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From circular strategies to actions: 65 European circular building cases and their decarbonisation potential

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ABSTRACT

The application of the circular economy (CE) in the building industry is critical for achieving the carbon reduction goals defined in the Paris Agreement and is increasingly promoted through European policies. In recent years, CE strategies have been applied and tested in numerous building projects in practice. However, insights into their application and decarbonisation potential are limited. This study analysed and visualised 65 novel real-world cases of new build, renovation, and demolition projects in Europe compiled from academic and grey literature. Cases were analysed regarding the circular solution applied, level of application in buildings, and decarbonisation potential reported, making this study one of the first comprehensive studies on the application and decarbonisation potential of circular strategies in the building industry in practice. The identified challenges of using LCA for CE assessment in buildings are discussed and methodological approaches for future research are suggested.

1. Introduction

1.1. The role of buildings in climate change mitigation

The building sector is responsible for 39% of global carbon emissions (WBCSD, 2021) and large shares of global material use, including 50% of concrete and brick (Herczeg et al., 2014) and 40% of steel (Müller et al., 2011; Zhong et al., 2021). With an expected 60% growth of the urban built environment by 2050 (UNEP, 2013) and significant demand for housing upgrades in urban areas (European Commission, 2019a), decarbonisation (i.e., reduction, elimination and/or removal of greenhouse gas emissions from processes) of the building stock is critical to meet climate change mitigation goals set in the Paris Agreement (United Nations, 2015).

Carbon emissions arise throughout the whole lifecycle of buildings and can be divided into operational carbon (for the use of buildings) and embodied carbon (from the materials extraction and production, transportation, construction, maintenance, replacement, refurbishments, repair, and end-of-life treatment of buildings) (De Wolf et al., 2017; Ibn-Mohammed et al., 2013; Rasmussen et al., 2018). Because of past efforts by policy and industry to increase the energy efficiency of buildings, e.g., through net-zero energy building design, energy renovation, electrification, and system upgrades (Belussi et al., 2019; Röck et al., 2020), about half of the climate impact of a building's life cycle stems from embodied carbon (Röck et al., 2020). Reducing embodied carbon is increasingly being recognized as a crucial focus area to enable effective climate change mitigation in the building industry (Röck et al., 2022, 2020). In this paper, we study the carbon reduction potential, - or, synonymously, decarbonisation potential - of the building industry.

1.2. Reducing embodied carbon through the application of circular economy

Embodied carbon can be reduced through the application of circular economy (CE) strategies (Malmqvist et al., 2018; Moncaster et al., 2019;

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Pomponi and Moncaster, 2016). The CE paradigm proposes a set of strategies to maintain resources at their highest possible quality for as long as possible while using renewable energy and environmentally low-impact, toxic-free materials (Stahel, 2010). CE strategies have been summarised under four categories of principles: *narrowing resource loops* (i.e., using fewer resources per product), *slowing resource loops* (i.e., keeping products in use as long as possible), *closing resource loops* (i.e., recycling materials) and *regenerating resource loops* (i.e., using renewable resources and regenerating the natural environment) (Bocken et al., 2016; Konietzko et al., 2020; McDonough and Braungart, 2010; Stahel, 2010). In recent years, many studies have explored how CE strategies can be applied to buildings, henceforth referred to as 'circular building strategies' (Çetin et al., 2021; Eberhardt et al., 2020; Guerra et al., 2021; Malmqvist et al., 2018; Pomponi and Moncaster, 2016). These studies have identified various strategies relevant to different life cycle stages of buildings. Fig. 1 illustrates how these strategies can be adopted in different project types: (1) new build, (2) renovation, and (3) demolition. It should be noted that buildings will never be fully 'circular' but will be circular to a varying degree.

With precious little time left to prevent irreversible changes to the climate (IPCC, 2022), low-carbon and circular building strategies need to quickly become common practice in the building industry. This notion is also promoted in several European Union (EU) policies relevant to the industry, such as the Renovation Wave Strategy (European Commission, 2020a), the European Green Deal (European Commission, 2019b) and the Circular Economy Action Plan (European Commission, 2020b). Also, the International Panel on Climate Change (IPCC) (IPCC Special Report: Global Warming of 1.5 °C - Chapter 5, 2018) regards the CE as a key pathway to mitigating climate change in the built environment.

1.3. *Lack of an overview of real-world applications and their decarbonisation potential*

In recent years, circular building strategies have been applied and tested in numerous building projects in practice (e.g., Upcycle Studio, Circle House, etc.). Applying circular building strategies in practice faces many barriers (Bilal et al., 2020; Çetin et al., 2021; Guerra et al., 2021; Hart et al., 2019) and requires significant innovation efforts to meet the functional, aesthetic, financial, process, and legal requirements in building development, construction, and management (Hart et al., 2019). One barrier to initiating such innovation efforts has been a lack of knowledge regarding the environmental performance and related benefits of the various strategies (Andersen et al., 2020; De Wolf et al., 2020; Eberhardt et al., 2020). Environmental benefits can differ greatly with the specific strategies applied (Gallego-Schmid et al., 2020; Nußholz et al., 2020; Rasmussen et al., 2020; van Stijn et al., 2021). They can also be outweighed by the environmental impacts of processes to enable circularity (e.g., transport of heavy materials (Eberhardt et al., 2020; Martínez et al., 2013; Vitale et al., 2017)) or by the impacts of additional materials (e.g., glue and chemicals in timber products that prevent recycling and composting (Sotayo et al., 2020)).

To date, insight into the application and decarbonisation potential of circular building strategies in real-world projects is limited. In a recent review, Gallego-Schmid et al. (2020) analysed 30 assessments of circular initiatives related to the building industry and identified a range of decarbonisation potentials for *narrowing, slowing* and *closing resource loops*. Our study adds to the insights provided by Gallego-Schmid et al. (2020) through several differences in research design (Table 1). By reviewing real-world building cases only, rather than scenarios or

Table 1
Contribution and difference of the present study compared with the review of decarbonisation potential by Gallego-Schmid et al. (2020).

Key differences	Study by Gallego-Schmid et al. (2020)	This study
Cases	Real-world, models, scenarios	Real-world
Method	Literature review	Literature and practice review
Assessment level	Product level, building level, value chain level, urban level	Building and product level
Circular principles	Narrow, slow, close	Narrow, slow, close, regenerate
Geographic focus	World-wide	Europe-wide
Number of cases	30	65

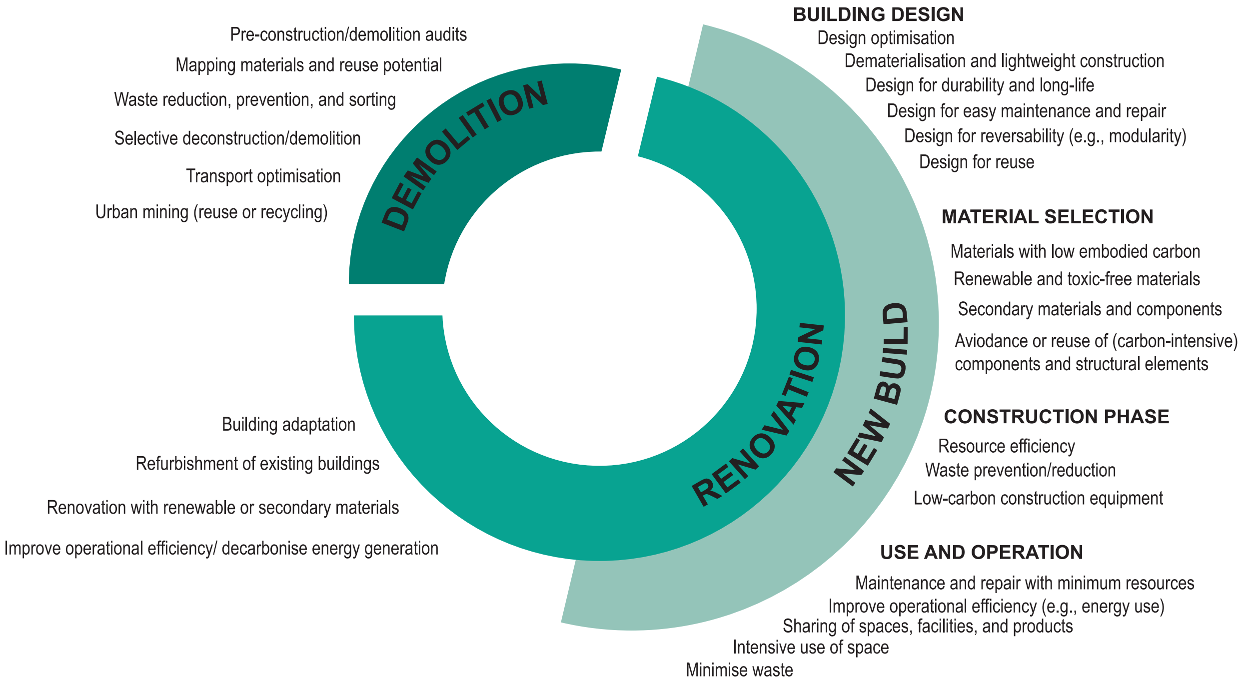


Fig. 1. Circular building strategies compiled from review papers on CE in the built environment (Adams et al., 2017; Çetin et al., 2021a; Eberhardt et al., 2020a; Guerra et al., 2021; López Ruiz et al., 2020; Malmqvist et al., 2018; Pomponi and Moncaster, 2016) and mapped for three different project types.

models, the present study aims to reveal applications of circular building strategies with a higher level of maturity that are usable in practice. We also include the *regeneration* strategy as an emerging and important resource approach, in addition to *slowing, closing* and *narrowing* the resource loops (Bocken and Geradts, 2022; Çetin et al., 2021; Konietzko et al., 2020). The narrower geographic focus (i.e., Europe-wide) and assessment level (i.e., building and product level) of the reviewed studies are considered useful to create a more homogenous sample for comparison, as also suggested by Gallego-Schmid et al. (2020).

1.4. Research aim and questions

To capture the state-of-the-art application of circular building strategies in the European building industry, this study aims to compile real-world cases - drawn from both literature and practice - realised over the last five years, including those published in grey literature. Quantitative evidence of decarbonisation potential is gathered from the cases' life-cycle assessments (LCAs) in order to answer the following research question: "*What applications of circular strategies have been used in buildings and what were their individual carbon saving potentials?*". For reasons of simplicity, the term 'carbon' is used synonymously with 'greenhouse gas emissions'. Therefore, this paper focuses on the definition of decarbonisation potential as the reduction of greenhouse gas emissions (see Section 2.4 for a more detailed explanation). Considering that business practice is ahead of academia in this field, reviewing practitioners' literature is useful for identifying the latest examples and forming a complete picture (Bocken et al., 2014). Cases are categorised into three types of building project types: (*1) new build*, (*2) renovation*, and (*3) demolition* – in order to relate to the work of practitioners and group cases with similar characteristics. Based on the 65 case studies, 133 real-world applications of circular building strategies are featured. Based on the analysis of the LCAs from the cases from the peer-reviewed articles, the main inconsistencies in application of LCA are discussed that hamper comparability of decarbonisation potentials amongst the cases. The findings aim to inspire stakeholders with influence in building projects (e.g., architects, developers, contractors, consultants) and to inform them about the individual decarbonisation potentials of the cases.

The paper proceeds with a description of the material and methodology (Section 2), results (Section 3), discussion and conclusion (Section 4).

2. Material and methodology

Between November 2021 and January 2022, the authors conducted a bibliographic search to identify applications of circular building strategies and their decarbonisation potential. The review considered publications in peer-reviewed literature and was complemented with a review of grey literature. Fig. 2 presents an overview of the literature and practice review and the data extraction process, further explained in the following subsections.

2.1. Literature review

For the literature review, data were collected from Scopus by using a search string that consisted of four elements:

(1) Building
(2) Circular strategies (compiled from review papers presented in Section 1.2)
(3) Climate change impact
(4) Case study

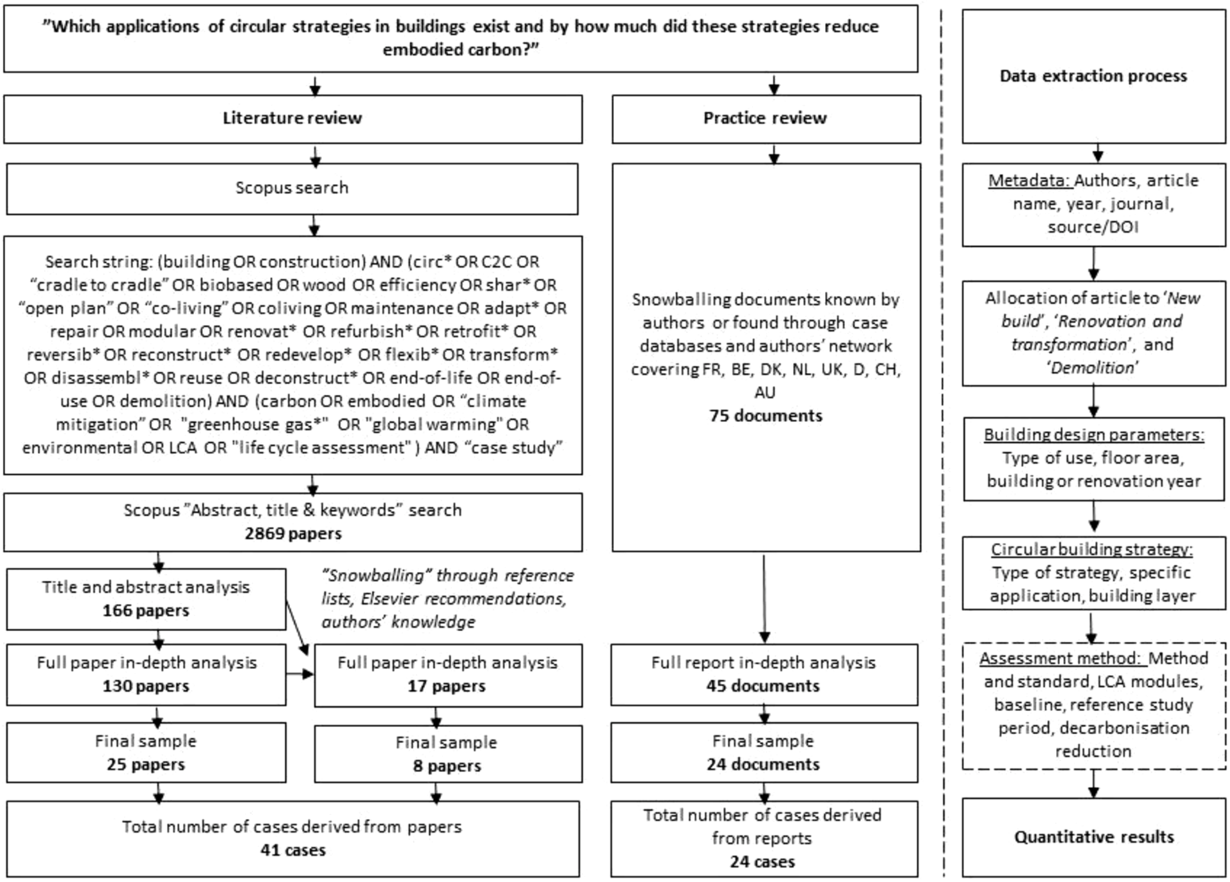


Fig. 2. Illustration of the bibliographic search and data extraction process.

For each element, variants of commonly used terms were included. During the search, new keywords were identified, and additional searches were conducted resulting in the search string presented in Fig. 2.

The literature search with the scope criteria applied (see Section 2.3) resulted in an initial sample of 2869 papers. After checking the articles' titles and abstracts for relevance, 166 papers remained. After deleting duplicates, the remaining 130 papers were read in detail to confirm relevance in accordance with four selection criteria (Table 2). This resulted in a sample of 25 papers. To identify missed articles, snowballing (Bell et al., 2022; Wohlin, 2014) was applied by adding papers that the authors were aware of, paper recommendations on Elsevier, and papers included in other reviews of LCAs, CE, or decarbonisation potential in the building industry (Andersen et al., 2022; Gallego-Schmid et al., 2020). This snowballing process resulted in the inclusion of eight additional papers. The search and selection process resulted in the final sample of 41 cases from 33 papers (see Section 2.4). Full lists of the included cases from the literature review are provided in Appendices A–C, including the sources for each case, and additional information on the building type and project, the assessment methods used, and the circular solution.

2.2. Practice review

The literature review confirmed that only a limited number of real-world projects that apply circular strategies have been described in academic publications. Therefore, examples from practice were an important addition to our review. Example cases were identified through the snowballing technique (Bell et al., 2022) including (1) publicly accessible databases from organisations, (2) grey literature (e.g., reports from consultancy firms such as Arup), and (3) authors' knowledge from working in the industry and their network. Databases used for sourcing cases included those from organisations such as Construction21, the Knowledge Hub of Circle Lab, CE Club, Ellen MacArthur Foundation, Circulaire Bouw Economie, Historic Building Energy Retrofit Atlas, and the Danish Database for the Voluntary Sustainability Class. Studies sourced through the authors' knowledge and network were limited to those countries, in which authors had proficiency in the national language(s), as many practice publications are published in the language of their respective nations. The included languages were German, Danish, English, Dutch, and French. To select cases, the same selection criteria as for the literature review were applied (see Section 2.3).

In total, 45 documents were identified that were analysed in depth. 24 documents were selected for the final sample, resulting in 24 cases. The full list of practice cases identified in the review, including a more detailed description of the circular strategy applied, can be found in Appendix D.

Table 2
Selection criteria for final articles.

Selection criteria	Included	Excluded
Real-world case	Circular solution that has been used in an actual built project	Hypothetical model, scenario or concept
Circular building strategy	Solutions implementing a circular strategy (e.g., reuse, durability, disassembly, recycling)	Solutions that can support implementation of a circular strategy (e.g., policy, value chain or management approaches, tools as building information models)
Building level	Analysis at building level (incl. components or materials)	Analysis at other levels (e.g., industry, urban, national, global level)
Decarbonisation potential	Quantitative results on decarbonisation potential	No assessment of decarbonisation potential

2.3. Scope and selection criteria

Due to the rapid developments within the field, the following limits to the search scope were applied. Firstly, only results published since 2015 were considered. This time scope coincides with the popularisation of the CE concept (Blomsma and Brennan, 2017) and is regarded as a valuable way of keeping the focus on the most recent cases. Furthermore, Albertí et al. (2019) found that LCA results cannot be considered reliable after 15–20 years. Secondly, the geographic scope was limited to building projects in Europe in order to limit the variety of location-specific characteristics amongst cases (e.g., markets, building regulations and requirements, and LCA methods). Given the existence of the EU CE action plan (part of the European Green Deal), which made circularity a priority, Europe is considered a relevant geographic scope.

Four selection criteria were applied for both literature and practice sampling: (1) *real-world case*, (2) *circular building strategy*, (3) *building level*, and (4) *decarbonisation potential* (see Table 2). The selection criterion '*real-world case*' was chosen considering the urgency to implement solutions for net zero carbon buildings (IPCC, 2022). Real-world cases are considered to have a higher level of maturity and readiness for implementation. The focus on assessments at the *building and product level*, rather than assessments at the industry or urban level, was chosen to increase the homogeneity of the sample as a means of facilitating comparability (Miller et al., 2016) (see Section 3.4). Papers did not need to mention CE explicitly but could use different terms for circular building strategies (e.g., increasing efficiency, modularity, improving recycling, renovation, retrofit, etc.). Only articles that provided quantitative results on *decarbonisation potential* were chosen. Quantitative results were predominantly derived from LCA, which was considered suitable as it is a scientifically accepted method to measure the carbon impact of buildings and products and has undergone several decades of standardisation work for industrial (Del Borghi, 2013; Durão et al., 2020). Papers were excluded when the selection criteria were not clearly met.

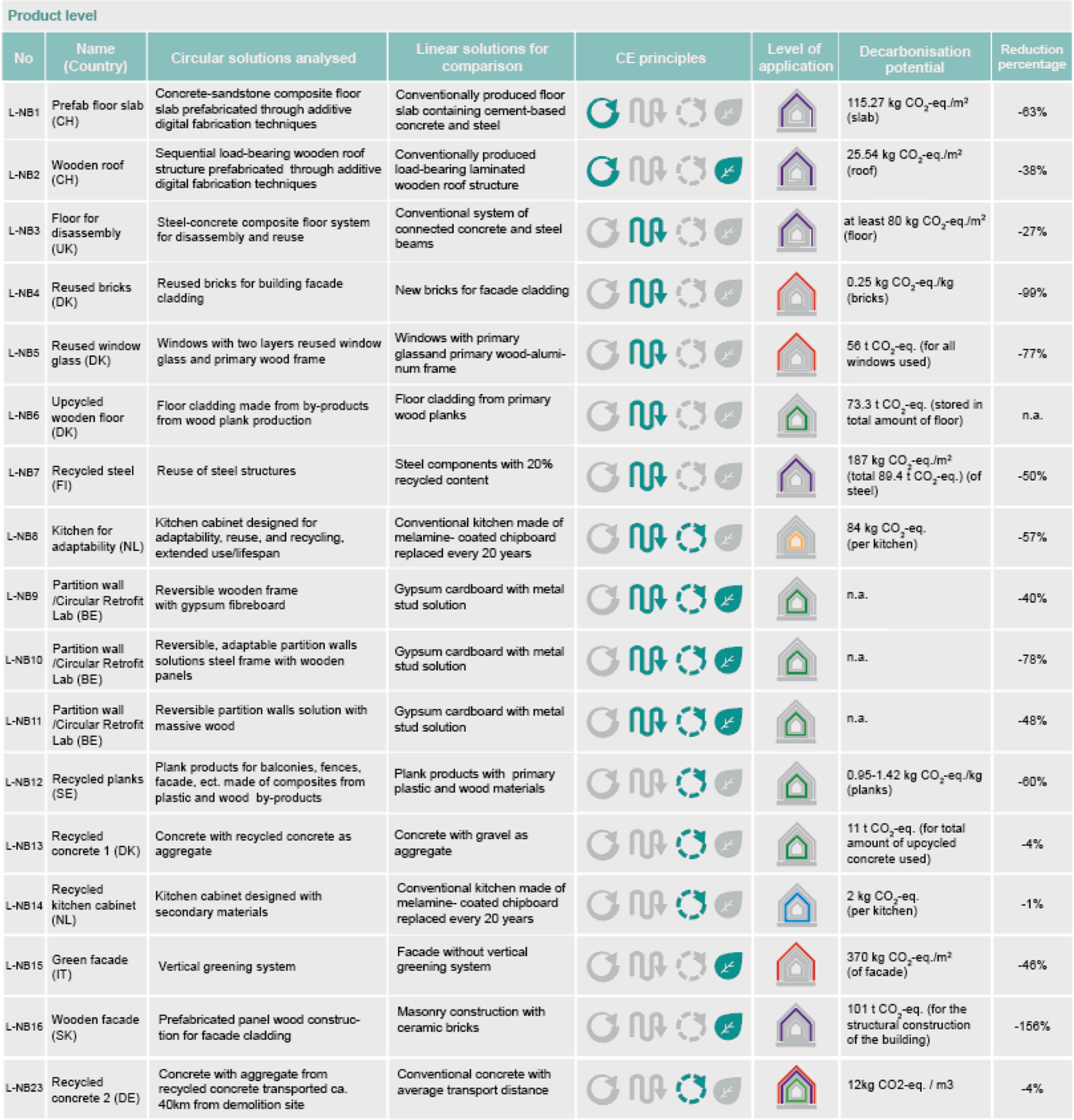
The Appendices contain full lists of the included cases from literature review (Appendices A–C) and practice review (Appendix D) including the sources for each case and additional information.

2.4. Data extraction and processing

As a first step before the actual data collection, six categories of features and parameters for case study data were identified and used for a data collection template (see explanation of data extraction process in Fig. 2). Each case in the final sample was analysed by at least one of the authors and information was collected in a data collection template. If the author was unsure, the paper was checked by another author until the information was captured correctly.

Cases were analysed regarding the country of construction, the circular solution applied, the type of *circular principle*, and the *level of building layer* (Brand, 1995), and *decarbonisation potential* (Sections 3.1–3.3 and Figs. 3,5,6).

As for the type of *circular principle*, we categorised cases under the four categories of CE principles: closing resource loops (e.g., recycling material), slowing loops (e.g., using products for longer), narrowing loops (e.g., reducing raw material use) and regenerating resource loops (using renewable materials and innovations positively contributing to nature revival) (Bocken and Geradts, 2022; Konietzko et al., 2020). Cases that reduce energy and raw material inputs, for example, through energy retrofits, were classified within the *narrowing category* while if renewable energy systems were used, cases were also captured under the *regenerating category*. The use of renewable materials, such as timber is also captured under the *regenerating category*. As for strategies that involve design for dis- and re-assembly, we investigated on a case-by-case basis, whether the intention was recycling (i.e., *closing* the loop) or reuse of products (i.e., *slowing* the loop) and classified strategies accordingly. If reclaimed materials were reused or recycled in a



Product level

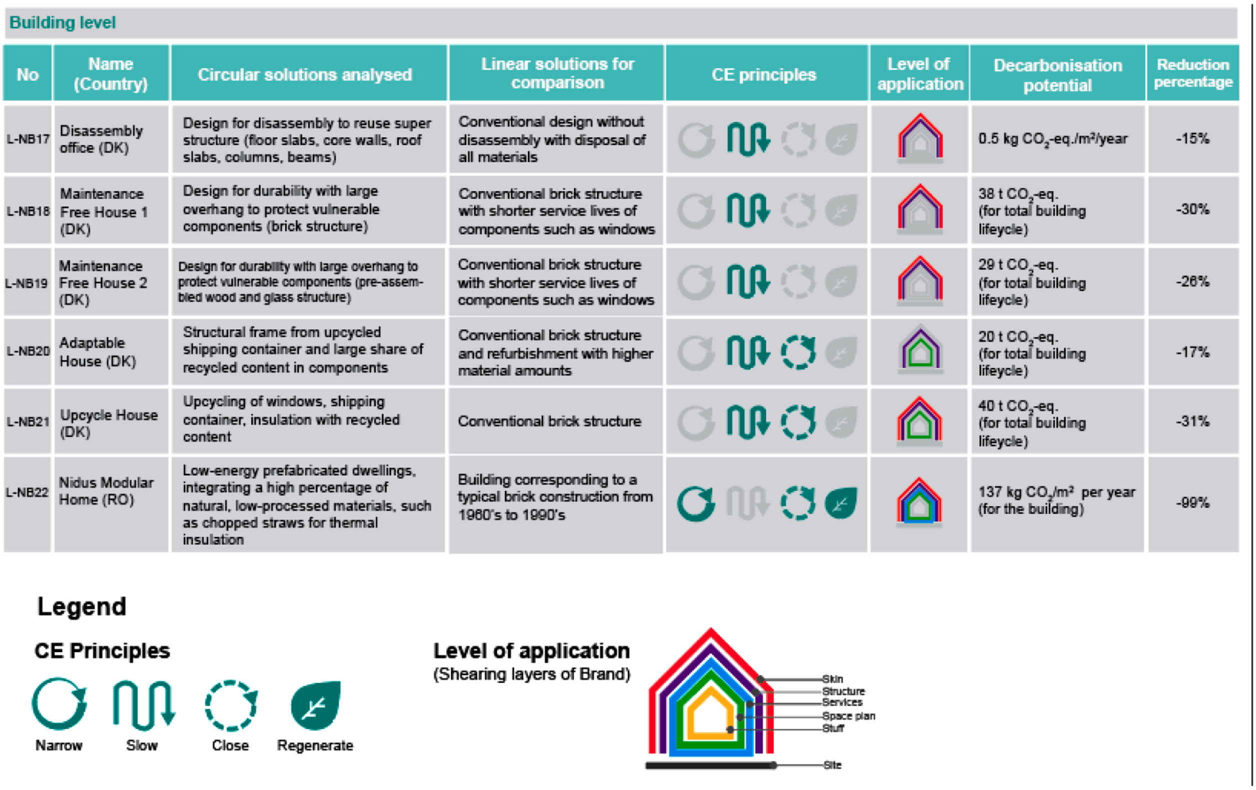
No	Name (Country)	Circular solutions analysed	Linear solutions for comparison	CE principles	Level of application	Decarbonisation potential	Reduction percentage
L-NB1	Prefab floor slab (CH)	Concrete-sandstone composite floor slab prefabricated through additive digital fabrication techniques	Conventionally produced floor slab containing cement-based concrete and steel	● ○ ○ ○	🟪	115.27 kg CO_2-eq./m² (slab)	-63%
L-NB2	Wooden roof (CH)	Sequential load-bearing wooden roof structure prefabricated through additive digital fabrication techniques	Conventionally produced load-bearing laminated wooden roof structure	● ○ ○ ●	🟪	25.54 kg CO_2-eq./m² (roof)	-38%
L-NB3	Floor for disassembly (UK)	Steel-concrete composite floor system for disassembly and reuse	Conventional system of connected concrete and steel beams	○ ● ○ ○	🟪	at least 80 kg CO_2-eq./m² (floor)	-27%
L-NB4	Reused bricks (DK)	Reused bricks for building facade cladding	New bricks for facade cladding	○ ● ○ ○	🟥	0.25 kg CO_2-eq./kg (bricks)	-99%
L-NB5	Reused window glass (DK)	Windows with two layers reused window glass and primary wood frame	Windows with primary glassand primary wood-aluminum frame	○ ● ○ ○	🟥	56 t CO_2-eq. (for all windows used)	-77%
L-NB6	Upcycled wooden floor (DK)	Floor cladding made from by-products from wood plank production	Floor cladding from primary wood planks	○ ● ○ ○	🟩	73.3 t CO_2-eq. (stored in total amount of floor)	n.a.
L-NB7	Recycled steel (FI)	Reuse of steel structures	Steel components with 20% recycled content	○ ● ○ ○	🟪	187 kg CO_2-eq./m² (total 89.4 t CO_2-eq.) (of steel)	-50%
L-NB8	Kitchen for adaptability (NL)	Kitchen cabinet designed for adaptability, reuse, and recycling, extended use/lifespan	Conventional kitchen made of melamine- coated chipboard replaced every 20 years	○ ● ● ○	🟧	84 kg CO_2-eq. (per kitchen)	-57%
L-NB9	Partition wall /Circular Retrofit Lab (BE)	Reversible wooden frame with gypsum fibreboard	Gypsum cardboard with metal stud solution	○ ● ● ●	🟩	n.a.	-40%
L-NB10	Partition wall /Circular Retrofit Lab (BE)	Reversible, adaptable partition walls solutions steel frame with wooden panels	Gypsum cardboard with metal stud solution	○ ● ● ●	🟩	n.a.	-78%
L-NB11	Partition wall /Circular Retrofit Lab (BE)	Reversible partition walls solution with massive wood	Gypsum cardboard with metal stud solution	○ ● ● ●	🟩	n.a.	-48%
L-NB12	Recycled planks (SE)	Plank products for balconies, fences, facade, ect. made of composites from plastic and wood by-products	Plank products with primary plastic and wood materials	○ ○ ● ○	🟩	0.95-1.42 kg CO_2-eq./kg (planks)	-60%
L-NB13	Recycled concrete 1 (DK)	Concrete with recycled concrete as aggregate	Concrete with gravel as aggregate	○ ○ ● ○	🟩	11 t CO_2-eq. (for total amount of upcycled concrete used)	-4%
L-NB14	Recycled kitchen cabinet (NL)	Kitchen cabinet designed with secondary materials	Conventional kitchen made of melamine- coated chipboard replaced every 20 years	○ ○ ● ○	🟦	2 kg CO_2-eq. (per kitchen)	-1%
L-NB15	Green facade (IT)	Vertical greening system	Facade without vertical greening system	○ ○ ○ ●	🟥	370 kg CO_2-eq./m² (of facade)	-46%
L-NB16	Wooden facade (SK)	Prefabricated panel wood construction for facade cladding	Masonry construction with ceramic bricks	○ ○ ○ ●	🟪	101 t CO_2-eq. (for the structural construction of the building)	-156%
L-NB23	Recycled concrete 2 (DE)	Concrete with aggregate from recycled concrete transported ca. 40km from demolition site	Conventional concrete with average transport distance	○ ○ ● ○	🟥🟪🟩	12kg CO2-eq. / m3	-4%

Fig. 3. Overview of circular strategies and their decarbonisation potential of case studies at the product and building level for new build. The results are given exactly as in the cited papers, with the level of precision and the functional unit used in the papers. Product level cases are highlighted in light grey and building level cases are highlighted in darker grey.

renovation or new build case, the strategy was also classified as *slowing* or *closing* loops depending on the application.

Regarding the *level of the building layer*, we use Brand's (1995) conceptualisation of six shearing layers. Buildings are considered to consist of various layers and components, rather than one product, that are characterised by different longevity and impacts. The shearing layers are Site (the geographical setting and location), Structure (the foundation and load-bearing elements), Skin (exterior surfaces and building envelope), Services (systems such as electrical wiring, plumbing, HVAC, and elevators used for the operation of the building), Space Plan (the interior layout including walls, doors, floors, and ceilings) and Stuff (interior and appliances).

Decarbonisation potentials are reported based on the functional unit and reference of each case study's LCA - presented in the original article or data source. The reference products or scenarios used in the original case studies are presented in Figs. 3,5, and 6 to help readers critically evaluate the results of each case. Kg CO_2 eq. (including both CO2 and non-CO2 GHG emissions) were expressed per m^2, m^2/ year, or a quantity of material, depending on how results are reported in the case studies. Additional information on the LCA method applied in each case (e.g., standard followed, reference period selected, life cycle modules included) are presented for the cases from academic literature in Appendices A–C. For cases from grey literature, it was more common that data on the assessment method was missing (see dotted boxes in Fig. 1 for omitted steps in data processing for cases from grey literature). Even though the methods for assessing decarbonisation potential in the



Building level

No	Name (Country)	Circular solutions analysed	Linear solutions for comparison	CE principles	Level of application	Decarbonisation potential	Reduction percentage
L-NB17	Disassembly office (DK)	Design for disassembly to reuse super structure (floor slabs, core walls, roof slabs, columns, beams)	Conventional design without disassembly with disposal of all materials	Slow	Skin, Structure	0.5 kg CO_2-eq./m²/year	-15%
L-NB18	Maintenance Free House 1 (DK)	Design for durability with large overhang to protect vulnerable components (brick structure)	Conventional brick structure with shorter service lives of components such as windows	Slow	Skin, Structure	38 t CO_2-eq. (for total building lifeycle)	-30%
L-NB19	Maintenance Free House 2 (DK)	Design for durability with large overhang to protect vulnerable components (pre-assembled wood and glass structure)	Conventional brick structure with shorter service lives of components such as windows	Slow	Skin, Structure	29 t CO_2-eq. (for total building lifeycle)	-26%
L-NB20	Adaptable House (DK)	Structural frame from upcycled shipping container and large share of recycled content in components	Conventional brick structure and refurbishment with higher material amounts	Slow, Close	Structure, Space plan	20 t CO_2-eq. (for total building lifeycle)	-17%
L-NB21	Upcycle House (DK)	Upcycling of windows, shipping container, insulation with recycled content	Conventional brick structure	Slow, Close	Skin, Structure, Space plan	40 t CO_2-eq. (for total building lifeycle)	-31%
L-NB22	Nidus Modular Home (RO)	Low-energy prefabricated dwellings, integrating a high percentage of natural, low-processed materials, such as chopped straws for thermal insulation	Building corresponding to a typical brick construction from 1960's to 1990's	Narrow, Close, Regenerate	Skin, Structure, Services, Space plan	137 kg CO_2/m² per year (for the building)	-99%

Fig. 3. (*continued*).

cases from grey literature may be less transparent and rigorous compared with the peer-reviewed cases, the 24 cases are included in this study to showcase recent applications of circular building strategies in industry that were not yet covered in academic literature (Fig. 4).

3. Results

3.1. New build

Real-life cases of CE applications in new build projects were sourced from academic literature and from practice. Fig. 3 presents the results from the literature cases and Fig. 4 presents the results from the practice cases. Decarbonisation potentials reported in the case studies are based on the functional unit applied in the individual cases. In the following, cases from literature are presented, followed by the cases from practice (see Appendices for A and D for sources and additional information on the cases).

3.1.1. Cases from literature

In total, 23 cases of circular building strategies applied in *new build projects* were identified. These include both (1) building products that were used in new buildings, and (2) entire new buildings, in which several circular strategies were applied. This differentiation is indicated in Fig. 3. The presented decarbonisation results are thus either for decarbonisation potential assessed at the product-level (compared to a linear reference product) or at the building level (the impact of the entire building compared to a reference building).

Regarding the product-related cases, two cases applied strategies for *narrowing* the loop both through digital fabrication techniques (Prefab Floor Slab (L-NB1) and Sequential Wooden Roof (L-NB2)). *Slowing* the loop was identified in nine product-related cases (L-NB3 to L-NB11), mostly through the reuse of building products (e.g., bricks, window glass, wood off-cuts) or design for disassembly (e.g., partition walls and a steel-concrete floor system). *Closing* the loop was found in seven product cases (L-NB8 to L-NB14), either through design for disassembly and recycling (e.g., kitchen cabinet and partition walls) or with secondary materials in products (e.g., concrete, kitchen cabinet, plank products). Six product cases applied strategies for *regenerating* the loop (L-NB2, L-NB9, L-NB10, L-NB11, L-NB15, L-NB16), either with timber (e.g., wooden roof, or partition wall studs, wooden facade) or via a green façade with a vertical greening system.

Six case studies assessed the decarbonisation potential of circular building strategies in *new build* at building level. *Slowing* the loop was most prominent with five cases (L-NB17 to L-NB 21), for example through design for durability, adaptability, and disassembly, but also through reusing building products in the construction of new buildings (L-NB21 Upcycle House). *Closing* the loop was found in three cases through design for disassembly (L-NB20, Adaptable House and L-NB17, Disassembly Office) and through reuse of materials (L-NB21, Upcycle House). *Regenerating* the loop was found in one case with bio-sourced materials (L-NB22, Nidus Modular Home, a prefab-low energy dwelling with renewable materials). Three case studies incorporated several circular strategies (L-NB20, L-NB21 and L-NB22).

3.1.2. Cases from practice

In total, 14 cases for *new build* were found from grey literature. *Slowing* the loop was found in 12 of the cases, for example through design for disassembly (HAUT Timber (P-NB1), Juff Nienke (P-NB2), Koning Willem I College (P-NB3), UMAR Unit (P-NB7), The Flat House (P-NB12), The Cradle (P-NB11)), but also via design for adaptability (Juff Nienke (P-NB2), The Dutch Mountains (P-NB6)), modularity (Juff Nienke (P-NB2), UMAR Unit (P-NB7), The Flat House (P-NB12)) and component reuse (Ressourcerækkerne (P-NB8), Upcycle Studio (P-NB9), Super Circular Estate (P-NB4), Segro Warehouse (P-NB13)). *Closing* the loop was found in eight cases through material reuse (Umar Unit (P-NB7), Upcycle Studio (P-NB9), Super Circular Estate (P-NB4), The Flat House (P-NB12), Segro Warehouse (P-NB13)), for example, concrete aggregates (Upcycle Studio (P-NB9)) or agricultural wastes for the

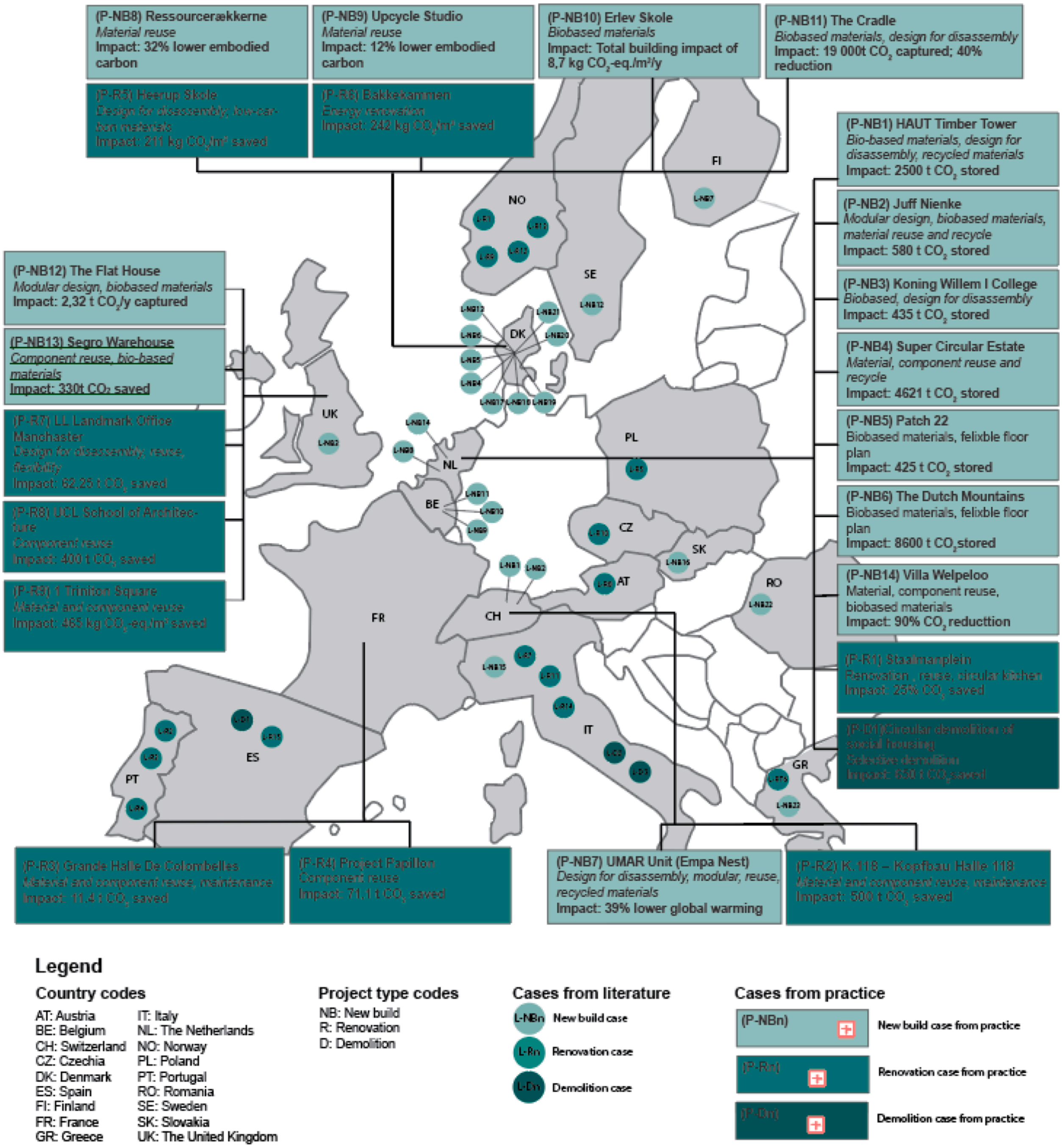


Fig. 4. Overview of cases from literature (circles with case codes) and practice (in boxes), pinned on the European map. The results are given exactly as in the case descriptions (see Appendix D for references), with the level of precision and the functional unit used in the reported calculations.

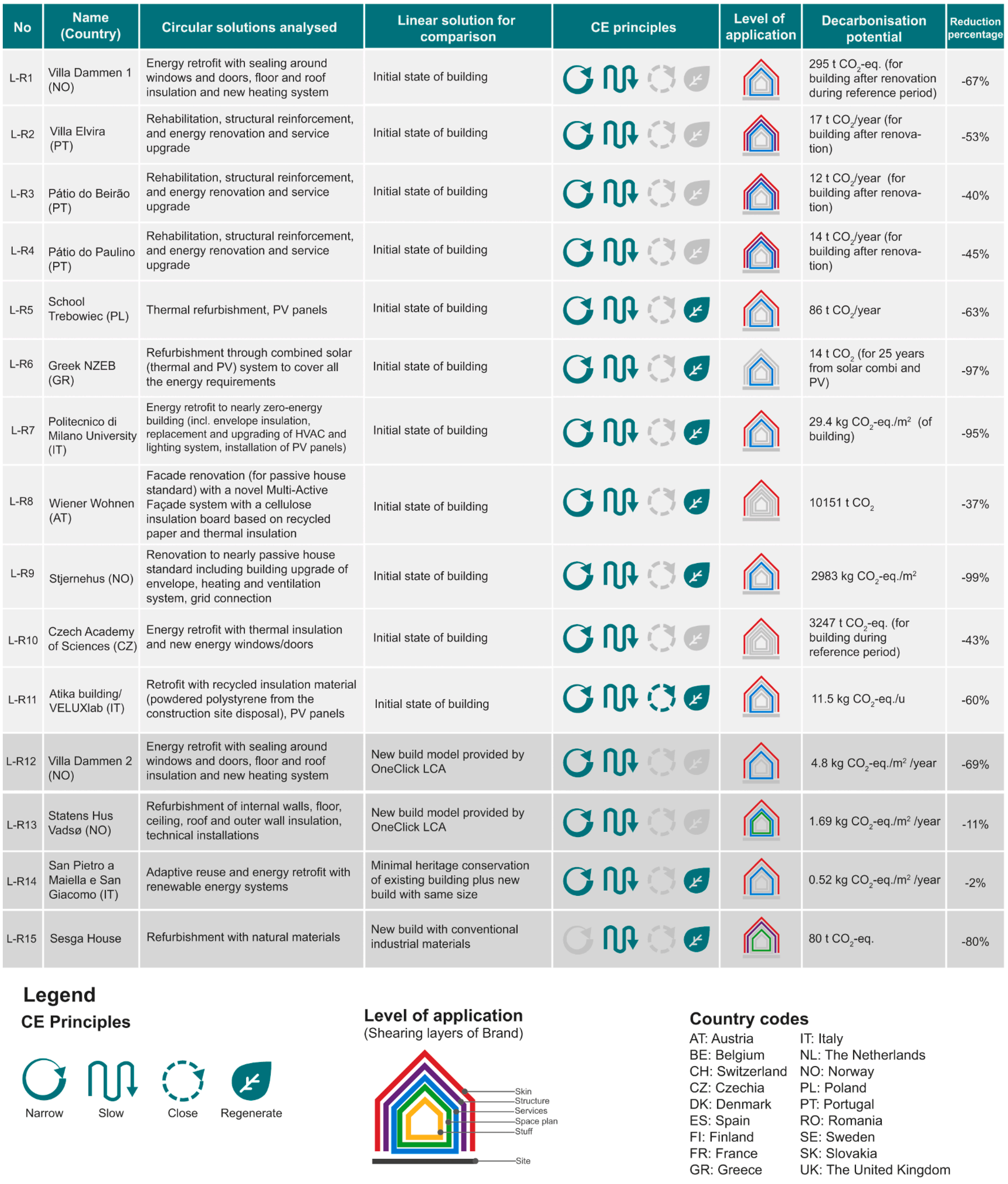
external cladding (The Flat House (P-NB12)). *Regenerating* the loop was found in ten cases, via the use of cross-laminated timber (Erlev Skole (P-NB10)), the use of other biobased materials (The Flat House (P-NB12), Segro Warehouse (P-NB13), The Dutch Mountains (P-NB6), The Cradle (P-NB11)), green roofs with planting for biodiversity (Juff Nienke (P-NB2), Ressourcerækkerne (P-NB8)) or PV panels (Juff Nienke (P-NB2)). *Narrowing* the loop was found in two cases through prefabrication (The Flat House (P-NB12) and Juff Nienke (P-NB2)). 12 of the 14 cases applied several strategies simultaneously.

3.2. Renovation

Real-life cases of CE applications in renovation projects were also sourced from academic and grey literature. Fig. 5 presents the results from the literature cases and Fig. 4 the results from the practice cases. Decarbonisation potentials reported in the case studies are based on the functional unit applied in the individual cases. First are cases from literature presented, followed by the cases from practice. Sources and additional information for the cases can be found in Appendices B and D.

3.2.1. Cases from literature

18 cases of *renovation* projects applying CE strategies were found in academic literature. All cases apply strategies of *slowing* and *narrowing* the loop as the building's lifetime is prolonged and the operational efficiency of the building increased. Eight of the cases also applied strategies of *regenerating* the loop by installing renewable energy systems (L-



No	Name (Country)	Circular solutions analysed	Linear solution for comparison	CE principles	Level of application	Decarbonisation potential	Reduction percentage
L-R1	Villa Dammen 1 (NO)	Energy retrofit with sealing around windows and doors, floor and roof insulation and new heating system	Initial state of building	● ● ○ ○		295 t CO_2-eq. (for building after renovation during reference period)	-67%
L-R2	Villa Elvira (PT)	Rehabilitation, structural reinforcement, and energy renovation and service upgrade	Initial state of building	● ● ○ ○		17 t CO_2/year (for building after renovation)	-53%
L-R3	Pátio do Beirão (PT)	Rehabilitation, structural reinforcement, and energy renovation and service upgrade	Initial state of building	● ● ○ ○		12 t CO_2/year (for building after renovation)	-40%
L-R4	Pátio do Paulino (PT)	Rehabilitation, structural reinforcement, and energy renovation and service upgrade	Initial state of building	● ● ○ ○		14 t CO_2/year (for building after renovation)	-45%
L-R5	School Trebowiec (PL)	Thermal refurbishment, PV panels	Initial state of building	● ● ○ ●		86 t CO_2/year	-63%
L-R6	Greek NZEB (GR)	Refurbishment through combined solar (thermal and PV) system to cover all the energy requirements	Initial state of building	● ● ○ ●		14 t CO_2 (for 25 years from solar combi and PV)	-97%
L-R7	Politecnico di Milano University (IT)	Energy retrofit to nearly zero-energy building (incl. envelope insulation, replacement and upgrading of HVAC and lighting system, installation of PV panels)	Initial state of building	● ● ○ ●		29.4 kg CO_2-eq./m^2 (of building)	-95%
L-R8	Wiener Wohnen (AT)	Facade renovation (for passive house standard) with a novel Multi-Active Façade system with a cellulose insulation board based on recycled paper and thermal insulation	Initial state of building	● ● ○ ●		10151 t CO_2	-37%
L-R9	Stjernehus (NO)	Renovation to nearly passive house standard including building upgrade of envelope, heating and ventilation system, grid connection	Initial state of building	● ● ○ ●		2983 kg CO_2-eq./m^2	-99%
L-R10	Czech Academy of Sciences (CZ)	Energy retrofit with thermal insulation and new energy windows/doors	Initial state of building	● ● ○ ○		3247 t CO_2-eq. (for building during reference period)	-43%
L-R11	Atika building/ VELUXlab (IT)	Retrofit with recycled insulation material (powdered polystyrene from the construction site disposal), PV panels	Initial state of building	● ● ● ●		11.5 kg CO_2-eq./u	-60%
L-R12	Villa Dammen 2 (NO)	Energy retrofit with sealing around windows and doors, floor and roof insulation and new heating system	New build model provided by OneClick LCA	● ● ○ ○		4.8 kg CO_2-eq./m^2 /year	-69%
L-R13	Statens Hus Vadsø (NO)	Refurbishment of internal walls, floor, ceiling, roof and outer wall insulation, technical installations	New build model provided by OneClick LCA	● ● ○ ○		1.69 kg CO_2-eq./m^2 /year	-11%
L-R14	San Pietro a Maiella e San Giacomo (IT)	Adaptive reuse and energy retrofit with renewable energy systems	Minimal heritage conservation of existing building plus new build with same size	● ● ○ ●		0.52 kg CO_2-eq./m^2 /year	-2%
L-R15	Sesga House	Refurbishment with natural materials	New build with conventional industrial materials	○ ● ○ ●		80 t CO_2-eq.	-80%

Legend

CE Principles

Narrow Slow Close Regenerate

Level of application

(Shearing layers of Brand)

Country codes

AT: Austria
BE: Belgium
CH: Switzerland
CZ: Czechia
DK: Denmark
ES: Spain
FI: Finland
FR: France
GR: Greece
IT: Italy
NL: The Netherlands
NO: Norway
PL: Poland
PT: Portugal
RO: Romania
SE: Sweden
SK: Slovakia
UK: The United Kingdom

Fig. 5. Overview of circular strategies of renovation case studies and their decarbonisation potential. The results are given exactly as in the cited papers, with the level of precision and the functional unit used in the papers. Cases which compare decarbonisation potential from circular strategy with the initial state of the building are highlighted in light grey, and dark grey when comparison was made with demolition and new build.

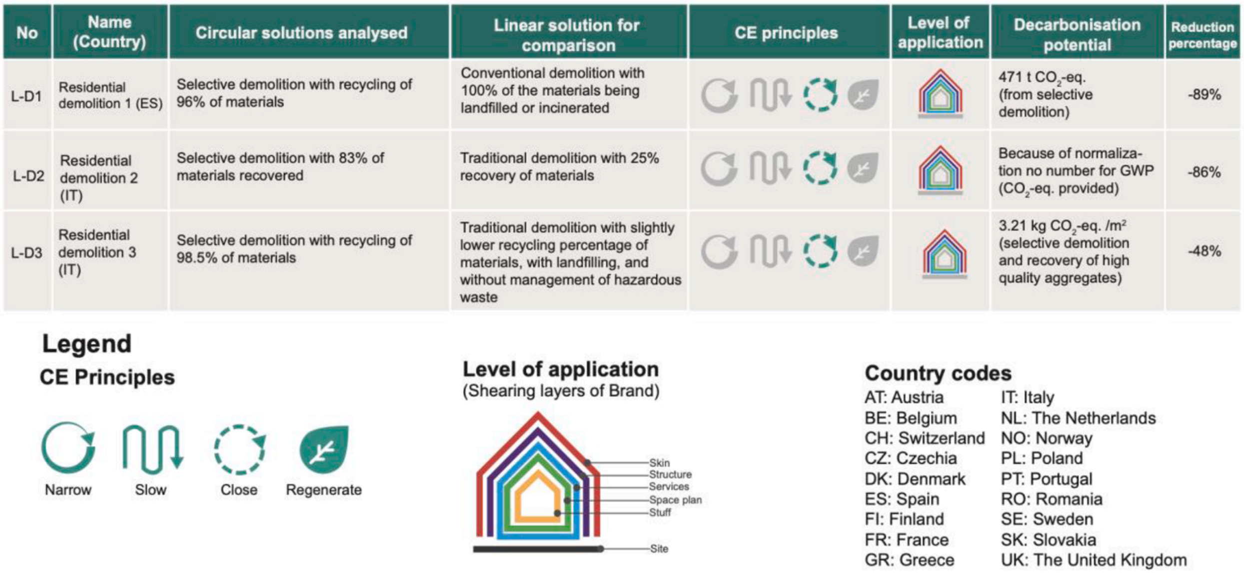
R5-L-R9, L-R11, L-R14, L-R15) and, in the case of the Sesga House (L-R15), by using natural materials for refurbishment. The case of Atika building/VELUXlab (L-R11) applied closing loops by using insulation from recycled materials. None of the cases described strategies for reclaiming materials in the renovation process and enabling their reuse in the same or another project. This was, however, found in the practice cases (Fig. 4).

3.2.2. *Cases from practice*

In total, nine cases for *renovation* were found in grey literature (Fig. 4). All nine cases can be regarded as applying *narrowing* the loop strategies because of the upgrade of energy systems and thermal properties. In addition, all cases implement *slowing* the loop principles as they prolong the lifetime of the building. *Regenerating* the loop was found in two cases (kitchen from biobased materials in Circular Renovation Staalmanplein (P-R1) and cross-laminated-timber construction designed for disassembly in Heerup Skole (P-R5)). Six of the cases applied *slowing* the loop strategies through reuse of reclaimed materials (Circular Renovation Staalmanplein (P-R1), K.118 (P-R2), Grande Halle (P-R3), Project Papillon (P-R4), JLL Landmark Office Manchester (P-R7), UCL School of Architecture (P-R8), 1 Triniton (P-R9)), predominantly from the respective building, but in two cases also from a building demolition in close proximity (Circular Renovation Staalmanplein (P-R1) and Project Papillon (P-R4)).

3.3. *Demolition*

Real-life cases of CE applications in renovation projects were also sourced from academic and grey literature. Fig. 6 presents the results from the literature cases and Fig. 4 the results from the practice cases.



No	Name (Country)	Circular solutions analysed	Linear solution for comparison	CE principles	Level of application	Decarbonisation potential	Reduction percentage
L-D1	Residential demolition 1 (ES)	Selective demolition with recycling of 96% of materials	Conventional demolition with 100% of the materials being landfilled or incinerated			471 t CO_2-eq. (from selective demolition)	-89%
L-D2	Residential demolition 2 (IT)	Selective demolition with 83% of materials recovered	Traditional demolition with 25% recovery of materials			Because of normalization no number for GWP (CO_2-eq. provided)	-86%
L-D3	Residential demolition 3 (IT)	Selective demolition with recycling of 98.5% of materials	Traditional demolition with slightly lower recycling percentage of materials, with landfilling, and without management of hazardous waste			3.21 kg CO_2-eq. /m^2 (selective demolition and recovery of high quality aggregates)	-48%

Fig. 6. Overview of circular strategies of demolition case studies and decarbonisation potential. The results are given exactly as in the cited papers, with the level of precision and the functional unit used in the papers.

Decarbonisation potentials reported in the case studies are based on the functional unit applied in the individual cases. First, cases from literature are presented, followed by the case from practice. Sources and additional information for the cases can be found in Appendices C and D.

3.3.1. Cases from literature

Three cases of *demolition* with a focus on more circular practices were found in the academic literature. All three cases can be regarded as *closing* resource loops as they apply selective demolition to recycle larger fractions of materials (83%–98.5% of the total amount of materials) than if conventional demolition techniques were used. All three cases were demolitions of residential buildings and included recovery of materials from the building layers skin, structure, services, and space plan. The reduction potential of the case Residential Demolition 3 (L-D3) is 48%, while the other two cases estimate larger reduction potentials. An explanation for the different result may be that the reference scenario assumes only slightly lower recycling rates for conventional demolition. However, management of hazardous waste is performed in the circular solution, but not performed in the reference scenario of conventional demolition (see Fig. 6). In this case, also the optimisation of transport distances was explicitly mentioned as a factor to ensure decarbonisation (Pantini and Rigamonti, 2020).

3.2.2. Case from practice

Only one case of demolition applying circular strategies beyond conventional practice was found (P-D1 in Fig. 4). In this case, strategies for *closing* and *slowing* resource loops were applied. Components as radiators, kitchen elements, and armatures were reused in other building and refurbishing projects. Materials from bricks, concrete, and wooden beams were recycled for new construction materials. According to the demolisher, this resulted in an overall carbon saving of 650 tons CO_2 compared to conventional demolition practices and treatment of resources and waste.

4. Discussion and conclusion

This study contributes to the understanding of the application and decarbonisation potential of circular strategies in the building industry by investigating real-life cases of *new build, renovation*, and *demolition*. Cases were analysed and visualised regarding the type of CE strategy – *narrowing, slowing, closing*, and *regenerating resource loops* –, level of application in the building (i.e., shearing layers (Brand, 1995)), and their decarbonisation potential. The sample of this study consisted of 65 real-life circular building cases and showcased many cases from practice that have not yet been studied in literature.

In total, 133 applications of circular strategies (53 of *slowing*, 29 of *regenerating*, 28 applications of *narrowing*, 23 of *closing* resource loops) across the cases were identified. In *new build* projects, slowing the loop has been most prominent in the analysed cases mostly enabled through design for durability, adaptability, disassembly and reuse. In six of the cases of new build projects, strategies for *slowing* resource loops were combined with strategies for *closing* and/or *regenerating* resource loops. In *renovation projects*, combinations of *narrowing* the loop, *slowing* the loop and *regeneration* were found, showing a great potential for combining strategies by not only improving operational efficiencies for the use of buildings, but also enabling materials reuse and choice of materials with lower carbon impacts. However, cases enabling reuse of materials and components of the existing building were only found amongst the cases sourced from the grey literature, indicating a research gap in academic literature. For *demolition* projects, all strategies perhaps unsurprisingly focused on *closing* the loop, so materials could be recycled, which also lead to a carbon reduction potential. Reuse of building products was only found in the practice case from grey literature. Generally, only a few case studies studying the application and decarbonisation potential of circularity in demolition projects were found, indicating another research gap in academic literature and potentially a development area in practice.

Analysis of the sample has provided evidence of the significant decarbonisation potential from application of circular building strategies across *new build, renovation*, and *demolition* projects. This shows that for each of the three project types, circularity can be considered as a key strategy to mitigate carbon emissions in the building industry. However, decarbonisation potentials also vary greatly between different building projects and applications of circular strategies, indicating that effective implementation of circular building strategies to capture potential environmental benefits is imperative (Gallego-Schmid et al., 2020; Rasmussen et al., 2020).

4.1. Limitations

Decarbonisation potentials identified in this study are specific to the individual cases and should not be compared to each other. LCA results are generally heavily dependant on the methodological choices during the assessment (Tillman, 2000). When applying LCAs to complex and long-lived systems such as buildings, the number of critical choices increases, such as functional unit choice or system boundaries that influence the LCA results (Khasreen et al., 2009; Miller et al., 2016; Rasmussen et al., 2018; Rodriguez et al., 2019). Moreover, buildings are unique products which are inherently hard to compare to each other as they serve different functional needs (medical office versus software engineering office, multi-family residence versus nursing home, etc.) or physical requirements (earthquake, climate, etc.) (Khasreen et al., 2009).

Current application of LCA assessments in academia and industry varies significantly (Andersen et al., 2022), despite developed LCA standards for the building industry, such as EN15804 and EN15978 (European Committee for Standardisation, 2011, 2012). For case studies from grey literature, information on assessment methodology was largely absent. Inconsistencies in LCA application in the case studies from academic literature (see Appendices A–C for an overview) are common for buildings and building products (Miller et al., 2016; Andersen et al., 2022). Inconsistencies stem particularly from the following factors:

- Different system boundaries were chosen in the studies, especially the included LCA modules, showing results for different parts of a building's or product's life cycle.
- Studies had different reference study periods, and hence assumed different lifetimes of the buildings and products investigated.
- Kg CO_2 eq. were expressed in different units e.g., per m^2, m^2 and year, or a unit of material quantity.
- Different sources were used for the environmental impact data (ICE database versus EcoInvent versus GaBi versus EPDs, etc.).
- Different levels of detail were used in the analysis of the cases.

Another limitation of this study relates to the focus on the environmental impact category of global warming. Consideration of other impact categories, however, is critical to prevent burden-shifting to other categories or human health risks. Circular building strategies that perform well in reducing carbon impact, may not necessarily perform as well in other impact categories (Eberhardt et al., 2020). A recent study of Egemose et al. (2022) showed that life cycle inventories and characterization models are insufficiently developed to capture the actual human toxicity impacts. Also, depletion of renewable and non-renewable resources is of high salience to the building industry, where companies are experiencing an increase in resource scarcity (Arcadis, 2022). Furthermore, other sustainability requirements of buildings - such as affordable housing, better indoor air quality and the electrification of mobility - have not been addressed.

Previous studies have stressed that the decarbonisation potential of circular building strategies is not realised by default (Gallego-Schmid et al., 2020; Nußholz et al., 2020; Pantini and Rigamonti, 2020; Vitale et al., 2017). Each case requires careful optimisation of how circular strategies are implemented. Impacts from additional processes (e.g., transport and fuels for enabling reuse (Martínez et al., 2013; Pantini and Rigamonti, 2020; Vitale et al., 2017)) or materials (e.g., chemicals in biobased materials (Sotayo et al., 2020)) to realise a circular strategy can outweigh the environmental savings. Carbon savings of circular building strategies are also dependent on specific conditions, such as the number of reuse cycles in design for disassembly (De Wolf et al., 2020; Eberhardt et al., 2019) or the relationship between the environmental impacts from the construction and the impacts saved during operation of the building (Montana et al., 2020). These conditions for realising decarbonisation potential of different circular building strategies have been outside the scope of this paper but are critical for capturing decarbonisation potential of circular strategies in buildings in practice.

Classification of the cases into the categories of narrowing, slowing, closing and regenerating resource loops was done on a case-by-case basis based on the underlying frameworks by Bocken and Gerardts (2022) and Konietzko et al. (2020) and performed interventions described in the case studies (see Section 2.4). This was necessary as no consistent definition of CE applications in buildings exist today, which results in a diverse and rather wide understanding of circular solutions in buildings. In future, CE application in buildings might have a more standardised definition as the introduction of the EU taxonomy is setting metrics and thresholds on what defines a circular building, such as specific recycling percentages (European Commission, 2022).

4.2. Future research and practice

An important research gap arose from the review, namely comparability of decarbonisation potentials, which has hindered recommendations on how to prioritise circular building strategies. A previous study by Gallego-Schmid (2020) reported ranges of reduction potential of strategies of *narrowing, slowing,* and *closing,* compared to each other, but the present study found that applications often incorporated several strategies at once, which hindered identification of the relationship between strategies for *narrowing, slowing, closing,* and *regenerating* and their decarbonisation potential. Instead, this study sought to delve deeper into the application of circular building strategies and provide a critical discussion on the challenges of using LCA for CE assessment in buildings. To advance, both practice and research, consensus and harmonisation of LCA methodology for assessment of circular strategies in buildings is needed at the European level. Also, transparency and clear documentation are indispensable to facilitate the use of LCA results for larger scale analysis that can benefit decision-making and should always be solicited when writing and/or reviewing scientific papers and reports (Miller et al., 2016; Rodriguez et al., 2019).

Future research is needed to identify applications of circular strategies with high decarbonisation potential that are suitable to be implemented beyond a one-time project (e.g., reuse of bricks and steel beams). Limitations of this study could potentially be overcome through a larger sample size, potentially with LCAs from databases of practitioners. Collecting LCAs with disaggregated data - so that missing data, such as LCA modules, could be replaced with statistical averages and reference period and units could be harmonised (Miller et al., 2016; Röck et al., 2022) - could be another research design for future studies. Alternatively, top-down modelling of the impacts of different circular building strategies could provide insights into their decarbonisation potential relative to each other, as the recent study of Zhong et al. (2021) demonstrates.

Practitioners are advised to continue to develop and test circular strategies in building projects and identify the parameters for assessing scalability of high-potential solutions. Needs for policy, market development, and the building development processes of high-potential, scalable solutions should be addressed to roll out CE application in the building industry.

CRediT authorship contribution statement

Julia Nußholz: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Project administration. **Sultan Çetin:** Conceptualization, Investigation, Visualization, Writing – review & editing. **Leonora Eberhardt:** Investigation, Writing – review & editing. **Catherine De Wolf:** Investigation, Writing – review & editing. **Nancy Bocken:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix A: Overview of the 23 cases from academic literature for new build (grouped into the assessment level of products and buildings)

Code	Case Name	Refs.	Type of building	Floor area (m2)	Country	Method and standard	LCA modules included	Lifetime used in LCA
Products								
L-NB1	Prefab floor slab (ETH Zuerich)	Agustí-Juan et al. (2019)	School	n.a.	CH	LCA, EN 15,978	A1-A3, A5, B4	60 years
L-NB2	Wooden roof (Arch_Tech_Lab ETH Zuerich)	Agustí-Juan et al. (2019)	School	n.a.	CH	LCA, EN 15,978	A1-A3, A5, B4	60 years
L-NB3	Floor for disassembly	Brambilla et al. (2019)	Office	2600	UK	LCA, EN 15,804 and EN 15,978	A1–5; C1–3; D	50 years
L-NB4	Reused bricks	Nußholz et al. (2019)	Residential	n.a.	DK	Streamlined LCA	A1-A3	n.a.
L-NB5	Reused window glass	Nußholz et al. (2020)	Residential	n.a.	DK	LCA	A1-A3	n.a.
L-NB6	Upcycled wooden floor	Nußholz et al. (2020)	Residential	n.a.	DK	A-D	A1-A3	n.a.
L-NB7	Recycled steel	Vares et al. (2020)	Industrial	480	FI	LCA, ISO 15,686–5 and EN 16,627	A-C	27 years
L-NB8	Kitchen for adaptability	van Stijn et al. (2021)	Social housing	n.a.	NL	LCA, EN 15,979	A1-A3, B1, C2-C6	80 years
L-NB9	Partition wall for disassembly/ Circular Retrofit Lab	Rajagopalan et al. (2021)	Student housing	n.a.	BE	Circular Building Life Cycle Assessment (CBLCA) - Product Environmental Footprint LCA Method (EN15798)	A-D	60 years
L-NB10	Partition wall for adaptability/ Circular Retrofit Lab	Rajagopalan et al. (2021)	Student housing	n.a.	BE	Circular Building Life Cycle Assessment (CBLCA) - Product Environmental Footprint LCA Method (EN15798)	A-D	60 years
L-NB11	Partition wall for disassembly with wood studs/ Circular Retrofit Lab	Rajagopalan et al. (2021)	Student housing	n.a.	BE	Circular Building Life Cycle Assessment (CBLCA) - Product Environmental Footprint LCA Method (EN15798)	A-D	60 years
L-NB12	Recycled planks	Nußholz et al. (2019)	Residential	n.a.	SE	Streamlined LCA	A1-A3	n.a.
L-NB13	Recycled concrete	Nußholz et al. (2020)	Residential	n.a.	DK	LCA, EN16487	A1-A3	n.a.
L-NB14	Recycled kitchen cabinet	van Stijn et al. (2021)	Social housing	n.a.	NL	LCA, EN 15,978	A1-A3, B1, C2,5,6	80 years
L-NB15	Green facade	Perini et al. (2021)	Residential	n.a	IT	LCA, n.a.	A1-A3	25 years
L-NB16	Wooden facade	Švajlenka and Kozlovská (2017)	Residential	144	SK	LCA, n.a.	A1-A3	n.a.
L-NB23	Recycled Concrete (2)	Mostert et al. (2021)	Office	n.a.	DE	LCA, DIN EN 15,804	A1-A3; C1-C3	n.a.
Buildings								
L-NB17	Disassembly office	Eberhardt et al. (2019)	Office	37,839	DK	LCA, EN 15,978, ISO 14,040, ISO 14,044	A-D	80
L-NB18	Maintenance Free House 1	Rasmussen et al. (2020)	Residential	139	DK	LCA, EN 15,804	A1-A3; B4, B6; C3-C4	120
L-NB19	Maintenance Free House 2	Rasmussen et al. (2020)	Residential	136	DK	LCA, EN 15,804	A1-A3; B4, B6; C3-C4	120
L-NB20	Adaptable House	Rasmussen et al. (2020)	Residential	149	DK	LCA, EN 15,804	A1-A3; B4, B6; C3-C4	120
L-NB21	Upcycle House	Rasmussen et al. (2020)	Residential	134	DK	LCA, EN 15,804	A1-A3; B4, B6; C3-C4	120
L-NB22	Nidus Modular Home	Petcu et al. (2021)	Residential	n.a.	RO	Building models and heating simulation	n.a.	n.a.

Appendix B: Overview of the 15 cases from academic literature for renovation (grouped into LCAs that assess decarbonisation potential compared with the initial state of the building or with demolition and new build)

Code	Name	Refs.	Type of building	Building year	Year of renovation	Floor area (m2)	Country	Assessment method and standard	LCA modules included	Lifetime used in LCA
Initial state										
L-R1	Villa Dammen 1	Berg and Fuglseth (2018)	Historic building	1936	2014–15	n.a.	NO	LCA, NS 14,040:2006 and NS 14,044:2006	n.a.	60 years
L-R2	Villa Elvira	Alba-Rodríguez et al. (2021)	Historic building	1917	n.a.	979	PO	Ecological Footprint and energy simulation software	n.a.	n.a.
L-R3	Pátio do Beirão	Alba-Rodríguez et al. (2021)	Historic building	1890	n.a.	1837	PO	Ecological Footprint and energy simulation software	n.a.	n.a.
L-R4	Pátio do Paulino	Alba-Rodríguez et al. (2021)	Historic building	1871	n.a.	374	PO	Ecological Footprint and energy simulation software	n.a.	n.a.
L-R5	School Trebowiec	Alba-Rodríguez et al. (2021), Michalak et al. (2021)	School	1970	n.a.	981 + 143	PO	Own algorithm	n.a.	n.a.
L-R6	Greek NZEB	Martinopoulos (2018)	Residential	n.a.	n.a.		GR	LCA, EN15316–4–3	A1-A3	15 years (equippment)
L-R7	Politecnico di Milano University	Ferrari and Beccali (2017)	Office	n.a.	n.a.	n.a.	IT	Thermographic analysis, ISO 6781:1983	n.a.	30 years
L-R8	Wiener Wohnen	Sattler and Österreicher (2019)	Residential	1950–70s	n.a.	2522 + 1891	AT	LCA, ISO 14,040	n.a.	100 years
L-R9	Stjernehus	Wrålsen et al. (2018)	Residential, high-rise	1960	ca. 2016	3700	NO	LCA, EN15804 and EN15978	A1-A5; B1, B6; C2, C3, C4; D4	30 years
L-R10	Czech Academy of Sciences	Fořt et al., 2018; Wrålsen et al. (2018)	School	1962	n.a.	5000	CZ	LCA, ISO 14,067, 14,040, 14,044, 14,020, 14,025, 14,067	A1-A3	60 years
L-R11	Atika building/ VELUXlab	Brambilla et al. (2018)	Office building	n.a.	2012	n.a.	IT	Heat flow metre method, Uni Iso 9869 standard; LCA	A1-A3	n.a.
Demolition and new build										
L-R12	Villa Dammen 2	Fufa et al. (2021)	Residential	1936	2015	117	NO	LCA, NS 3720, EN 15,978, ISO 14,044/44,	A1–3, B4, B6, C1–4	60 years
L-R13	Statens Hus Vadsø	Fufa et al. (2021)	Office	1936	2024	4297	NO	LCA, NS 3720, EN 15,978, ISO 14,044/44,	A1–3, B4, C1–4	60 years
L-R14	San Pietro a Maiella e San Giacomo.	Gravagnuolo et al. (2020)	Historic	1332	n.a.	2455	IT	LCA, n.a.	A1–4, B1-B6, C1–4	60 years
L-R15	Sesga House	Mileto et al. (2021)	Historic	1732	n.a.	n.a.	SP	LCA, EN 15,978	A, B5, C1,2,4	50 years

Appendix C: Overview of the 3 cases from academic literature for demolition

Code	Name	Refs.	Type of building	Floor area (m2)	Country	Assessment method and standard	LCA modules included	Lifetime used in LCA
L-D1	Residential demolition 1	Martínez et al. (2013)	Residential	1600	ES	LCA, ISO 14,040:2006	n.a.	n.a.
L-D2	Residential Demoliton 2	Vitale et al. (2017)	Residential (multifamily dwelling of 24 flats)	1550	IT	LCA, n.a.	n.a.	n.a.
L-D3	Residential Demolition 3	Pantini and Rigamonti (2020)	Residential (four buildings)	7000	IT	LCA, ISO 14,040 (2006)	n.a.	n.a.

Appendix D: Overview of the 24 practice cases for new build, renovation, and demolition

Code	Name	Refs.	Country	Type of building	Types of CE strategies	CE strategies	Circular solution	Impact
New Build								
P-NB1	HAUT Timber Tower	ARUP (2017)	NL	Residential	Narrow, slow, close, regenerate	Bio-based materials; design for disassembly; recycled materials	Cross-laminated timber (CLT) high-rise construction, energy producing facade with PV, city heating and local cooling, rainwater capture, bird nests	2500 t CO_2 stored
P-NB2	Juff Nienke	SeARCH (2018)	NL	Residential	Narrow, slow, close, regenerate	Modular design; bio-based materials; material reuse and recycle, bio-based and recycled and low-environmental impact materials	Prefabricated timber modules, completely demountable, adaptable; special planting for biodiversity, green roof, vegetation, area heating system and PV panels; energy-neutral	580 t CO_2 saved
P-NB3	Koning Willem I College	Nieuwe Architecten (2020)	NL	Educational	Slow, regenerate	Bio-based materials, design for disassembly and flexibility	Prefabricated wooden load-bearing structure (locally sourced wood) and concrete floors, adaptable design, energy neutral and PV panels	435 t CO_2 stored
P-NB4	Super Circular Estate (Type A), Kerkrade	Durmisevic (2019)	NL	Residential	Slow, close	Reuse of components and materials	Ca. 90% materials reclaimed from the existing 10-story flat building; recovery of concrete for aggregate in new concrete; reuse of load-bearing structure from deconstruction; reuse of facade, infill walls, doors, brick facade (cut out).	4621 t CO_2 saved
P-NB5	Patch 22	Lemniskade (2015)	NL	Residential (with office spaces)	Slow, regenerate	Bio-based, flexible floor plan	Wooden supporting structure, CO2-neutral wood-fired central heating, energy neutral building	425 t CO^2 stored
P-NB6	The Dutch Mountains	Laudes Foundation and BLOC (2020)	NL	Mixed use	Slow, close, regenerate	Biobased materials, flexible design	Partial wood construction, incl. floors, columns, ceilings and the roof construction	8600 t CO_2 saved; 70% reduction

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Code	Name	Refs.	Country	Type of building	Types of CE strategies	CE strategies	Circular solution	Impact
P-NB7	UMAR Unit (Empa Nest)	Hakkos et al. (2019)	CH	Residential	Slow, close, regenerate	Design for disassembly, modular, reuse, recycled materials	Modular de-constructible frame structure with replaceable wall, floor and roof elements, which are obtained only from reused, recyclable and/or recycled, or compostable materials free of glues, paints, foams or other wet sealants.	39% lower global warming impact
DK.NB8	Ressourcerækkerne	Lendager Group (2020)	DK	Residential	Slow, regenerate	Reuse of components	Reuse of bricks in panels cut out from demolished buildings, green roofs	32% lower embodied carbon
P-NB9	Upcycle Studio	Lendager Group (2020)	DK	Residential	Slow, close	Reuse of components and materials	Reuse of wooden floor, concrete aggregates, window glass	12% lower embodied carbon
P-NB10	Erlev Skole	Arkitema (2021)	DK	School	Regenerate	Bio-based materials	Wooden construction and facade	Total building impact of 8,7 kg CO_2 eq./m^2./ y.
P-NB11	The Cradle	Handelsblatt (2022)	DE	Office	Close, regenerate	Design for disassembly, bio-based materials	Wood structure for disassembly	19 000 t CO_2 captured; 40% reduction
P-NB12	The Flat House	The Prince's Responsible Business Network (2020)	UK	Residential	Slow, regenerate	Modular design; biobased materials; standardisation; design for disassembly,	The main body of the house is constructed out of prefabricated 'hempcrete' panels – a mixture of hemp shiv and lime, based on timber I-joists; The external cladding of the building is a composite material made from the hemp fibre grown on site and sugar-based resin from agricultural waste; reuse of steel frame; off-grid	2,32 t CO_2/ y. captured
P-NB13	Segro Warehouse	Progress (2020)	UK	Warehouse	Slow, close, regenerate	Reuse of components; bio-based materials	Relocation of warehouse building, reusing as much as possible of the original building (e.g., steel frame, concrete beams, ground beams, floors, staircases, lift, doors)	330 t CO_2 saving

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Code	Name	Refs.	Country	Type of building	Types of CE strategies	CE strategies	Circular solution	Impact
P-NB14	Villa Welpeloo	Superuse (2022)	NL	Residential	Slow, close, regenerate	Reuse of components and materials; biobased materials	The load-bearing steel structure reclaimed from a paternoster and textile machine. Wooden façade cladding made of redundant cable reels from near-by cable factory	90% CO^2 reduction of structure
Renovation								
P-R1	Circular renovation Staalmanplein	AEDES (2022)	NL	Residential	Narrow, slow, regenerate	Renovation, reuse of components, bio-based materials	Renovation instead of demolition, reuse of sanitary units from other locations, mechanical connections in the roof bitumen layer, circular kitchens out of biobased materials with modular design	25% CO_2 saved
P-R2	K.118 – Kopfbau Halle 118	Global Holmci Awards (2021)	CH	Mixed use	Narrow, slow	Maintenance, reuse of components and materials	Preserve, ca. 50% (direct) reuse and recycle building components; 50 groups of salvaged components were used, e.g.,. steel beams structural steel beams; granite façade panels for balcony pavers	500 t CO_2 saved
P-R3	Grande Halle De Colombelles	Construction21 (2021a)	FR	Mixed use	Narrow, slow	Maintenance, reuse of components and materials	Material reuse from deconstruction sites in the region: radiators, sanitary facilities, wood, earthenware, windows and fire doors; The original envelope, bearer of memory, consisting of two concrete naves, is preserved and repaired	11.4 t CO_2 saved
P-R4	Project Papillon	Construction21 (2021b)	FR	Office	Narrow, slow	Reuse of components	Reuse of 178 curved glasses and 35 tons of scrap steel from the Centre Pompidou	71,1 t CO_2 saved
P-R5	Heerup Skole	Christensen and Co (2022)	DK	School	Narrow, slow, regenerate	Design for disassembly, low-carbon materials	Cross-laminated timber construction designed for disassembly	211 kg CO_2/m^2 saved; 52% reduction
P-R6	Bakkekammen	Realdania By and Byg (2021)	DK	Historic	Narrow, slow	Energy renovation	Roof insulation, energy optimisation, upgrades of windows, new heating installation.	242 kg CO2/m3 saved; reduction of 98%

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Code	Name	Refs.	Country	Type of building	Types of CE strategies	CE strategies	Circular solution	Impact
P-R7	JLL Landmark Office Manchaster	The Prince's Responsible Business Network (2020)	UK	Office	Narrow, slow	Design for disassembly and flexibility, reuse of components	Flexible space plan through using low tack adhesives to move meeting pods and kitchen island when required; easy conversion of room types; circular procurement of products and reused electronic equipment and furniture.	62,25 t CO_2 saved
P-R8	UCL School of Architecture	Gilbert-Ash (2020)	UK	Education	Narrow, slow	Reuse of components	Reuse of original concrete frame	400 t carbon saved
P-R9	1 Triniton	BBP (2020)	UK	Office	Narrow, slow	Reuse of components and materials	Reuse of components and materials 3300 m^2 of limestone, 35,000 t of concrete and 1900 t of steel	465 kg CO_2 eq./ m^2 saved; 56% reduction
Demolition								
P-D1	Circular demolition of social housing	AEDES (2022)	NL	Residential	Close, slowing	Selective demolition, urban mining	Reuse of radiators, armatures; recycling of bricks, concrete and wooden beams.	650 t CO_2 saved

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