO2 eq./m2) over an 80-year building lifespan (Eberhardt et al., 2019a). Therefore, the carbon savings from material substitution can be up to 300% higher (+105 kg CO2 eq. m2 more savings) than the carbon savings from DfD for material reuse. Accordingly, material substitution can represent a more suitable solution for mitigating GHG emissions 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 CO2 eq./component), 92% (-32 kg CO2 eq./component) and 99% (-3.2 kg CO2 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. in 80 years). 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](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/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 performed for one component at a time using a given disassembly 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](https://www.sciencedirect.com/topics/engineering/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 CO2 eq. to 897 kg CO2 eq. (+77%). Sánchez and Haas (2018) demonstrate the relevance of applying selective disassembly to reduce the disassembly steps and time dramatically, thereby reducing environmental impacts and costs.

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 CO2 eq. (year 2050) |
| Brambilla et al. (2019) | Steel-concrete composite systems | Reuse | -27% (-80 kg CO2 eq./m2) to -35% (-120 kg CO2 eq./m2) |
| Brütting et al. (2019a) | Cantilever truss | Reuse  | -46% (-76 kg CO2 eq./infrastructure) |
| Brütting et al. (2019b) | Train station roof | Reuse | -56% (-2.3 t CO2 eq./infrastructure). |
| Buyle et al. (2019) | Wall assemblies | Reuse | -14% to -37% CO2 eq. savings per wall assembly unit |
| Campbell (2019) | Mass timber (buildings) | Durability | Mass timber in buildings represents -1.2 Mt CO2 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 CO2 eq./m2); reuse & optimisation: -26% (- 60 kg CO2 eq./m2); material substitution: -59% (-140 kg CO2 eq./m2); 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 CO2 eq./column); window: -92% (-32 kg CO2 eq./window); roof felt: -99% (-3.2 kg CO2 eq./roof felt) |
| Eberhardt et al. (2019c)c  | Concrete structure, façade & columns | Reuse, durability and material substitution | Reuse of the prefabricated concrete structure: -40% CO2 savings (two reuses) & -55% CO2 savings (three reuses); reuse glass facade with wooden columns: -80% CO2 savings (three reuses) & -73% CO2 savings (two reuses); reuse beams: - 33% CO2 savings (three reuses); reuse roof: -41% CO2 savings (three reuses); reuse core walls: -50% CO2 savings (three reuses); substitution of wood columns by steel (+101% CO2 emissions) & by concrete (+239% CO2 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 potentiald. |
| Hertwich et al. (2019) | Buildings | Reuse and intensive use | CO2 emissions of intensively-used buildings: -50% compared to baseline; reuse of energy-intensive components (e.g. steel): - 0.36 kg CO2/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 CO2 per brick; concrete: -97% C emissionse. |
| Nußholz et al. (2019) | Wood-plastic composite (WPC), concrete & bricks | Reuse | -56% to -64% (-0.95 to -1.42 kg CO2 eq./kg WPC; -12,400 to -18,400 t CO2 eq./year for the Scandinavian market.); -67% (-0.008 kg CO2 eq./kg secondary concrete; -7,300 t CO2 eq./year in Denmark); -99% (-0.025 kg CO2 eq./kg brick; -25,300 t CO2 eq./year in Denmark). |
| Ros-Dosda et al. (2019)  | Floor coverings | Durability  | Between +8.1 and +38.9 CO2 eq./m2 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 CO2 eq. to 897 kg CO2 eq.). |
| Scott et al. (2019) | Construction sector in the UK | Reuse | -0.49 to -3.69 Mt CO2 eq. (years 2023-2027) & -0.70 to -5.23 Mt CO2 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)

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 objective is to significantly reduce the resource intensity, 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 compared to adopting new weight-optimised solutions made from primary steel. The reuse of steel elements in the cantilever truss can reduce the embodied carbon by up to 46% (-76 kg CO2 eq./infrastructure), whereas the carbon savings from the reuse of materials in the train station roof are 56% (-2.3 t CO2 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 Brütting et al. (2019a,b), reuse is a more environmentally sustainable option and implies higher emission savings than recycling construction products when they reach their 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.

Brambrilla et al. (2019) focus on steel-concrete composite floor systems. These systems 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. Brambrilla et al. (2019) compare the life-cycle environmental impacts of a demountable composite floor system (ReuseStru) using pretensioned high-strength friction grip bolts as shear connectors to facilitate disassembly and reuse, with the life-cycle environmental impacts of 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 are the UK and 100 years, respectively. The findings demonstrate that the ReuseStru system can reduce carbon emissions from 27% (-80 kg CO2 eq./m2) to over 35% (-120 kg CO2 eq./m2) compared to the conventional steel-concrete composite structures. In a building with a floor surface of 2232 m2 covered by the composite floor system, the carbon savings arising from the implementation of the ReuseStru range from 180 to 270 t CO2 eq. The ReuseStru only have higher GHG emissions than the conventional composite systems if the distance for transporting reused material by heavy trucks exceeds 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. In the absence of the end-of-life reuse or recycling, construction products with low emissions at the manufacturing stage 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% lower GHG emissions when the reuse scenario is applied compared to the four conventional models with the current-practice waste treatment. However, the emission savings are only 14% when both assembly groups use current end-of-life waste management practices. In fact, one of the conventional assemblies becomes the best alternative within the present end-of-life scenario due to lower GHG emissions during its 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 their findings confirm that research on CE innovations is limited and focuses on the reuse of the building stocks (from a technical, economic and environmental standpoint), Hopkinson et al. (2019) 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). Hopkinson et al. (2019) also mention a study demonstrating the technical feasibility of a 3250 m2 steel frame warehouse relocation and reassembly in the UK leading to 38% carbon reductions compared to a benchmark building (Segro, 2013). The Rebrick project (Nielsen, 2013) is also mentioned, where it was estimated that each reused brick could save 0.5 kg of CO2 emissions compared to building with new bricks in Denmark, Germany and Italy. Finally, concrete reuse can lower carbon emissions by 97% compared to 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 review is provided by Hertwich et al. (2019), who evaluate the product-level carbon emission savings from material efficiency solutions applied to buildings. The reuse of energy-intensive building materials, such as steel, could result in 0.36 kg CO2 saved per kg of material (?) compared to recycling given the energy requirements of remelting in an electric arc furnace, which has lower, but still not negligible, emissions than replacing virgin steel (1.78 kg CO2/kg) (Hertwich et al. 2019; Dunant et al., 2017).

#### *3.2.1.2. Reuse at the sector level*

The potential environmental savings of material reuse have also been analysed from a sector-wide perspective, including business model and policy considerations. For example, Nußholz et al. (2019) investigate the contribution of secondary material to decarbonising 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 CO2 eq.) of carbon emissions per kg of WPC produced, ii) 67% (0.008 kg CO2 eq.) of carbon emissions per kg of aggregate prepared for concrete production, and iii) 99% (0.025 kg CO2 eq.) of 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 among the three cases, with estimated annual savings of 25,300 t CO2 eq. in Denmark. Annual carbon savings for concrete production are around 7,300 t CO2 eq. The annual carbon saving potential of WPC production is estimated to be 12,400 to 18,400 t CO2 eq. for the Scandinavian market. The results demonstrate that all three case studies can offer substantial carbon savings, although such savings vary significantly depending on the production processes, market dynamics, and readiness to supply (and accept) secondary products.

Following this sector-wide perspective, other studies analyse how reusing construction materials could reduce embodied GHG emissions at a country or region level. For instance, Scott et al. (2019) calculate 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 consider three scenarios based on the level of implementation of each CE solution: high (100% implementation), medium (66%) and low (33%). For the reuse solutions, potential reductions in the consumption of virgin materials for each scenario correspond to 10-35% for steel, 3-18% for timber, 2-30% for brick, and 1-5% for other construction materials. These levels of reuse would lead to GHG savings of 0.49-3.69 Mt CO2 eq. and 0.70-5.23 Mt CO2 eq. during 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 impacts of implementing CE solutions on embodied primary energy consumption and exergy for 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 with three levels of implementation: maximum (100% implementation), advanced (60%) and intermediate (30%). 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. Of these 22 solutions, only nine are associated with reuse. Cooper et al. (2017) present the global results without disaggregating them; therefore, it is not possible for us to report the individual impacts of the nine reuse solutions.

Finally, Ghisellini et al. (2018) review the recent literature on selected CE solutions (reduce, reuse, and recycle) for construction and demolition waste to determine if the adoption of the CE framework is environmentally sustainable. According to their review, material reuse and recycling after a selective deconstruction can generate a 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 substantial reduction in environmental impacts when shifting from zero recycling to 95% recycling of waste materials for reuse in new constructions in Portugal. Such a shift can decrease material-related GWP by 77%. However, it requires high quantities of well-maintained salvaged materials from deconstruction activities that must be carried out by experienced deconstruction workers. Accordingly, Ghisellini et al. (2018) conclude 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 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, recycling, and incineration over landfilling cannot be predefined.

#### *3.2.1.3. Durability*

Campbell (2019) analyses the application of different CE approaches to mass timber[[1]](#footnote-1): i) modify less (avoid the need to adapt timber, increase production efficiency and reduce the use of non-renewable resources like glues); ii) hold (increase adaptability and durability); iii) loop (increase inner cycles, particularly reuse); and iv) sell a product as a service (among other new business models). From the climate change perspective, the authors assessed the dual benefit of timber mass for both reducing the embodied GHG emissions of buildings and locking up CO2 until their end-of-life. Regarding the embodied emissions, Campbell (2019) highlights 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 sector’s emissions. Particularly, durability remains one of the crucial issues identified by both developers and insurers as requiring further research. Facade and roof waterproofing detailing, the analysis of possible risks from internal water damage (such as bathrooms) and methods to repair damaged timber systems are aspects to be considered. The measurement of the embodied emissions should be consistent and comprise the processes to improve timber durability (preservative, flame spread, surface protection coatings or acetylation) and 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 CO2 sequestration in mass timber used in buildings, Campbell (2019) argues that it only represents around 0.03% (1.2 Mt CO2 eq./yr) of the EU and Iceland’s annual emissions (4317 Mt CO2 eq./yr) and that this ratio is not expected to increase in the near future.

Eberhardt et al. (2019c) link durability to the reuse of building components, with more durable components able to withstand a larger number of reuses. They also argue 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. Eberhardt et al. (2019c) estimate that emissions savings from reusing (thrice) smaller components such as beams (33% in CO2 savings), roof (41% in CO2 savings), and core walls (50% in CO2 savings) were usually lower than those from reusing the building's prefabricated concrete structure (55% in CO2 savings). The reuse of a prefabricated concrete structure leads to only 40% in CO2 savings if reused twice. A glass facade with wooden columns reused three times resulted in 80% in CO2 savings, as opposed to 73% in CO2 savings if reused twice. The substitution of wood by steel or concrete for the columns would increase CO2 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) analyse 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, they conclude 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 CO2 eq./m2.

#### *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 demand (Hertwich et al., 2019). Nevertheless, time- and space-related decisions involved in the refurbishment of a building have a significant impact on the building’s life-cycle 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. Castro and Pasanen (2019) 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) conclude 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 by up to 166 kt CO2 eq. in 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 contrast 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). It is important to be cautious when directly comparing emissions of closing-loop solutions (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. As an example shown in Table 2, Jimenez-Rivero and Garcia-Navarro (2016) propose several monitoring indicators (e.g. traceability of the waste, cost, and GHG emissions) to measure the management performance of end-of-life for gypsum if upcycled (i.e. 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 transportation due to long distances to recycling facilities. For example, in one of the pilot plants, a farther distance to the recycling facility lead to 1037 kg CO2 eq./t gypsum waste associated only with the transport, which is significant compared to the 2033 kg CO2 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 CO2 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 are yet to be comprehensibly analysed (Nusselder et al., 2015). Regarding the recycling of other construction materials, Antunes et al. (2019) conduct a systematic review of incorporating Reclaimed Asphalt Pavement (RAP) in new bituminous mixtures, considering design requirements, limitations and performance at the European level. For example, Zaumanis et al. (2014) report significant environmental benefits of RAP recycling in France, with carbon emission savings of 35% (-18 kg CO2 eq./t RAP bituminous mixtures) and 20% in energy savings per tonne when comparing virgin Hot Mix Asphalt (HMA) with HMA containing 100% RAP. The critical challenge is maintaining the quality of the product, as the specification criteria should apply equally to both RAP and virgin aggregates. Likewise, the durability performance of 100% RAP requires further investigation.

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 CO2 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 CO2 eq. per t) |
| Nasir et al. (2017) | Insulation | Upcycling | -39% (from 1.51 kg CO2 eq./kg virgin stone wool to 0.92 kg CO2 eq./kg recycled textile). |
| Rasmussen et al. (2019) | Building | Upcycling and design for disassembly (DfD) | Innovative upcycling of a building: -0.7 kg CO2 eq./m2/year compared to DfD building and -1.1 kg CO2 eq./m2/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)

Rasmussen et al. (2019) propose 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. They compare the environmental impacts of this CE solution with the construction of the same building following DfD principles and with common material recycling, such as aluminium or oriented strand boards. It is found that the innovative upcycling solution results in reductions of 0.7 kg CO2 eq./m2/year compared to the DfD, and reductions of 1.1 kg CO2 eq./m2/year compared to common material recycling.

In the same line of open-loop upcycling, Migliore et al. (2018) assess the carbon footprint of producing one brick incorporating waste from localised marble quarries in the Apuan district in 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 are reduced by up to 50% compared to a brick produced from virgin materials (2.6 and 5.2 kg CO₂ eq./t, respectively). This case study shows that it is possible to promote GHG savings systematically by reusing waste from different processes in the construction sector.

Regarding construction insulation products, Nasir et al. (2017) compare the carbon emissions of using recycled textile materials as insulators with traditional insulation materials, such as stone wool. They conclude that the GHG emissions associated with using virgin stone wool are 64% higher than when using recycled textile (1.51 kg CO2 eq./kg versus 0.92 kg CO2 eq./kg). Their supply chain carbon mapping shows that the use of chemicals in the treatment of both types of insulation products contributes significantly to the total life-cycle GHG emissions. The results also show that transportation takes up a larger proportion of the emissions in the circular supply chain than in a linear supply chain. The authors conclude that future research should consider adopting a more closed-loop end-of-life for traditional 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 that focus on material optimisation and material substitution in combination with other CE solutions. We consider the articles analysing material substitution as part of the 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 CO2 eq./m2 compared to synthetic carpets, 28.8 kg CO2 eq./m2 compared to parquet, and 9.7 kg CO2 eq./m2 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 CO2 eq./m3 timber, although the entire range spans from 310 kg CO2 eq./m3 in extra emissions to 1060 kg CO2 eq./m3 in avoided emissions (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, leading to environmental burden shifting. Considering the limited global availability of timber, it is important to limit its use to the structures with the largest carbon benefits (Hertwich et al., 2019).

Cutting 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/m2 per year per building. Combining these passive-house measures 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 lead to reductions of 118 kWh/m2 per year. With an added heat pump, the annual energy savings can be brought up to 127 kWh/m2.

Focusing on the country-level, Scott et al. (2019) model GHG embodied emissions savings in the UK through the reduction of material inputs resulting from design optimisation. These design measures (e.g. optimised roll-out reinforcement steel meshes or optimal building information modelling) can generate up to 9.23 Mt CO2 eq. and 13.07 Mt CO2 eq. savings for the periods 2023-2027 and 2028-2032, respectively. Likewise, material substitution (e.g. increasing the use of hybrid timber-steel, cross-laminated timber/glulam or of other biotic materials such as straw bale) would reduce GHG emissions by up to 19.82 Mt CO2 eq. and 28.08 Mt CO2 eq. within the same periods.

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/m2 yr; passive house & more efficient but conventional building system: -118 kWh/m2 yr; passive house & more efficiency & heat pump: -127 kWh/m2 per year |
| Barret and Scott (2012) | Construction sector | Substitution & modular building | Substitution of cement: Between -298 and -1240 kt CO2 eq. (year 2050); Modular building: Between -27 and -165 kt CO2 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 CO2 eq./m3  |
| 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 CO2 eq./m2; parquet: -28.8 kg CO2 eq./m2; PVC -26.4 kg CO2 eq./m2; laminate: -19.9 kg CO2 eq./m2; natural stone: -9.7 kg CO2 eq./m2. |
| Scott et al. (2019) | Construction sector | Design optimisation to reduce material inputs and substitution | Optimization design: between -0.52 & -9.23 Mt CO2 eq. (years 2023-2027) and - 0.73 & -13.07 Mt CO2 eq. (years 2028-2032); substitution: between -1.79 & -19.82 Mt CO2 eq. (years 2023-2027) and -2.53 & -28.08 Mt CO2 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

Cooper et al. (2017) analyse 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, 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), analyse 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. Barret and Scott (2012) compare 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 solutions 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 and 20%-40% by 2050). The application of modular building and off-site construction can reduce the GHG emissions by 27-165 kt CO2 eq. The CE solution with the highest emission reductions is the substitution of cement by low carbon materials, resulting in emission savings of 298-1240 kt CO2 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

**4.1. Key findings and their implications**

The findings of this literature review suggest that the implementation of CE strategies (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 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 it 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 among the CE principles, where upcycling and reuse should be prioritised.

The six studies that focus on closing loop solutions were selected based on the CE principles and, therefore, excluded 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 logistics of delivering the recycled materials can affect the level of emission reductions and that the virgin materials could become lower-carbon 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 CO2 eq. for years 2023-2027 in the UK) or material substitution (e.g. reductions of up to 19.82 Mt CO2 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 their benefits and expenses, and limited 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 such as mass timber remain understudied (Campbell, 2019; CIB, 2014).

The reviewed studies demonstrate that, in most cases, emission reductions can be achieved at the product level. 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 urbanisation 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 CE practices, such as reuse, refurbishment and materials upcycling can lead to significant GHG and environmental savings. Demand for construction materials and associated 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 solutions that reduce emissions (Barrett and Scott, 2012; Buyle et al., 2019).

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, CE solutions targeting new buildings are more critical in developing countries, whereas actions 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. 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. In pratice, 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 a 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 essential 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 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 removing remaining barriers (Tingley et al., 2017).

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. It is not apparent which future circumstances (e.g. context-related recycling scenarios) should be considered in assessments, 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 solutions. Therefore, a cradle-to-grave life cycle perspective considering the embodied emissions of the materials is crucial for analysing the effects of CE solutions 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)

**4.2. Challenges and future research**

Based on the reviewed literature, the following aspects should be addressed to overcome the barriers to the implementation of CE solutions 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.
* 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](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/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](https://www.sciencedirect.com/topics/engineering/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.

# 5. Conclusions

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 greenhouse gas (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, and the barriers to creating value from these solutions.

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](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/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 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 (thereby 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, Writing - Review & Editing, Visualization.

# Acknowledgements

This work has been funded by the Sustainable Consumption Institute (grant reference: 118206) at the University of Manchester.

# References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2013. Material efficiency: providing material services with less material production. [Philosophical Transitions of the Royal Society A](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3575569/) 371: 20120496.

Allwood, J.M., Cullen, J.M., Carruth, M.A., Cooper, D.R., McBrien, M., Milford, R.L., Moynihan, M., Patel, A.C.H., 2012. Sustainable Materials With Both Eyes Open. UITCambridge, Cambridge, 375 pp.

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environmental Science and Technology, 44 (6), pp. 1888-1894.

Andrade, J., Araújo, C., Castro, M.F., Bragança, L., 2019. New Methods for Sustainable Circular Buildings. IOP Conf. Series: Earth and Environmental Science 225.

Antunes, V., Freire, A.C., Neves, J., 2019. A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling. Construction and Building Materials, 211, pp. 453-469.

Barret, J., Scott, K., 2012. Link between climate change mitigation and resource efficiency: A UK case study. Global Environmental Change, 22, pp. 299–307.

BIS, 2010. Estimating the amount of CO2 emissions that the construction industry can influence – supporting material for the Low Carbon Construction. Department for Business, Innovation and Skills, London, United Kingdom.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33 (5), pp. 308-320.

Brambilla, G., Lavagna, M., Vasdravellis, G., Castiglioni, C.A., 2019. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resources, Conservation & Recycling, 141, pp. 133–142.

Brütting, J., Desruelle, J., Senatore, G., Fivet, C., 2019a. Design of Truss Structures Through Reuse. Structures, 18, 128–137.

Brütting, J., De Wolf, C., Fivet, C., 2019b. The reuse of load-bearing components. IOP Conf. Series: Earth and Environmental Science 225.

Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. Journal of Cleaner Production, 218, pp. 141-156.

Camilleri, M.A., 2018. Closing the Loop for Resource Efficiency, Sustainable Consumption and Production: A Critical Review of the Circular Economy. International Journal of Sustainable Development.

Campbell, A., 2019. Mass timber in the circular economy: Paradigm in practice? Proceedings of the Institution of Civil Engineers: Engineering Sustainability, 172 (3), pp. 141-152.

Castro, R., Pasanen, P., 2019. How to design buildings with Life Cycle Assessment by accounting for the material flows in refurbishment. IOP Conf. Series: Earth and Environmental Science 225.

Cheshire, D., 2016. Building Revolutions: Applying the Circular Economy to the Built Environment. Riba Publishing, London, UK.

CIB, 2014. Barriers for Deconstruction and Reuse/Recycling of Construction Materials. International Council for Research and Innovation in Building and Construction, Delft, the Netherlands.

Circle Economy, 2019. The Circularity Gap Report – Closing the Circularity Gap in a 9% world. Circle Economy, Amsterdam, The Netherlands.

Coelho, A., De Brito, J., 2012. Influence on construction and demolition waste management on the environmental impact of buildings. Waste Management, 32, pp. 532-541.

Cooper, S.J.G., Giesekam, J., Hammond, G.P., Norman, J.B., Owen, A., Rogers, J.G., Scott, K., 2017. Thermodynamic insights and assessment of the ‘circular economy'. Journal of Cleaner Production, 162, pp. 1356-1367.

Cuellar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: life cycle assessment of houses. Building and Environment, 54, pp. 86-99.

Defra and NS, 2019. Monthly Statistics of Building Materials and Components. March 2019. Department for Environment, Food and Rural Affairs and National Statistics, London, United Kingdom.

Diliberto, C., Lecomte, A., Mechling, J.M., Izoret, L., Smith, A., 2017. Valorisation of recycled concrete sands in cement raw meal for cement production. Materials and Structures, 50 (127), pp. 1-12.

Drummond, P., Ekins, P., 2017. Cost-effective decarbonization in the EU: an overview of policy suitability. Climate Policy, 17, pp. 51–71.

Dunant C.F., Drewniok M.P., Sansom, M., Corbey, S., Allwood, J.M., Cullen J.M., 2017. Real and perceived barriers to steel reuse across the UK construction value chain Resource Conservation and Recycling, 126, pp. 118–31.

Eberhardt, L.C., Birgisdóttir, H., Birkved, M., 2019a. Life cycle assessment of a Danish office building designed for disassembly. Building Research & Information, 47 (6), 666-680.

Eberhardt, L.C, Birgisdottir, H., Birkved, M., 2019b. Comparing life cycle assessment modelling of linear vs. circular building components. IOP Conference Series: Earth and Environmental Science 225.

Eberhardt, L.C, Birgisdóttir, H., Birkved, M., 2019c. Potential of Circular Economy in Sustainable Buildings. IOP Conference Series: Materials Science and Engineering 47.

EMF, 2015. Growth within – A Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation, Isle of Wight, UK.

Esa, M.R., Halog, A., Rigamonti, L., 2017. Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy. [Journal of Material Cycles and Waste Management](https://link-springer-com.manchester.idm.oclc.org/journal/10163), 19, 1144-1154.

European Commission, 2018. A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission, Brussels, Belgium.

European Commission, 2019a. Energy performance of buildings. Available at: <https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings> (Last access: 14/12/2019).

European Commission, 2019b. Developments and Forecasts on Continuing Urbanisation. Available at: [https://ec.europa.eu/knowledge4policy/foresight/topic/ continuing-urbanisation/developments-and-forecasts-on-continuing-urbanisation\_en](https://ec.europa.eu/knowledge4policy/foresight/topic/continuing-urbanisation/developments-and-forecasts-on-continuing-urbanisation_en) (Accessed: 14/12/2019)

European Parliament and Council, 2003. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. OJ L 275, 25.10.2003, pp. 32-46.

European Parliament and Council, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. OJ L 153, 18.6.2010, p. 13–35.

European Parliament and Council, 2012. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. OJ L 315, 14.11.2012, p. 1–56.

Ferreira, J., Duarte Pinheiro, M., De Brito, J., 2015. Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction - a Portuguese benchmarking. Building Engineering, 3, 114-126.

Gastaldi, D., Canonico, F., Capelli, L., Buzzi, L., Boccaleri, E., Irico, S., 2015. An investigation on the recycling of hydrated cement from concrete demolition waste. Cement and Concrete Composites, 61, pp. 29–35.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, pp. 757-768.

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. Journal of Cleaner Production, 178, pp. 618-643.

Giesekam, J., Barrett, J., Taylor, P., Owen, A., 2014. The greenhouse gas emissions and mitigation options for materials used in UK construction. Energy and Buildings, 78, pp. 202-214.

Giesekam, J., Tingley, D.D., Cotton, I., 2018. Aligning carbon targets for construction with (inter)national climate change mitigation commitments. Energy and Buildings, 165, pp. 106-117.

Glias, A., 2013. The ‘Donor Skelet’: Designing with Re-used Structural Concrete Elements. MSc thesis, Delft University of Technology, Delft, the Netherlands.

Guo, Z., Shi, H., Zhang, P., Chi, Y., Feng, A., 2017. Material metabolism and lifecycle impact assessment towards sustainable resource management: A case study of the highway infrastructural system in Shandong Peninsula, China. Journal of Cleaner Production, 153, pp. 195-208.

Haneef, M., Nasir, A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F., 2017. Comparing linear and circular supply chains: A case study from the construction industry. International Journal of Production Economics, 183, pp. 443-457.

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q., Wolfram, P., 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environmental Research Letters, 14, 043004.

Heyes, G., Sharmina, M., Mendoza, J.M.F., Gallego-Schmid, A., Azapagic, A., 2018. Developing and implementing circular economy business models in service-oriented technology companies. Journal of Cleaner Production, 177, pp. 621-632.

HM Government, 2010. Low carbon construction innovation & growth team: Final Report, London, United Kingdom.

Hoornweg, D., Bhada-Tata, P., Kennedy, C., 2013. Waste production must peak this century. Nature 502, 615–617.

Hopkinson, P., Chen, H.M., Zhou, K., Wang, Y., Lam, D., 2019. Recovery and reuse of structural products from end-of-life buildings. Proceedings of the Institution of Civil Engineers – Engineering Sustainability, 172 (3), 119–128.

Ibn-Mohammed, Y., R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, 2013. Operational vs. embodied emissions in buildings-A review of current trends. Energy and Buildings, 66, pp. 232–245.

Ingrao, C., Arcidiacono, C., Bezama, A., Ioppolo, G., Winans, K., Koutinas, A., Gallego-Schmid, A., 2019. Sustainability issues of by-product and waste management systems, to produce building material commodities: A comprehensive review of findings from a virtual special issue. Resources, Conservation and Recycling, 146, pp. 358-365.

Ingrao, C., Arcidiacono, C., Bezama, A., Ioppolo, G., Winans, K., Koutinas, A., Gallego-Schmid, A., 2018. Virtual Special Issue on sustainability issues of by-product and waste management systems to produce building material commodities Resources, Conservation and Recycling 126, pp. A4-A5.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. International Panel on Climate Change, Geneva, Switzerland.

Jiménez-Rivero, A., García-Navarro, J., 2016. Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. Waste and Biomass Valorization, 7 (4), pp. 913-927.

Jimenez-Rivero, A., García-Navarro, J., 2017. Best practices for the management of end-of-life gypsum in a circular economy. Journal of Cleaner Production, 167, pp. 1335-1344.

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy – From review of theories and practices to development of implementation tools. Resources, Conservation & Recycling, 135, pp. 190-201.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling, 127, pp. 221–232.

Li, J., Tharakan, P., Macdonald, D., Liang, X., 2013. Technological, economic and financial prospects of carbon dioxide capture in the cement industry. Energy Policy, 61, pp. 1377–1387.

Mendoza, J.M.F., Gallego-Schmid, A., Azapagic, A., 2019. Building a business case for implementation of a circular economy in higher education institutions. Journal of Cleaner Production, 220, pp. 553-567.

Mendoza, J.M.F., Sharmina, M., Gallego-Schmid, A., Heyes, G., Azapagic, A., 2017. Integrating backcasting and eco-design for the circular economy: the BECE framework Journal of Industrial Ecology, 21(3), pp. 526-544.

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. Journal of Cleaner Production, 178, pp. 703-722.

Migliore, M., Carpinella, M., Paganin, G., Paolieri, F., Talamo, C., 2018. Innovative use of scrap and waste deriving from the stone and the construction sector for the manufacturing of bricks. Review of the international scenario and analysis of an Italian case study. Environmental Engineering and Management Journal, 17 (10), pp. 2507-2514.

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., Brattebø, H., 2013. Carbon emissions of infrastructure development. Environmental Science & Technology, 47, pp. 11739–11746.

Nasir, M.H.A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F., 2017. Comparing linear and circular supply chains: A case study from the construction industry. International Journal of Production Economics, 183, pp. 443-457.

Ng, S.T., Wong, J.M.W., Skitmore, M., 2013. Challenges facing carbon dioxide labelling of construction materials. Proceedings of the Institution of Civil Engineers: Engineering Sustainability, 166 (ES1), pp. 20-31.

NHBC Foundation, 2012. NF34 Operational and Embodied Carbon in New Build Housing: A Reappraisal. NHBC Foundation, Milton Keynes, United Kingdom.

Nielsen, 2013. Market uptake of an automated technology for reusing old bricks (REBRICK).Available at: [https://ec.europa.eu/environment/eco-innovation/projects/en/ projects/rebrick](https://ec.europa.eu/environment/eco-innovation/projects/en/projects/rebrick) (Accessed: 14/12/2019)

Nusselder, S., Maqbool, A.S., Deen, R., Blake, G., Bouwens, J., Taufiq Fauzi, R., 2015. Closed Loop Economy: Case of Concrete in the Netherlands. Universiteit Leiden, Delft, The Netherlands.

Nußholz, J.L.K., Rasmussen, F.N., Milios, L., 2019. Circular building materials: Carbon saving potential and the role of business model innovation and public policy. Resources, Conservation & Recycling, 141, pp. 308–316.

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G., 2017. Industrial ecology in integrated assessment models. Nature Climate Change, 7, 13–20.

Petersen, A.K., Solberg, B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics, 7, pp. 249–59.

Pongiglione, M., Calderini, C., 2014. Material savings through structural steel re-use: a case study in Genoa. Resources, Conservation and Recycling, 86, pp. 87–92.

Rasmussen, F.N., Birkved, M., Birgisdóttir, H., 2019. Upcycling and Design for Disassembly - LCA of buildings employing circular design strategies. IOP Conference Series: Earth and Environmental Science, 225.

Robèrt, K.H., Broman, G.I., Basile, G., 2013. Analyzing the concept of planetary boundaries from a strategic sustainability perspective: how does humanity avoid tipping the planet?. Ecology and Society, 18 (2), 5.

Ros-Dosda, T., Celades, I., Vilalta, L., Fullana-i-Palmer, P., Monfort, E., 2019. Environmental comparison of indoor floor coverings. Science of the Total Environment, 693, 133519.

Sánchez, B., Haas, C., 2018. A novel selective disassembly sequence planning method for adaptive reuse of buildings. Journal of Cleaner Production, 183, pp. 998-1010.

Scott, K., Barrett, J., Baiocchi, G., Minx, J., 2009. Meeting the UK climate change challenge: The contribution of resource efficiency. WRAP, Banbury, United Kingdom.

Scott, K., Giesekam, J., Barrett, J., Owen, A., 2019. Bridging the climate mitigation gap with economy-wide material productivity. Journal of Industrial Ecology, 23, pp. 918–931.

Scott, K., Roelich, K., Owen, A., Barrett, J., 2018. Extending European energy efficiency standards to include material use: an analysis. Climate Policy, 18 (5), pp. 627-641.

Segro, 2013. Delivering: Corporate Responsibility and Sustainability Report 2013. Segro. Slough, UK.

Sung, K., 2015. A review on upcycling: current body of literature, knowledge gaps and a way forward. Proceedings of the 17th International Conference on Environment, Cultural, Economic and Social Sustainability, Venice, 13-14 April, pp. 28-40

Szalay, A.Z.Z., 2007. What is missing from the concept of the new European building directive? Building and Environment, 42, pp. 1761–1769.

Tingley, D.D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production 148, pp. 642-652.

UKGBC, 2017. Embodied Carbon: Developing a Client Brief. UK Green Building Council, London, United Kingdom.

UNEP, 2013. City-Level Decoupling - Urban resource flows and the governance of infrastructure transitions. Summary for Policy Maker. A Report of the Working Group on Cities of the International Resource Panel. United Nations Environmental Programme (UNEP), Nairobi, Kenya.

UNEP, 2019. Global Resources Outlook 2019: Natural Resources for the Future We Want. United Nations Environment Programme, Nairobi, Kenya.

United Nations, 2015a. Paris Agreement.United Nations Framework Convention on Climate Change, Paris France

United Nations, 2015b. Transforming the World: the 2030 Agenda for Sustainable Development. A/RES/70/1. United Nations, New York, USA.

URBACT, 2013. Cities of Tomorrow – Action Today. URBACT II Capitalisation. Building energy efficiency in European cities. URBACT, Paris, France.

Zaumanis, M., Mallick, R. B., Frank, R., 2014. "100% recycled hot mix asphalt: A review and analysis." Resources, Conservation and Recycling, 92, pp. 230-245.

Zink, T., Geyer, R., 2017. Circular economy rebound. Journal of Industrial Ecology, 21, pp. 593-602.

1. Mass timber are large timber products like panels or beams made by connecting together smaller timber elements [↑](#footnote-ref-1)