



Timing matters: life cycle embodied GHG emissions of circular building strategies

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ABSTRACT

Circular building strategies (CBS) aim to reduce greenhouse gas (GHG) emissions related to the construction, maintenance and end-of-life of buildings. However, the timing of these reductions, whether immediate or in the future, is often overlooked. Given the urgency of addressing climate change, accounting for the temporal dimension is crucial to understand accurately the decarbonisation effects of CBS. Existing life cycle assessment (LCA) studies on CBS are analysed for the timing of reported reductions and the connected temporal considerations in the model. The analysis of LCA studies ($n = 42$) shows consistent reduction patterns for upstream CBS (e.g. reuse of existing components), but the assessment model includes little temporal detail. The reductions are more inconclusive for downstream CBS (e.g. design for disassembly), and they highly depend on temporal modelling. The findings highlight the need for a consistent LCA framework that accounts for the timing of GHG emission reductions when applying CBS. The identification of when actual GHG reductions occur arising from different circular strategies will aid in the understanding of CBS's role in meeting climate targets.

POLICY RELEVANCE

CBS do not deliver GHG emission reductions equally over time, which has direct implications for policy design and decision-making. CBS acting early in the life cycle (e.g. component reuse) consistently reduce upfront emissions, supporting near-term climate targets. However, downstream CBS (e.g. design for disassembly) produce uncertain or delayed benefits, limiting their effectiveness for urgent decarbonisation goals. Current assessment methods often overlook this temporal dimension, risking misaligned incentives. LCA frameworks should be updated to explicitly report and account for when GHG emissions occur, not just the overall reduction. Additionally, policy frameworks should differentiate between short- and long-term mitigation, aligning subsidies, GHG emission limits, and reporting standards accordingly. Recommendations are provided to support evidence-based decisions and ensure the building sector contributes effectively to near- and long-term climate targets.

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1.1 BACKGROUND

Buildings account for almost 40% of all global greenhouse gas (GHG) emissions (UNEP 2024). Building-related GHG emissions can be divided into operational and embodied emissions (Ibn-Mohammed et al. 2013). The relative importance of embodied GHG emissions has increased throughout the European Union (EU) due to energy regulations improving operational efficiency (Röck et al. 2020). The largest share of embodied emissions occurs upfront during the production of materials, and reducing them is essential for the building sector to meet decarbonisation goals (Röck et al. 2020; Zhong et al. 2021). To address embodied emissions, the Energy Performance of Buildings Directive (EPBD) requires EU member states to introduce limit values for the total life cycle global warming potential of new buildings from 2030 (European Commission 2026).

One approach to reducing embodied emissions is the adoption of a circular economy (CE), through rethinking how materials are sourced, used and repurposed while maintaining the functional requirements of buildings (Pomponi & Moncaster 2017). CE represents a transformation from the traditional linear ‘take, make, dispose’ model to a regenerative system where materials circulate continuously through reduction, reuse and recycling strategies (Ellen MacArthur Foundation n.d.). Circular building strategies (CBS) are defined as practical applications of CE principles in new buildings through a modification of the building design or material choices to narrow, slow, close and regenerate resource loops (Bocken et al. 2016; Nußholz et al. 2023; Wöhler et al. 2024).

Life cycle assessment (LCA) is a standardised method used to assess the environmental impacts of a product, service or system throughout its entire life cycle (ISO 2006a, 2006b). Even though LCA is commonly used to assess the environmental impacts of CBS (Butković et al. 2023), building LCA standards EN 15978 and EN 15804 have been criticised for not fully capturing the effects of circular practices (Andersen & Birkved 2022; Van Gulck et al. 2022). These standards were initially designed for linear, ‘cradle-to-grave’ assessments but not the multicycle ‘cradle-to-cradle’ systems inherent to a CE (Lam et al. 2022). Building LCA is further complicated by the long service life of buildings (Eberhardt et al. 2019) and their complexity, as they consist of many materials and components with different service lives (Nußholz et al. 2023). The introduction of CBS and future life cycles often extends the assessment period even more, which adds complexity and uncertainty (Santoro & van der Feen 2022). These uncertainties can lead to burden-shifting over time, meaning that environmental impacts can be shifted to other life cycle stages or postponed to the future. Given the urgency of global and local climate targets set for the coming decades, knowing the temporal distribution of GHG emissions is crucial. Only by taking the temporal dimension into account can the effectiveness of different CBS for meeting time-bound goals like those set by the Paris Agreement be assessed (Hvid Horup et al. 2024).

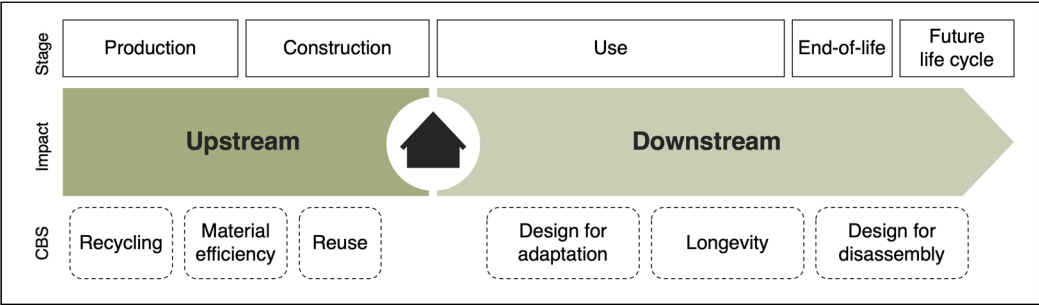
1.2 TIMING OF IMPACT REDUCTIONS IN CBS

The ‘timing’ of impact reductions refers to the temporal position or distribution of emissions within the building life cycle. CBS can be divided into two groups based on the timing of their expected reductions: up- and downstream (De Wolf et al. 2020; Wöhler et al. 2024) (Figure 1). Upstream CBS address the upfront reduction of GHG emissions during the production or construction by improving material efficiency or using secondary materials. Practical examples include prefabrication as well as the use of recycled materials and reused building components. Downstream CBS are design or material adaptations that aim at future reductions of GHG emissions by reducing material and energy input during the use, at the end of life or in future life cycles. Examples include design for adaptation (DfA), durability and low maintenance, as well as design for disassembly (DfD). Such CBS aim at extending service lives and enable future reuse and recycling.

Despite their intended mechanisms, CBS do not always lead to an overall impact reduction. They may cause increased impacts at other stages of the building life cycle. Upstream CBS may result in higher impacts during maintenance or replacements due to shorter material lifespans (Castro & Pasanen 2019), and downstream CBS can increase environmental impacts due to more

complex designs or premature deconstruction, despite the potential for future reuse (De Wolf et al. 2020). The environmental benefits of CBS can also be offset by the impacts of related activities (Nußholz et al. 2023), such as the transportation of heavy materials (Eberhardt 2020), the storage of materials between use cycles (De Wolf et al. 2020), the need for additional materials to enable reuse (Mahdavi pour et al. 2026), and the treatment with chemicals that hinder future applications (Sotayo et al. 2020).

Figure 1: The concept of up- and downstream circular building strategies (CBS) with examples from the analysis.

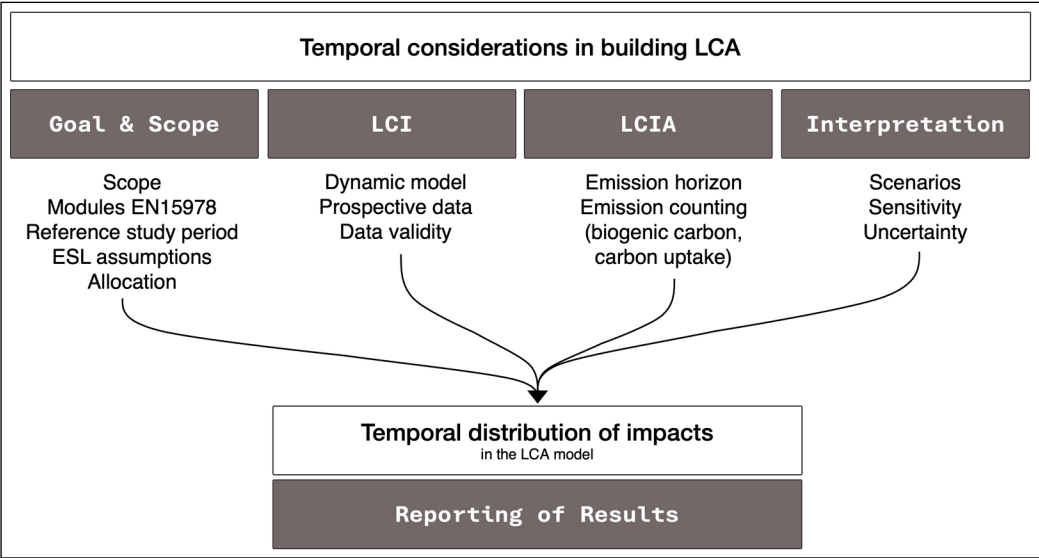


1.3 TEMPORAL CONSIDERATIONS IN BUILDING LCA

Temporal considerations in LCA define how the temporal dimension is modelled and represented within the product system (Beloin-Saint-Pierre et al. 2020; Lueddeckens et al. 2020). They are particularly relevant in building LCA due to the long service lives and complexity of buildings (Lira & da Silva 2025; Negishi et al. 2018). At the time of the assessment, a large share of the building’s life has not yet happened, meaning that building LCA involves assumptions about the timing and duration of processes during the building life cycle and about changes in technologies in the background (Negishi et al. 2018). Figure 2 shows examples for temporal considerations based on the four phases of building LCA; definitions for temporal terms used in this study are available in Appendix A in the supplemental data online.

In Europe, EN 15978 and EN 15804 provide a general framework for temporal considerations in building LCA. While building on a static LCA approach, they structure the life cycle into modules for production, construction, use and end-of-life. For future impacts beyond the first life cycle, the norm introduces module D (Figure 3). EN 15978 requires the definition of a reference study period (RSP) but does not prescribe a value. The norm differs between different types of service life assumptions, such as required (RqSL), estimated (ESL) and reference service life (RSL). Time-related processes during the building’s use, such as component replacements, are subject to scenarios and modelled based on building and component service lives. The norms also define requirements for how the system boundaries and temporal information must be reported.

Figure 2: Temporal considerations in building life cycle assessment (LCA) connected to the four phases.



Results must be disclosed per module of the life cycle, and future impacts are modelled and disclosed separately in module D. However, LCA studies of CBS often extend beyond the first building life cycle to account for multiple life cycles of components, requiring adaptations such as expanded system boundaries and the allocation of impacts (van Stijn et al. 2021). Allocation has not been categorised as a temporal subject in previous LCA research, but rather as a logical problem (Lueddeckens et al. 2020). However, in the context of long-lived systems such as buildings with multiple life cycles, allocation carries an important temporal dimension: it determines how the environmental impacts are distributed not only between two parallel product systems but also between two periods in time (McCann et al. 2025).

1.4 RESEARCH GAP AND AIM

Existing reviews focus on CBS for reducing GHG emissions in buildings (Gallego-Schmid et al. 2020; Nußholz et al. 2023). While they identify potential GHG savings of up to 99%, they do not evaluate when these reductions occur in the building life cycle. Furthermore, they describe methodological differences, which make it difficult to compare results and draw general conclusions. Other reviews on building CE-LCA analyse how circularity is assessed in building LCA, but do not specifically focus on temporal considerations and how they influence the results (Andersen et al. 2022; Hossain & Ng 2018; Lei et al. 2021). Consequently, there is limited understanding of when GHG reductions from CBS occur (Butković et al. 2023) and how temporal considerations affect the model and results of LCA studies of CBS (Fnais et al. 2022; Lei et al. 2021).

The aim of this study is to investigate how temporal considerations are addressed in LCA case studies on CBS and how they are related to the reported embodied GHG emission reductions across the building life cycle. Three research questions are formulated:

- RQ1: How are temporal considerations and assumptions addressed in LCA studies of CBS?
- RQ2: When do CBS reduce GHG emissions across the building life cycle?
- RQ3: How do temporal considerations influence the timing of GHG emission reductions?

Based on a review of academic LCA case studies, the temporal dimension in comparative LCAs on CBS for new buildings is explored. First, temporal considerations and assumptions such as the temporal approach, the temporal scope (RSP, ESL) and the modelling of future processes are analysed. This is followed by a qualitative assessment of reported GHG emission reductions across the building life cycle based on stages and modules of EN 15978 (Figure 3).

Production			Construction		Use							End of Life				Beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Production	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use*	Operational water use*	Demolition	Transport	Waste Management	Disposal	Reuse Recovery Recycling

* excluded from analysis

Figure 3: Life cycle modules from EN 15978 used for the analysis.

The scope of the review is limited to European and new construction cases to ensure consistency. The European focus reflects both LCA and building practice within the European regulatory and methodological context. Limiting the review to new construction provides a consistent reference context in line with regulations on new building emission reductions as prescribed by the EPBD. Renovation, adaptive reuse and demolition projects are excluded because their ‘existing building’ perspective introduces a different temporal and methodological context that is not directly comparable with new construction (McCann et al. 2025; Zimmermann et al. 2023).

2.1 RETRIEVAL OF RELEVANT CASE STUDIES

Existing LCA studies comparing CBS with conventional scenarios were identified through a systematic literature search and complemented by snowballing of existing reviews on CE-LCA case studies. The literature search was conducted on Scopus in early August 2026 and targeted journal and conference articles in English which used titles, abstracts and keywords with terms related to LCA, CE, case studies and buildings (see the search string in [Figure 4](#)). The search yielded 293 records. As the literature on building CE-LCA case studies uses broad terminology, relevant studies can be difficult to identify through database searches alone. Therefore, the search was supplemented by snowballing three articles known to contain European LCA case studies on CBS: Gallego-Schmid et al. (2020), Nußholz et al. (2023) and Andersen et al. (2022).

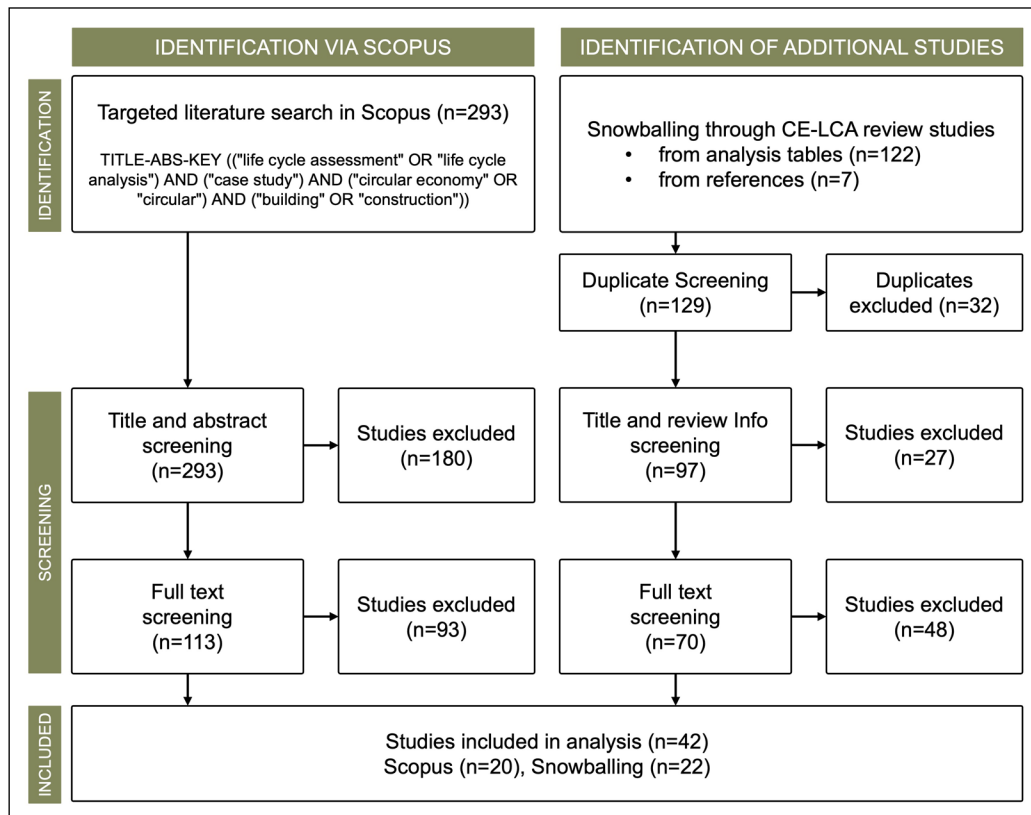


Figure 4: Literature search and screening stages.

2.2 FILTERING AND SELECTION OF STUDIES BASED ON DEFINED CRITERIA

The records identified through both approaches were first checked for duplicates and then screened in two stages according to the predefined inclusion criteria ([Table 1](#) and [Figure 4](#)). First, titles and abstracts were checked to identify potentially relevant studies. Information reported in the snowballed reviews was used as supplementary information during the review. Studies that appeared to meet the inclusion criteria, or for which eligibility could not be determined from the title and abstract, were retained for full-text assessment. Second, the full texts, including tables and figures, were assessed according to the criteria. The final sample consisted of 42 LCA studies.

2.3 ANALYSIS OF THE LCA METHOD AND RESULTS

An inductive qualitative content analysis was conducted on the 42 studies to identify patterns and synthesise methodologies. The analysis follows an iterative coding approach where categories are developed and refined throughout the process. The aim is to understand each LCA study in terms of CBS and comparison systems, temporal considerations, temporal resolution and distribution of the results.

CRITERIA	INCLUDE	EXCLUDE
Type	LCA (environmental)	Reviews, other modelling approaches such as material flow analysis, life cycle costing, social LCA or energy modelling; studies using secondary environmental data without describing a full LCA methodology
Studied object	CBS case studies, including material efficiency, reuse, recycling, DfD, DfA, longevity and combinations of strategies for new construction	Methodology or end-of-life studies without a described CBS case; regenerative strategies (biobased versus other material); infrastructure and other non-building cases; demolition, renovation or adaptive reuse
Geography	European case	Cases outside Europe
Scale	Material, component, building	Urban, region, country; sector, industry
Impact	GHG emissions results	Other emissions or grouped results
LCA character	Comparative (CBS versus linear alternative)	Non-comparative (reporting emissions without a direct comparison)

Table 1: Inclusion criteria and examples of excluded studies.

Note: CBS = circular building strategies; DfA = design for adaptation; DfD = design for disassembly; GHG = greenhouse gas; LCA = life cycle assessment.

The analysis is divided into study and case levels. The study-level analysis focused on the general LCA methodology and temporal considerations included in each study. The case-level analysis focused on reported GHG emission reductions. This distinction was necessary because some LCA studies presented several comparative cases with varying results based on different CBS categories. Where studies compared different design or material variations of a CBS or conventional system, the case with the most comparable material composition was included in the case-level analysis. This approach was applied to minimise the influence of secondary reduction strategies, such as material substitution (e.g. comparing a DfD wooden component with a conventional concrete component), and to better isolate the impact of the CBS itself. Methodological scenarios, such as different numbers of life cycles or alternative end-of-life scenarios, were not considered as separate cases but noted as scenarios or sensitivity. The 42 studies provide 62 individual cases (see Appendix D in the supplemental data online). Most studies delivered a single case, while the remaining studies provided between two and five cases. One conference paper (S07) is not included in the case-level analysis as the results provided in the Appendix online are identical to the connected journal publication (S08).

The raw information from each study was coded into categories. This was necessary as studies used different terminology and definitions. The coding process covered the CBS, assessment level, scope and temporal considerations. Where terminology differed between studies, the information was assigned to the corresponding category based on the definitions and descriptions by the authors.

3. RESULTS

3.1 TEMPORAL CONSIDERATIONS IN THE STUDIES (RQ1)

The general characteristics of the 42 reviewed studies are presented in Appendix B in the supplemental data online. The included studies covered a wide range of circular approaches, which were categorised based on the CBS definitions given in Appendix A online. The CBS were assessed at three different levels: material, component and building. To support the analysis, the studies were grouped according to the impact perspective of the assessed CBS (as described in Section 1.2), distinguishing between up- and downstream perspectives. Studies on multiple CBS cases with different impact perspectives were classified as having a ‘combined’ perspective. The following subsections address different aspects of the temporal dimension in building CE-LCA. For a detailed overview of the underlying data, see Appendix C in the supplemental data online.

3.1.1 Temporal approach

The majority of studies included in the review apply a static LCA approach. Only four apply dynamic or prospective models, all with a downstream perspective. Two studies on DfD model the LCA

dynamically and base their calculation on prospective data or scenarios (S01, S12). The other two studies (S07, S08) consider both retrospective and prospective marginal suppliers within a consequential LCA. The latter two studies share the same first author and report identical results.

3.1.2 System boundary

The studies defined and reported the system boundaries using EN 15978 information modules or descriptive terms without referring to a specific module. The analysis information provided in figures, tables and descriptions in the text reveals three main groups of system boundaries: 15 studies assessing only upfront impacts (stage A), eight studies assessing one life cycle (stages A–C) and 19 studies extending the assessment beyond the first life cycle, either through module D or system expansion. Some studies present more than one system boundary (S02, S20, S32), e.g. as different parts of the assessment or for different CBS cases. The main calculation scope is used for categorisation, or if no main scope could be identified, the maximum scope is used. Figure 5 shows that about 70% of downstream studies extend the system boundary beyond the first life cycle, and more than 80% of the upstream studies only include upfront impacts.

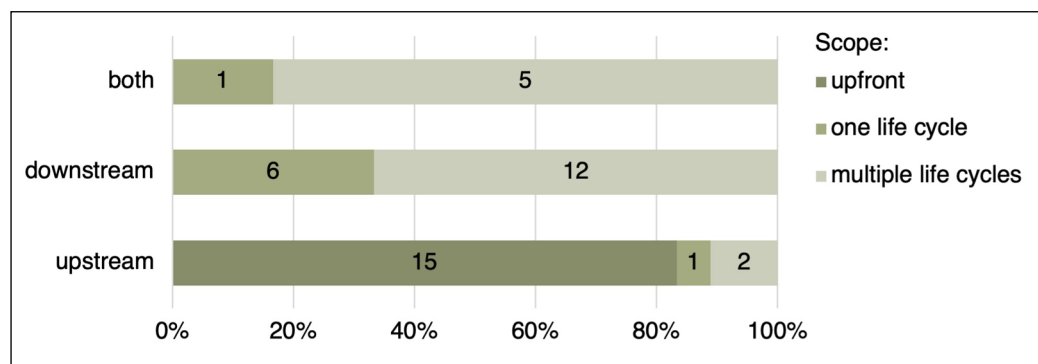


Figure 5: Scope in relation to the impact perspective of the studies.

Among the 24 studies using the EN 15978 modular framework to define their scope, all report the product stages A1–A3 as included. The construction stage modules A4 and A5 were also frequently included, whereas coverage of the use stage was more limited, except for module B4. End-of-life modules were more commonly assessed, particularly modules C3 and C4, and some studies also included module D (Figure 6). The application and reporting of life cycle modules were consistent across 16 of 24 studies, while inconsistencies between the stated scope and the further assessment were identified in eight studies. Inconsistencies included differences between the modules reported as included or excluded and those presented in the results (S18, S22). In other cases, modules were reported for individual parts of the analysis (S20, S26, S27) or were included only for specific CBS scenarios rather than consistently across all scenarios and alternatives (S32, S33; marked as conditional in Figure 6).

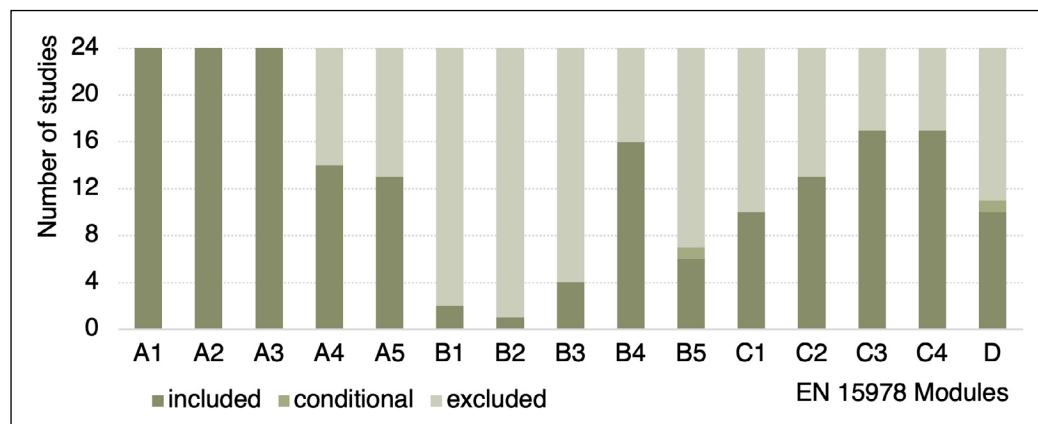


Figure 6: EN 15978 modules explicitly included in the life cycle assessment (LCA) studies.

3.1.3 Temporal scope and replacement modelling

While the system boundary determines the included modules and stages, the temporal scope sets the time horizon and temporal positioning of the processes and impacts within that system. In building LCA, temporal scope can be reflected in the functional unit (FU), the RSP and ESL of buildings and components.

Only 16 studies use temporal information in their FU. A total of 12 included a reference period and four expressed the FU/year. Among the 22 studies using a non-temporal FU, 13 assessed only upfront impacts, three assessed a full life cycle and six assessed multiple life cycles. The RSP was explicitly defined in 14 studies and implicitly based on the ESL within the model in 11 studies. The remaining 17 studies did not apply an RSP, of which 16 have an upstream and one a downstream perspective (S04). Only one study focusing exclusively on upstream CBS defines an RSP (S41). The applied RSPs ranged from 27 to 200 years (Figure 7). A 60-year RSP was most frequently used, followed by 100 years. The length of the RSP also varied in relation to the assessed scope. Studies assessing multiple life cycles generally used longer or multiple RSPs.

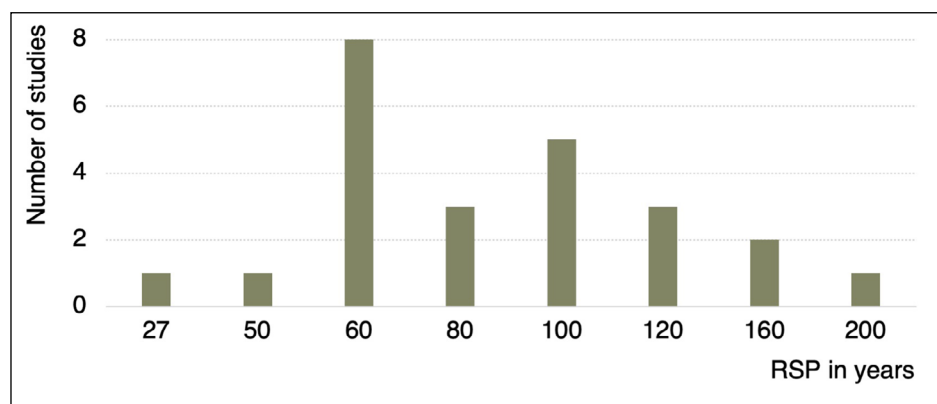


Figure 7: Distribution of reference study period (RSP) choices in the studies, ranging from 27 to 200 years.

Note: For studies using several RSPs, the maximum value was considered.

Of 27 studies including future processes beyond stage A, 18 included replacement processes during the use stage, while nine did not. Among the studies including replacement processes, eight reported replacements using module B4, while seven included both B4 and B5. In three studies, the relevant module was not clearly defined. The timing of replacements was commonly based on component-specific ESLs or fixed replacement periods, which often were connected to refurbishments in B5. The references used to define ESL assumptions vary between studies, based on their geographical context and scale. Not all studies provide exact references to their ESL choices. For buildings, national or international frameworks and guidelines, such as Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB), the European sustainability evaluation framework Level(s) (European Commission n.d.), The Royal Institution of Chartered Surveyors (RICS) or references from the literature are usually used. For individual components or materials, ESL values are typically based on manufacturer information, Environmental Product Declarations (EPDs) (EPD International n.d.), technical reports or previous LCA studies.

3.1.4 Temporal sensitivity and temporal resolution of the results

Of 27 studies including future impacts, 14 test their temporal considerations through scenarios, sensitivity or uncertainty assessments, while 13 do not test them. Of studies performing such checks, eight assessed different RSP or ESL assumptions, four varied the number of included life cycles, one tested different refurbishment rates and four applied variations in their background data. Most of these studies considered more than one type of sensitivity or scenario.

Overall, the reported results carried limited temporal information and had a low temporal resolution (Figure 8). Many studies represent time in their results only indirectly through EN 15978 modules or stages, which indicate when emissions occur but do not resolve them temporally. A total of 15 studies only presented upfront impacts, with no temporal detail. However, 11 studies including future processes also report their results without temporal detail. In these studies, impacts are either aggregated into a single value or allocated across several life cycles, thereby obscuring the timing of the reported impacts in both cases.

Only eight studies present a dedicated temporal distribution chart for the RSP, either as their main result chart (S12, S15) or as an additional presentation. However, in three studies, the distribution chart is affected by allocation (S13, S14, S39), hiding the actual timing of impacts. Also, stored or delayed emissions affect the results. Biogenic carbon, for example, was explicitly included in eight studies and excluded in six. The remaining studies did not state clearly if biogenic carbon was included or excluded from the results.

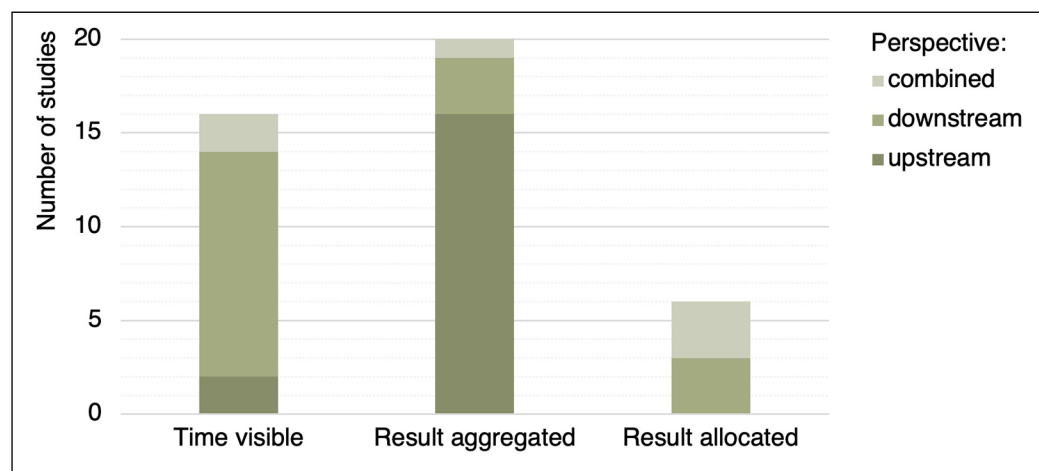


Figure 8: Result aggregation of the studies in relation to their impact perspective.

3.2 TIMING OF IMPACT REDUCTIONS (RQ2)

The timing of impact reductions in the results is analysed at the case level. Reductions differ for each individual CBS case in relation to the corresponding conventional system. Of the 62 retrieved cases, 44 were included in the analysis based on the level of resolution provided in the reported GHG emission results (analysed at the study level in Section 3.1.4). In 18 individual cases, the results are only reported in aggregated or allocated form, allowing no breakdown into modules or stages. The results carry no information on when impact reductions occur and were therefore excluded from the case-level analysis.

To examine how GHG reductions were distributed across the building life cycle, the reported relative impact changes were coded as a reduction (R), increase (I) or no change (=) for each EN 15978 module covering embodied impacts (A1–D). The resulting reduction matrix covers 44 cases grouped by their impact perspective as up- and downstream CBS (Table 2). Blank cells indicate that the module was either not reported or not included in the results. The reported results were noted at the aggregation level at which they were presented in the studies. Where results were reported for a specific module, the corresponding module was noted in the reduction matrix. Where no exact module was available, aggregated results were retained based on several modules (e.g. C2–C3), the relevant life cycle stage (e.g. A1–A3, A4–A5, B–D) or a combination of stages (e.g. A1–A5). This approach preserves the information provided by the studies. The matrix allows the analysis of the direction of change across life cycle modules or stages without treating the results with different system boundaries as directly comparable. For the studies that did not use the modular breakdown but reported clear stages for several cycles, all impacts of the second life cycle were included as module D (S12_C01, S15).

The patterns visible in Table 2 follow and support the categorisation in up- and downstream cases. Upstream cases ($n = 27$) showed a strongly concentrated pattern, with the reported effects occurring predominantly at the product stage (A1–A3). Reductions at this stage dominated the reported cases, while results for subsequent life cycle stages were in many cases excluded from the assessment. The cases including the end-of-life stage predominantly reported increased impacts or no changes, and module D shows mostly an increase in GHG emissions. Downstream cases ($n = 17$) showed a more distributed but uneven pattern, but all studies included the end-of-life impacts. Impacts were also reported during the use stage, especially for B4, but with inconclusive results. The only consistent pattern showed module D, which exclusively reported impact reductions.

	NUMBER	CBS	RESULT	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Upstream	S03_C01	Recycling	Modules		R											=		I
	S03_C02	Reuse	Modules		R											=		I
	S03_C03	Reuse	Modules		R											=		I
	S03_C04	Recycling	Modules		R											I		I
	S03_C05	Reuse	Modules		R											I		=
	S06_C01	Reuse	upfront only		R													
	S10_C01	Recycling	upfront only		R													
	S10_C02	Recycling	upfront only		I													
	S11_C01	Recycling	upfront only		R													
	S11_C02	Recycling	upfront only		I													
	S17_C01	Recycling	upfront only		R													
	S21_C01	Reuse	upfront only		R													
	S23_C01	Recycling	upfront only		I													
	S24_C01	Recycling	upfront only		R													
	S25_C01	Recycling	upfront only		R													
	S26_C01	Recycling	upfront only		R													
	S26_C02	Recycling	upfront only		I													
	S26_C03	Recycling	upfront only		I													
	S27_C01	Recycling	upfront only		R													
	S31_C01	Recycling	upfront only		R													
	S32_C01	Reuse	Modules		R							R				=	=	
	S33_C01	Reuse	Modules		R							R				I		
	S34_C01	Reuse	upfront only		R													
	S36_C01	Recycling	upfront only		R													
	S38_C01	Recycling	upfront only		R													
	S41_C01	Reuse	Modules		R		I							=				I
	S42_C01	Recycling	upfront only		R													
Downstream	S01_C01	DfD	Modules		=		=					R				R		R
	S05_C01	DfD	Modules		I		I	R						I	R		=	R
	S08_C01	DfD	Stages			I					R	I	R			R		
	S09_C01	DfD	Modules		I		I	I			R	R				I	R	R
	S12_C01	DfD	Stages			R										=		R
	S15_C01	DfD	Stages			R										=		R
	S15_C02	DfD	Stages			=										I		R
	S15_C03	DfD	Stages			=										I		R
	S16_C01	DfD	Modules		R		R	R				I				R	I	R
	S19_C01	DfD	Modules		R		R	=				I				R	R	R
	S20_C01	DfD	Modules		R		R	R				R				R	R	R
	S22_C01	DfD	Stages			=						R				=		
	S32_C02	DfD	Modules		I							I					R	R
	S33_C02	Longevity	Modules		R							R					I	
	S33_C03	Longevity	Modules		R							R					I	
	S33_C04	DfA	Modules		R							I	R				R	
	S37_C01	DfD	Modules		I		I	R				I				R	R	=

Table 2: Timing of impact reduction: matrix for 44 circular building strategies (CBS) cases based on modules of EN 15978.

Note: DfA = design for adaptation; DfD = design for disassembly; I = increase; R = reduction; '=' is no change; blank cell = module was either not reported or not included in the results.

3.3.1 Upstream impact

Studies on upstream CBS generally included little temporal information in the model. Most did not define a temporal FU or RSP. The narrow system boundary represents only the impacts of production at one point in time, rather than the impact of the system over its full life cycle. The few cases that included modules beyond the upfront production tend to show higher emissions during end-of-life modules (S03, S32, S33, S41), demonstrating that the absence of future life cycle stages does not equal the absence of future impacts. Biogenic carbon accounting confirms the limitations of a production-only scope: for biogenic materials assessed cradle-to-gate, the uptake of biogenic carbon is included while its release at end-of-life is excluded. Excluding later stages may therefore overlook the full temporal development of biogenic carbon flows and overestimate overall reductions (Andersen et al. 2024).

When upstream CBS are assessed within the same comparative LCA as downstream CBS, the system boundary is usually extended, and the temporal assumptions are better defined. Some studies comparing different CBS perspectives account for the possibility of a shorter ESL for reused components (S39, S40), which heavily affects the overall reductions. No study focusing entirely on upstream CBS applies such an ESL sensitivity assessment.

The reduction pattern assumes that the main benefit of recycling and reuse occurs in A1–A3: producing virgin materials is avoided by using secondary materials, but this does not automatically lead to GHG reductions. The reduction depends on the material composition and the processes required to implement the CBS. For example, aggregate recycling can change the cement content, which can strongly influence and even reverse the outcome (S10, S11). Changes in transport or processing, as well as over-dimensioning of reused components, can similarly reduce or reverse the expected benefit (S06, S21, S26, S41). This shows that environmental performance cannot be attributed to the CBS alone: it depends on what material or system is replaced and the additional processes required to achieve circularity.

Overall, the results indicate that the limited scope and non-temporal model applied in many upstream LCAs may be sufficient to capture part of the intended mechanism of CBS. However, this also means that future impacts of replacement and end-of-life remain invisible. The reported results should therefore be understood in relation to the selected system boundary, rather than as directly transferable to the complete life cycle of the material or component.

3.3.2 Downstream impact

In contrast to the early reductions of upstream cases, the reductions of downstream CBS are linked to emissions that may be avoided in future by extending a component's ESL or enabling its subsequent reuse. In longevity and DfA cases, extending the ESL of a system can avoid one or more replacement cycles of the whole system: the longer the ESL, the more replacement events can potentially be avoided. What differs between these cases is how the ESL is extended: through durable materials in longevity cases (S33: C02, C03) or by enabling adaptations within the system in DfA cases (S33_C04). This is further supported by the model descriptions of studies not included in the modular reduction analysis (S14, S39, S40).

For reuse-enabling CBS such as DfD, the reduction depends on the component having a sufficiently long ESL to reach a reuse event and is only realised when the component is actually recovered and reused. Depending on the system boundary and assessment level, DfD-related reductions were reported either in module B4 (S22) or module D (S05, S19) or both (S01, S20). This shows that the same CBS can result in different reduction patterns depending on the system boundary and assessment level. Scenario and sensitivity analyses further reveal that the results of downstream CBS can vary substantially depending on assumptions about ESL and future reuse events (S14, S22, S39).

This illustrates that the intended reduction mechanism of downstream CBS is closely linked to the temporal modelling and that assumptions are necessary to represent the intended mechanisms. However, an increased need for temporal modelling does not automatically result in transparent, clear and consistent temporal assumptions. Studies often use long assessment periods without clearly defining the RSP and ESL as prescribed in LCA standards. For new buildings, ESL assumptions are inherently prospective and therefore uncertain. The same applies to assumptions about whether a component will be demounted, whether it will replace a primary component, and whether future infrastructure and markets will support the circular pathway.

While many downstream studies include scenarios to accommodate such uncertainties, these do not always test the full range of possible futures: comparing two life cycles against three does not show what happens if no reuse occurs at all (S13, S18). The absence of a realistic no-reuse scenario makes it difficult to determine how much of the reported reduction is dependent on the assumption that the circular pathway will be realised. This concern grows as the temporal scope increases. The timing and uncertainty of the future processes are important parts of the result and should be evenly disclosed for all scenarios.

The analysis also reveals a discrepancy between a high temporal detail in downstream models and a low temporal resolution of the results. Many studies use detailed temporal models with different ESL scenarios, replacement assumptions and future life cycles. However, if the final results are reported as a single total value or subject to allocation, the results become non-temporal and the temporal assumptions are not visible (S04, S13, S14, S18, S28, S30, etc.). This makes it difficult to distinguish which share of a reported reduction is relatively certain and which depends strongly on assumptions about future processes.

Findings from dynamic and prospective LCAs further support the importance of accounting for uncertainty in future processes (S01, S12). These studies show that future emissions can change as background systems develop, and that static approaches may overestimate reductions from future processes by relying on static data based on today's technical standards and energy systems. A large reduction reported for a downstream CBS should therefore not automatically be interpreted as a reduction that will occur to the same extent in practice.

To improve comparability between systems and include technical advance, other authors recommend the application of scientific scenarios such as shared socio-economic pathways (SSPs) (Bruhn et al. 2023; Abu-Ghaida et al. 2025). SSPs describe possible future developments, such as population growth, economic development and societal change, and can be used to improve the modelling of future impacts.

4. DISCUSSION

4.1 DISCUSSION OF THE RESULTS

4.1.1 Absolute and relative timing

The timing of reductions reported in Section 3.2 is relative within each study's own temporal scope. The timing indicates when reductions occur in relation to the reference period, building lifespan or other temporal boundaries selected by the respective study. This provides a consistent basis for understanding the temporal distribution of impacts within individual studies. The beginning and end of the temporal scope differ between studies and are often not disclosed, especially since not all cases describe real-world applications of CBS. However, such relative timing should not be confused with absolute timing against a calendar, which is relevant for time-bound climate mitigation targets set for a specific year.

4.1.2 Temporal allocation of impacts

In some downstream studies, the lifetime of the assessed building or system is substantially longer than the RSP (S13, S35), which creates a need to allocate impacts between different life cycles or between the assessed and subsequent systems. The allocation method determines how the environmental impacts and benefits associated with future use are distributed between life cycles.

In some studies, allocation approaches were selected to ‘incentivise’ a specific CBS (S14, S18, S35, S39, S40). While this may support the purpose of promoting circularity, it can also influence the temporal representativeness of the result, as future reductions might be allocated to the first life cycle. This does not mean that the underlying process responsible for the impact occurs at that point in time, leading to a discrepancy between the reported result and the physical timing of the environmental benefit. A downstream CBS may create the possibility of future reuse, but the associated avoided production may occur many years later. Allocation can therefore affect both the magnitude and the temporal interpretation of the reported reduction.

4.1.3 Relative reductions and comparability

Reductions in GHG emissions are described by comparing a CBS with a conventional alternative. The comparability of circular and linear systems differed between cases and was assessed based on the comparable building functions, system boundaries and material compositions. Upstream CBS are more often assessed at the material or component level, which makes it easier to define relatively similar functions and materials. For example, a recycled or reused material can be compared with a new material of the same kind (S03, S26, S41). A clearly defined FU and fairer comparison can make it easier to isolate the effect of the CBS. Adding a temporal scope would also show a possible difference in lifetimes of the circular and linear system. Downstream CBS are more frequently assessed at the component, assembly or building level, allowing studies to capture them as design concepts rather than as isolated material changes. This also makes it harder to isolate the effect of the CBS itself. A DfD building may also incorporate material substitution, secondary materials or other design changes. The reported reduction can therefore reflect the combined effect of several strategies rather than DfD alone. In some cases, the effect was even mainly based on secondary strategies, such as comparing a wooden building with a concrete building (S16). To allow conclusions to be made on the effect of the CBS itself, it is important to assess the impacts individually at a level that allows disaggregation. However, comparing and evaluating CBS at the building level is essential for both up- and downstream CBS to assess the magnitude of reductions. CBS-related reductions and how they can contribute to meeting decarbonisation targets are always context dependent.

The impact reduction also depends on the often implicit but hypothetical scenario made for the comparison system. In downstream cases, the conventional system is typically assumed to be demolished and replaced at the end-of-life, while the circular system is assumed to enable future reuse or an extended ESL. However, there is a possibility that the conventional building will also be renovated or that conventional components are reused as well, which remains unconsidered. These assumptions for linear references directly determine the reduction potential and should be treated as explicit modelling choices rather than implicit defaults.

4.1.4 Inconsistency of terms and definitions

Understanding the temporal considerations of the reviewed studies is difficult due to the inconsistent use of terminology and definitions. The RSP is not always explicitly referred to as ‘reference study period’ but described using related terms such as ‘assessment period’ and often just indirectly based on the system’s ESL. Contrary, one study on recycling explicitly defines an RSP of 100 years but considers only upfront impacts and does not actually ‘use’ the RSP itself (S23). Also, service life assumptions are frequently reported without using the terminology proposed in EN 15978. Instead, terms such as ‘service life’, ‘lifetime’, ‘lifespan’, ‘design life’ or ‘expected lifetime’ were used, sometimes without disclosing what the assumption is based on.

Inconsistencies are also observed in the definition of system boundaries. The general scope of the assessments is commonly described using the ‘cradle-to’ terminology, but the processes and life cycle modules included within a given system boundary varied between studies. Two material-level LCA studies on recycling are described as ‘cradle-to-grave’, but one only includes production (S10) and another includes production and final disposal (S29). Although terms such as ‘cradle-to-grave’ suggest a unified system boundary, it is common that specific modules are excluded from the analysis. This supports the importance of clearly defining system boundaries, temporal scope, and other key parameters when assessing and comparing CBS-related environmental benefits.

The analysis indicates that GHG reduction claims of CBS should not be evaluated only based on the magnitude of their cumulative results. The comparison system and temporal dimension of the study are integral to the results. Making temporal considerations explicit in the model and improving the temporal resolution of the results would improve comparability between studies and provide a better basis for interpreting the reductions attributed to CBS.

The recently published EN 15978:2026 addresses some of the challenges identified in this study. Compared with the previous version, the revision improves the application to circular systems by explicitly defining reuse processes and by providing more detailed categories in module D and additional information for modelling future reuse and recycling. The norm strengthens requirements for defining the RSP, system boundaries and scenarios during the building life cycle. While still based on a static approach, it addresses technical progress and prospective scenarios, as well as biogenic carbon and carbon storage. Results should be reported by life cycle module, with module D reported separately.

Although the revised norm provides an important baseline for improving transparency and comparability in CE-LCA, it does not address the temporal resolution of the results beyond modules and uncertainties associated with replacement cycles during B4 and B5. While module D is excluded from the scope, B4 impacts are within the system boundary even though they involve a similar level of uncertainty. To improve transparency and consistency of the temporal dimension in comparative CE-LCA, recommendations for a standardised reporting framework are suggested in [Table 3](#).

RECOMMENDATION	PERSPECTIVE	DESCRIPTION
Define the reference study period (RSP)	Up- and downstream	Explicitly define and justify the RSP to distinguish it from the estimated service life (ESL)
Extend the scope	Upstream	Extend the assessed scope beyond upfront impacts to assess potential burden-shifting
State modules	Up- and downstream	State clearly which processes are included and excluded in the LCA through EN 15978 and apply consistently throughout the LCA
Assess uncertainty and sensitivity	Up- and downstream	Include wider sensitivity ranges for estimated service life (ESL), replacement frequency and number of life cycles, including plausible worst-case scenarios
Scientific future scenarios	Downstream	For long-term assessments, use scientifically supported scenarios, such as shared socio-economic pathways (SSPs), rather than relying only on study-specific assumptions
Disaggregate the results	Up- and downstream	Complement cumulative greenhouse gases (GHG) reductions with the standardised modular result framework in EN 15978
Include temporal distribution	Up- and downstream	Use temporal distribution charts covering the whole assessment period to add temporal resolution to the results before applying temporal allocation
Explicit allocation	Downstream	Clearly state and justify the allocation method used to calculate the headline reduction and report the results before applying time-relevant allocation
Mark uncertain results	Downstream	Clearly separate reductions that occur during production and construction from reductions that depend on uncertain future processes, also for reductions resulting from replacement and refurbishment scenarios within the life cycle

Table 3: Recommendations for temporal considerations in comparative life cycle assessment (LCA) on circular building strategies (CBS).

4.3 LIMITATIONS

As the topics ‘circular economy’ and ‘life cycle assessment’ are commonly discussed in building research, it is a challenge to construct a search string that sufficiently captures relevant studies while avoiding a large proportion of irrelevant results. To address this, the search is intentionally narrowed by including the term ‘case study’. To still include relevant studies that did not explicitly use this term, snowballing was conducted on relevant review studies on CE-LCA. This approach identified

additional studies not captured through the database search. The scope of the review was limited to European new-building LCA case studies reporting GHG emissions comparatively for a CBS and a conventional system (Table 1). These criteria improve consistency of the dataset, but the results should not be generalised beyond the applied context. Regenerative strategies were excluded from the study, meaning that the analysis does not cover all potential approaches to circular buildings. Renovation and adaptive reuse studies were also excluded, even though this topic engages with similar questions as the CBS applied to new buildings. While temporal considerations in biobased LCA have been explored in previous research (Andersen et al. 2024), future research should explore the temporal dimension of renovation or adaptive reuse in relation to new building CBS. The focus on GHG emissions is in line with the topic of climate goals, but is narrow, as CBS might lead to trade-offs in other impact categories, which offers another possibility for future extension.

Several limitations affect the interpretation of the analysis. The included LCA studies differ considerably in their aims. While many were formulated as comparative LCA studies, others focused primarily on methodology development, using the comparative case mainly as a means of verification. Because the review targeted scientific LCA studies, the methodologies employed are often experimental and do not follow the standard modelling and reporting structures set out in LCA norms. The findings should therefore in future be verified through practical LCA assessments. Due to different terms and formulations used in the source studies, the coding required interpretation of the definitions, systems and modelling approaches used in each study. CBS were categorised according to their main circular approach for analytical purposes. However, a clear distinction between up- and downstream strategies is not always possible, as individual cases combine multiple circular strategies. For example, two material-efficiency cases (S02) assume an extended service life and should therefore not be interpreted as upstream, despite the underlying CBS category. Similarly, some DfD cases (S14_CO2, S20) also incorporate secondary materials, making it difficult to isolate the effects of the downstream strategy alone. Overall, the heterogeneity of the available literature limits the extent to which the findings can be directly analysed, compared or generalised. The results should therefore primarily be understood as a qualitative synthesis of temporal considerations in existing LCA research on CBS.

5. CONCLUSIONS

Introducing circular building strategies (CBS) is commonly seen as one promising way to reduce the high greenhouse gases (GHG) emissions related to the built environment. While many studies have analysed the effects of CBS through life cycle assessment (LCA), there is a significant research gap regarding the temporal considerations and how these considerations influence the temporal distribution of the results.

This study reviewed 42 LCA studies on how they applied temporal considerations and how these are connected to the timing of GHG reductions in the results of specific CBS cases. The findings show that the temporal dimension is not only a methodological detail, but often is the main factor in modelling the processes that lead to impact reductions. The level of temporal information included in the assessment varies. While LCA studies on upstream CBS tend to have a short temporal scope and exclude temporal considerations, studies on downstream CBS often have a long temporal scope and include many temporal assumptions. The analysis also reveals that the temporal information is often lost in the results, as impacts are aggregated over the life cycle or allocated between life cycles to incentivise a specific CBS case.

For climate-change mitigation, the timing of emissions and reductions matters because near- and long-term changes in atmospheric GHG concentrations have different implications. Two CBS can have similar cumulative GHG totals over a long reference period while having substantially different temporal emission profiles over that period. Considering the need to drastically reduce GHG emissions quickly to stay within the GHG emission budget to limit global warming to well below 2°C, this timing is crucial. This study advances the LCA of buildings by demonstrating the importance of accounting for time in circular economy (CE)-LCA models and result-reporting. It also provides recommendations to improve the consistency, transparency and comparability of temporal considerations in future studies.

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AI DECLARATION

The research and writing are the authors' work and were not generated or written by programs using artificial intelligence (AI).

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COMPETING INTERESTS

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SUPPLEMENTAL DATA

Supplemental data containing Appendices A–D for this article can be accessed at: <https://doi.org/10.5334/bc.829.s1>

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