NIST Special Publication
NIST SP 1324

Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles

An Integrated Approach to Resilience and Sustainability

Yating Zhang
Siamak Sattar
Dustin T. Cook
Katherine J. Johnson
Juan F. Fung

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1324

NIST Special Publication 1324

Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles

An Integrated Approach to Resilience and Sustainability

Yating Zhang
Siamak Sattar
Dustin T. Cook
Katherine J. Johnson
Materials and Structural Systems Division
Engineering Laboratory

Juan F. Fung
Applied Economics Office
Engineering Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1324

September 2024

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

NIST SP 1324
September 2024

NIST Technical Series Policies

Publication History

Approved by the NIST Editorial Review Board on 2024-09-18

How to Cite this NIST Technical Series Publication

Zhang Y, Sattar S, Cook DT, Johnson KJ, Fung JF (2024) Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles. (National Institute of Standards and Technology, Gaithersburg, MD), NIST SP 1324. https://doi.org/10.6028/NIST.SP.1324

Author ORCID iDs

Yating Zhang: 0000-0002-0448-4829
Dustin T. Cook: 0000-0002-4841-4515
Katherine J. Johnson: 0000-0001-7199-8750
Juan F. Fung: 0000-0002-0820-787X

Contact Information

yating.zhang@nist.gov
siamak.sattar@nist.gov

Abstract

The building and construction sector is the largest carbon emitter, accounting for more than one-third of annual global emissions. The emissions can be divided into operational and embodied carbon, associated with building operations and building materials, respectively. To achieve carbon neutral buildings, both operational and embodied carbon should be minimized throughout a building's life cycle. However, most climate research and action focus on minimizing operational carbon, while efforts to reduce embodied carbon have lagged. This report provides an overview of the methodologies used to assess embodied carbon emissions at each life cycle stage of a building. The databases and tools designed for life cycle assessments (LCA) are compared in the U.S. context. The case studies that evaluate carbon reduction strategies are reviewed with a particular focus on resilient design, structural retrofits, structural system selection, and material specification. In addition, this report identifies areas of insufficient knowledge and outlines future research needs for embodied carbon assessment and reduction. Finally, this report provides an overview of international standards and building codes related to the embodied carbon of buildings. Overall, this report offers valuable guidance and insights to support ongoing decarbonization efforts in the building sector. By highlighting innovative strategies and best practices, it provides a useful resource for industry experts, policy makers, and researchers seeking to reduce carbon emissions and mitigate climate change.

Keywords

Buildings; embodied carbon; life cycle assessment; natural disasters; damage and repair; resilient design; structural retrofits; carbon offsets; design optimization

Table of Contents

1. Introduction 8
1.1. Background 8
1.2. Terminology 9
1.3. Motivations and objectives 10
1.4. Report organization 11
2. Methodology 12
2.1. Method for systematic review 12
2.2. Meta-analysis for selected articles 12
3. Methods for embodied carbon assessment 17
3.1. Quantifying embodied carbon at the production stage 17
3.1.1. Process method 18
3.1.2. Input-output method 19
3.1.3. Hybrid method 22
3.1.4. Streamlined parametric analysis 23
3.1.5. Dynamic flow analysis 24
3.2. Quantifying embodied carbon at the construction stage 25
3.3. Quantifying embodied carbon at the use stage 26
3.3.1. Hazus-based assessment 26
3.3.2. Component-based assessment 27
3.3.3. Damage-based assessment 29
3.4. Quantifying embodied carbon at the end-of-life stage 31
3.5. Quantifying embodied carbon throughout a building’s life cycle 32
3.5.1. Static and dynamic LCAs 32
3.5.2. Attributional and consequential LCAs 33
3.5.3. Uncertainty analysis 33
4. LCI data for buildings and construction materials 35
4.1. Commercial LCI data 35
4.2. Public LCI data 36
4.2.1. Federal LCA Commons 36
4.2.2. EPD documents 37
4.3. Data quality assurance 38
5. Tools for embodied carbon assessment 40
5.1. Product comparison tools 40
5.2. Whole building design decision support tools 43

5.3. Whole building assessment frameworks 47
6. Case studies for embodied carbon assessment and reduction 52
6.1. Structural system selection 52
6.2. Material specification 59
6.3. Resilient design 61
6.4. Structural retrofits 63
7. Future research needs 66
7.1. LCA Practice: Consistent and standardized LCA 67
7.2. LCA Methodology: Adapting LCA to a hybrid approach 68
7.3. LCA Methodology: Adapting LCA to a dynamic approach 69
7.4. LCA Methodology: Building damage in natural hazard-prone regions 69
7.5. LCA Applications: Structural retrofits and adaptive reuse 70
8. Standards and codes 72
8.1. International standards for life cycle assessment 72
8.2. Building codes for embodied carbon assessment and reduction 73
9. Conclusions 74
References 76

List of Tables

Table 1. Embodied carbon assessment methods. 17
Table 2. Repair assumptions for concrete buildings subjected to earthquake damage [58, 60]. 27
Table 3. Percentage of damage for a wood-frame building exposed to tornado winds [62]. 29
Table 4. Reinforced concrete buildings subjected to earthquake damage [67]. 30
Table 5. Reinforced concrete buildings subjected to fire damage (columns and beams) [70]. 31
Table 6. Reinforced concrete buildings subjected to fire damage (floor slabs) [70]. 31
Table 7. Commercial LCI data for buildings and construction materials. 36
Table 8. Public life cycle inventory databases for buildings and construction materials. 38
Table 9. Life cycle assessment tools used for building product comparison. 41
Table 10. Life cycle assessment tools used for whole building design decision support. 45
Table 11. Sustainability assessment frameworks for buildings. 49
Table 12. Life cycle assessment for structural system selection. 55
Table 13. Life cycle assessment for material specification. 60
Table 14. Embodied carbon assessment for resilient design. 62
Table 15. Embodied carbon assessment for structural retrofits. 64

List of Figures

Fig. 1. Building's embodied carbon assessment through the range of process stages. Adapted from [20]. 9

Fig. 2. Publication years of the studies included in this review. 12

Fig. 3. Building categories included in this review. 13

Fig. 4. Structural types included in this review. 14

Fig. 5. Research topics included in this review. 14

Fig. 6. Analysis methods. 15

Fig. 7. Data sources. 15

Fig. 8. Analysis tools. 16

Fig. 9. Procedure for economic input-output analysis. Adapted from [31]. 21

Fig. 10. The hybrid method spectrum. Adapted from [24]. 22

Fig. 11. Research gaps for life cycle assessment. 66

Executive Summary

This review includes 258 articles published between 2010 and 2023 that assess the embodied carbon emissions of buildings. These assessments cover various levels, including materials, components, entire buildings, building stock, and the building sector. The most widely used method for embodied carbon assessment is process method, followed by streamlined parametric analysis, hybrid method, and input-output method (Section 2). Each method offers unique advantages and presents specific challenges that should be addressed to ensure accurate and reliable results (Section 3.1).

> Process method. By tracing the carbon footprint of individual materials and processes, the process-based approach facilitates a detailed and precise analysis of a building's environmental impacts. The approach has been adopted by many Life Cycle Assessment (LCA) tools and has been integrated into Building Information Modeling (BIM) systems for project development at the early stages. Since data for some upstream and downstream processes are not available, this method tends to underestimate the total emissions of a building.
>
> Parametric analysis. Parametric analysis focuses on the key drivers of life cycle impacts. It is particularly useful for initial screening and design optimization as it allows practitioners to quickly identify areas of significant environmental impact and explore design alternatives to mitigate these impacts. However, this analysis cannot replace conventional LCA when the goal is to assess the total emissions of a building.
>
> Input-output method. Input-output analysis is primarily used to assess the supply chain contributions to building sector emissions. This approach is suitable for macro-level analysis, as it highlights the broader economic and environmental impacts of the construction industry but cannot evaluate a specific product.
>
> Hybrid method. Hybrid analysis combines detailed process data with comprehensive input-output data to provide a more accurate and reliable assessment of a building's environmental impacts. However, this approach is more complicated and time-consuming compared to other methods.

Sections 4 and 5 compare the databases and tools used by LCA studies[1] in the United States, respectively. Data transparency, quality, and availability are three issues frequently discussed in the literature. Some LCA tools are designed for comparing building products, while others focus on evaluating entire buildings. This varying level of detail allows these tools to serve different research purposes and stages of project development. Overall, LCA databases and tools play an important role in our continued efforts to better standardize LCA practices and ensure consistency across assessments conducted.

Section 6 provides an overview of case studies related to resilient design, structural retrofits, structural system selection, and material specification.

> Resilient design. Improving the performance of buildings to better withstand natural hazard events can reduce carbon emissions associated with repairs and reconstruction. A multi-

---

[1] LCA is defined as the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [11]. It is a primary tool used to evaluate the environmental impacts of individual buildings.

objective optimization method is needed to balance considerations for disaster resilience, sustainability, and costs when designing new buildings.

Structural retrofits. The environmental impact of retrofitting is often lower than that of new construction. The selection of retrofit methods can influence the environmental outcomes related to improving building performance, extending a building's lifespan, and meeting evolving functional demands.

Structural system selection. Improving material efficiency, reducing the self-weight of structural systems, and replacing pure reinforced concrete or steel with timber frames (e.g., timber-steel composite frames, timber-concrete composite frames) can reduce the carbon footprint of buildings. In addition, as a renewable material, timber can store GHGs during the life cycle of buildings. Its emissions at the end of a building's life can be offset by carbon sequestration (e.g., replanting trees). Studies also suggest that future technologies may enable permanent biogenic carbon sequestration, and thus timber frames may have a long-term climate cooling effect.

Material specification. High strength concrete can reduce the amount of concrete and reinforcing steel used in tall buildings. Replacing conventional cement with fly ash or other low-emission binder can reduce the overall carbon footprint of buildings. In addition, natural and bio-based materials and recycled materials have low environmental impacts. However, the lack of standards and guidelines has limited their use in building construction.

Section 7 summarizes the knowledge gaps and highlights five research needs:

- Develop guidelines for consistent and standardized LCA practices
- Adapt LCA to a hybrid approach
- Adapt LCA to a dynamic approach
- Incorporate natural hazard impacts into LCA
- Improve carbon reduction for existing buildings with LCA

Section 8 delineates the existing standards and codes related to the assessment and mitigation of embodied carbon in buildings. These efforts have contributed to improved transparency and consistency of LCA. However, further efforts are needed to standardize LCA practices in terms of functional units, system boundaries, analysis periods, databases, tools, and modeling approaches to facilitate the comparison of LCA results across different studies. In addition, building repair and replacement due to natural hazard events have not yet been adequately considered in standard LCA practices, suggesting an important gap that needs further improvement.

This review will be useful to industry professionals, policymakers, and researchers who seek to reduce carbon emissions and mitigate climate change. By understanding the innovative strategies and best practices, they can make informed decisions that balance structural resilience with carbon efficiency, ultimately contributing to more sustainable building practices and policies.

1. Introduction

1.1. Background

The building and construction sector was responsible for 37% of annual global carbon emissions in 2022, with 28% coming from building operations and 9% from construction materials [1]. Minimizing operational carbon (emissions from the energy used to operate a building, such as heating, cooling, ventilation, and lighting systems) has been a focus of climate research and action in recent decades [2-4]. However, efforts to reduce embodied carbon (emissions from the manufacture, transportation, installation, maintenance, and disposal of building materials) have lagged [2-4]. As energy efficiency continues to improve, building materials may become the dominant source of carbon emissions in new construction [3]. Therefore, it is imperative to minimize and reassess the impact of embodied carbon.

Over the past two decades, building energy codes have led to significant changes in building design and operation practices [5]. However, building materials and systems are largely unregulated as long as minimum life safety requirements are met [6]. The challenge of tracking upstream energy use and carbon emissions from the production of building materials and equipment may hinder the regulatory process [6]. In addition, the complexity of global manufacturing and supply chains makes it difficult to measure carbon emissions from material extraction to product assembly [6]. Given these challenges, improved knowledge and methodologies are needed to assess and manage embodied carbon.

At the national level, the Buy Clean Task Force, established under Executive Order 14057 on December 8, 2021, recommends that agencies identify building materials and products with the highest embodied carbon concerns, prioritize for lower embodied carbon in federal procurements and federally funded projects, increase transparency of embodied emissions through supplier reporting of Environmental Product Declarations (EPDs), provide incentives and technical assistance to help domestic manufacturers better report and reduce embodied emissions, launch pilot programs to increase federal procurement of cleaner building materials, and learn more about their performance in real-world applications [7]. The EPD is a third-party verified document that communicates the LCA results for a product or service [8].

In addition, the Inflation Reduction Act of 2022 invests $350 million to help manufacturers, institutional purchasers, real estate developers, builders, and others measure, report, and significantly reduce the levels of embodied carbon and other greenhouse gas (GHG) emissions associated with all relevant stages of the production, use, and disposal of building materials and products [9]. The act requires the Environmental Protection Agency (EPA) to develop an EPD assistance program to improve the transparency and disclosure of embodied GHG emissions data associated with building materials and products in the United States. Disclosure of EPDs based on robust and comprehensive data would enable fair comparison of building materials and products and facilitate the procurement of these products with lower embodied carbon [9].

Regionally, California Assembly Bill 2446 (the Carbon Intensity of Construction and Building Materials Act) passed in 2022 requires the state board to develop a comprehensive strategy for its building sector to achieve a 40 percent net reduction in GHG emissions from building materials by December 31, 2035, with an interim goal of a 20 percent net reduction by December 31, 2030 [10].

1.2. Terminology

Embodied carbon is the sum of carbon emissions from material extraction (module A1), transportation of raw materials to manufacturing (A2), manufacturing (A3), transportation of manufactured products to site (A4), and installation (A5), as shown in Figure 1. Some studies also include embodied carbon emissions from the use stage (B1-B5) and the end-of-life stage (C1-C4).

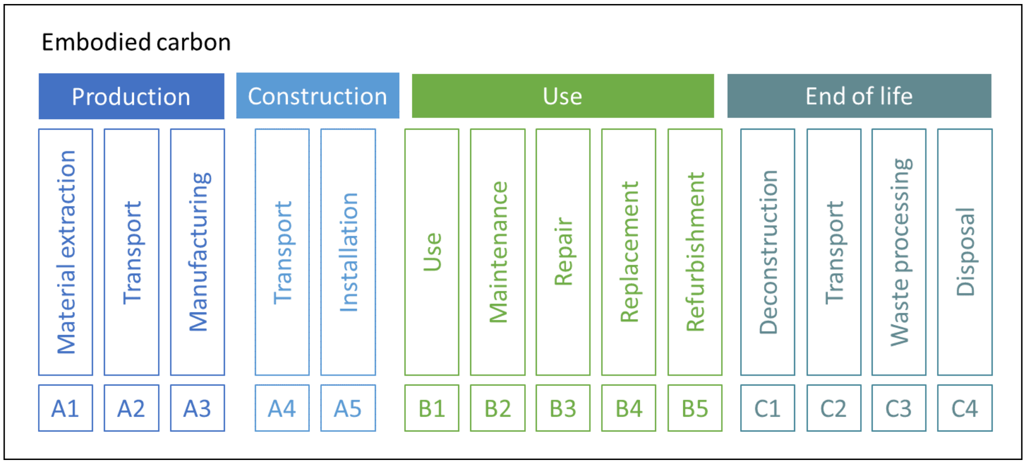

Fig. 1. Building's embodied carbon assessment through the range of process stages. Adapted from [20].

The embodied carbon of buildings is primarily evaluated through the Life Cycle Assessment (LCA). The International Organization for Standardization (ISO) defines LCA as the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [11]. Moreover, the *system boundary* of a LCA is a set of criteria that specify which unit processes are part of a product system [11]. Specifically, the *cradle-to-gate* system boundary includes the main upstream processes, from the beginning of raw material extraction to the end of manufacturing and prefabrication (A1-A3). The *cradle-to-site* system boundary covers the cradle-to-gate process, as well as the transportation process of building products from the factory to the construction site, and the construction and installation process (A1-A5). The *cradle-to-*

grave boundary further includes building use, maintenance, refurbishment, deconstruction, and waste disposal processes (A1-A5, B1-B5, and C1-C4). The *cradle-to-cradle* system boundary comprises reuse, recovery, and recycling processes in addition to the cradle-to-grave process. The system boundary may also involve time boundary (e.g., lifespan, full lifetime, remaining lifetime), spatial boundary (e.g., site, city), methodological boundary (e.g., process, input-output, hybrid methods), and functional boundary (e.g., occupancy class, structural type) [12].

The LCA can be performed at the flow, process, or product level, depending on the level of detail at which data can be collected [11, 13]. A *flow* is a material, energy, emission, or currency that enters or leaves a system under study. Input flows can include raw materials, energy, and water. Output flows may include emissions to air, water, and soil, and wastes generated throughout the life cycle of a product or process. A *process* can describe a single activity (a unit process) or a set of activities (an aggregate process), and it consists of a number of input and output flows. A *product system* is a combination of unit processes that together perform one or more functions. A *functional unit* is a quantitative description of the function(s) delivered by a product system. It serves as a basis for comparing similar products or services. The functional unit for a building can be defined in a variety of ways, such as a unit of floor area, a building system, or an entire building [13].

The impact of embodied carbon can be assessed using the 100-year Global Warming Potential (GWP), which quantifies the energy that the emissions of 1 ton of a gas will absorb over 100 years, relative to the emissions of 1 ton of CO_2 [14]. A higher GWP indicates that a particular gas contributes more to Earth's warming compared to CO_2 over that time frame. Using a standardized unit of measurement (kg CO_2e), analysts can compare and aggregate emission estimates of different gases, compile a national GHG inventory, and assess emission reduction opportunities across sectors and gases [14]. The GWP values are updated periodically to reflect the best knowledge of GHG impacts on the global environment [15]. Alternative metrics for assessing embodied carbon include the 20-year GWP, GHG concentration, radiative forcing, temperature change, temperature change rate, and global temperature potential [16,17].

1.3. Motivations and objectives

The literature on low-carbon buildings suggests that both operational and embodied carbon should be considered when designing and retrofitting buildings [18,19]. As operational carbon has been extensively studied, this study focuses on the embodied carbon of buildings (A1-C4). The objectives of this study are to (1) document the methods, databases, and tools used in LCA literature to assess embodied carbon emissions, (2) review the case studies for reducing embodied carbon through resilient design, structural retrofits, carbon offsets, and design optimization, (3) document the standards and codes related to embodied carbon, and (4) identify knowledge gaps and future research needs.

1.4. Report organization

This report is organized as follows:

- Section 2 presents the methodology employed in this literature review, including a statistical analysis of the literature reviewed to address the key research questions.
- Section 3 introduces and compares the methods for embodied carbon assessment.
- Section 4 introduces and compares the life cycle inventory (LCI) databases for buildings and construction materials.
- Section 5 introduces and compares the tools for embodied carbon assessment.
- Section 6 reviews the case studies on embodied carbon mitigation.
- Section 7 outlines future research needs.
- Section 8 summarizes standards and codes for embodied carbon assessment and reduction.
- Section 9 summarizes and concludes this study.

2. Methodology

2.1. Method for systematic review

Our review starts from searching articles published between 2000 and 2023 in the Web of Science and Scopus databases using a combination of keywords: "building" AND "embodied" AND "carbon"; "building" AND "carbon" AND "emission" OR "footprint". This results in a total of 11,279 original articles and 1,183 review articles. After removing duplicates, 10,263 articles remained. Then the studies focusing on infrastructure decarbonization (e.g., electricity grids), manufacturing decarbonization (e.g., clinker substitution), transportation decarbonization (e.g., electric vehicles), site development, energy retrofits, operational energy (e.g., thermal insulation, building envelope), embodied energy, and new materials (e.g., bacteria-based self-healing concrete) are excluded, and the research method is narrowed down to LCA. After three rounds of filtering by title, abstract, and full article, 225 original articles and 33 review articles remain. Figure 2 shows an upward trend in the number of publications over time, with most studies published after 2010.

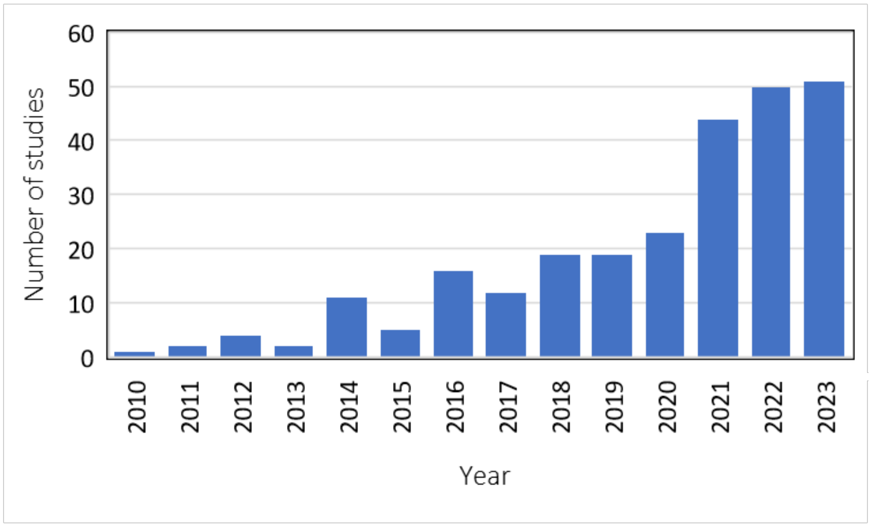

Fig. 2. Publication years of the studies included in this review.

2.2. Meta-analysis for selected articles

Further analysis of the 225 original articles reveals several key trends and areas of research focus. About 45 % of the studies analyzed residential buildings, followed by commercial buildings, office buildings, and school buildings (Fig.3). About 23 % of the studies evaluated only building materials or building components. Concrete, steel, and wood structures are extensively studied due to their widespread use in construction (Fig.4). In terms of research topics, about 25 % of the studies dealt with the selection of building structural systems and materials, followed by prefabrication and material specification (Fig.5). There is also a growing interest in carbon offsets, exploiting the ability of timber to sequester and store carbon. However, structural retrofits and resilient design, which aim to prevent damage and collapse of buildings from natural disasters, are relatively less studied, indicating a potential gap in the current research. A discussion of carbon reduction strategies is presented in Section 6.

The primary method employed in these studies is the process approach, followed by parametric analysis, hybrid approach, and input-output approach (Fig.6). The advantages and limitations of these approaches are discussed in Section 3. Environmental data were collected from multiple sources, including commercial and public databases, published literature, construction companies, and on-site surveys or interviews (Fig.7). Finally, about 60% of the studies manually assessed embodied carbon. Software tools are also used by numerous studies to evaluate the whole building life cycle impacts (Fig.8). These tools are introduced and compared in Section 5.

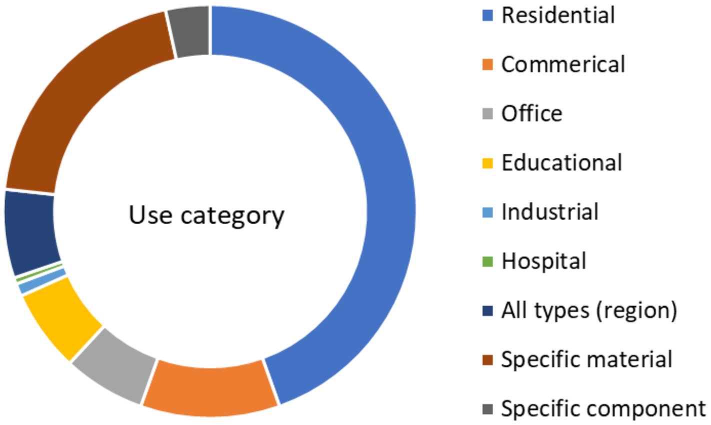

Fig. 3. Building categories included in this review. “All types” refers to all building categories in a study region.

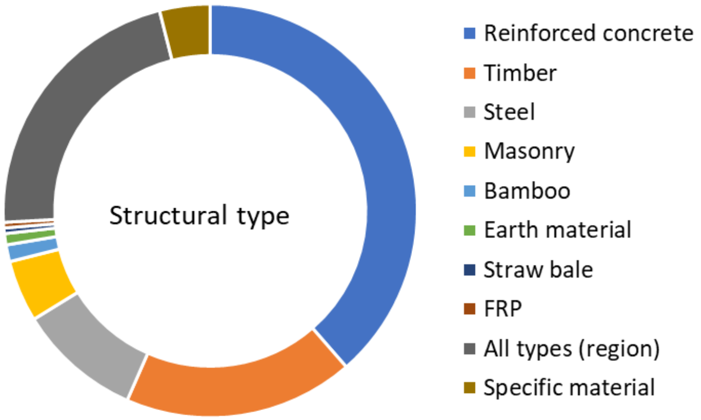

Fig. 4. Structural types included in this review. "Timber" includes mass timber, timber–concrete composite, and timber–steel composite frames. "FRP" denotes fiberglass reinforced plastic. "All types" refers to all types of structures in a study region.

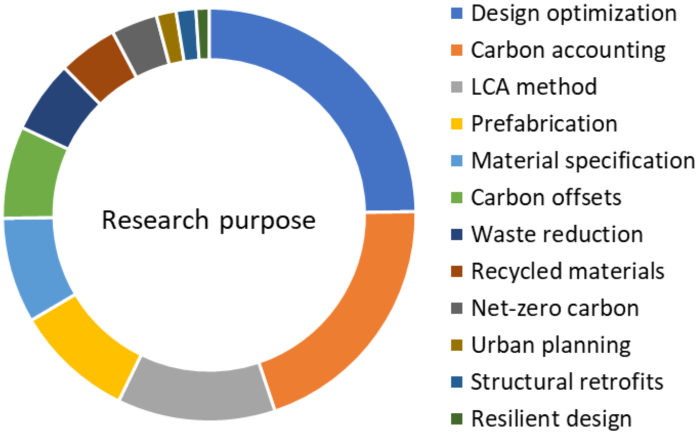

Fig. 5. Research topics included in this review. "Prefabrication" means that construction elements are manufactured off site but assembled on site. "Material specification" refers to mix design for low carbon concrete and cement. "Waste reduction" means designing buildings for adaptability, durability, and disassembly. "Net-zero carbon" involves design strategies aimed at minimizing both embodied and operational carbons.

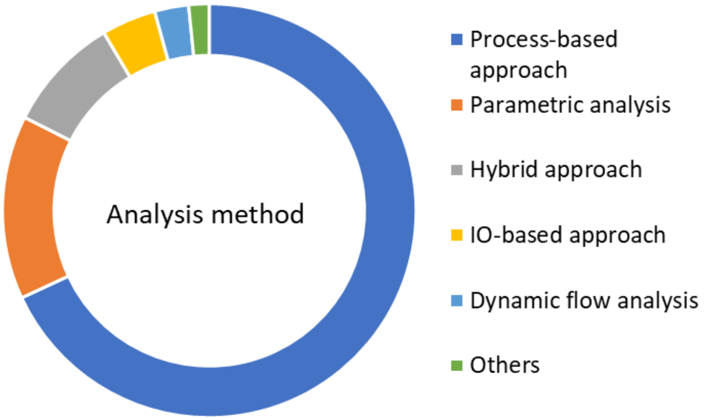

Fig. 6. Analysis methods. “IO” denotes input-output analysis. “Others” include stochastic analysis, Monte Carlo, Markov chain, decision tree, multi-criteria, fuzzy analysis, and unspecified methods.

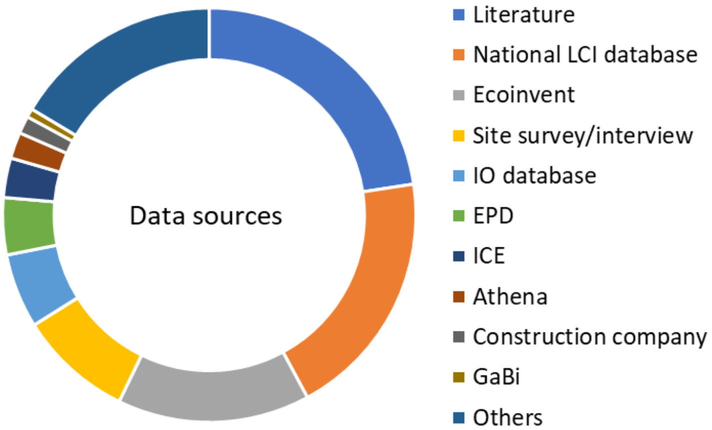

Fig. 7. Data sources. “LCI” denotes life cycle inventory. “IO” denotes input-output analysis. “EPD” denotes Environmental Product Declaration. “ICE” denotes the Inventory of Carbon and Energy.

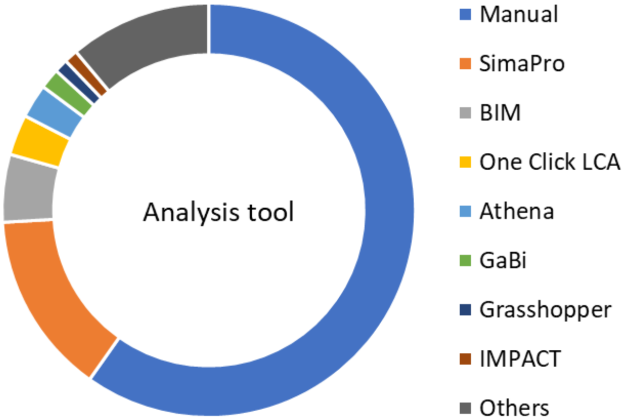

Fig. 8. Analysis tools. "BIM" denotes building information modeling (e.g., Revit).

The 33 review articles were published between 2014 and 2023. Seventeen articles reviewed LCA methods. Five studies evaluated the environmental performance of residential buildings and commercial buildings using quantitative analysis methods. Eleven articles discussed the environmental benefits of prefabricated buildings, structural retrofits, resilient design, waste reduction design, and recycled materials. One article provided an overview of the state of LCA practice in the United States.

3. Methods for embodied carbon assessment

3.1. Quantifying embodied carbon at the production stage

A number of methods have been used to quantify embodied carbon at the production stage, including process method, input-output method, hybrid method, streamlined parametric analysis, and dynamic flow analysis [21]. Table 1 summarizes the strengths and weaknesses of these methods, as well as the databases and tools that have been created based on these methods. Note that these methods can also be applied to the assessment of other life cycle stages. The following subsections discuss each method in detail.

Table 1. Embodied carbon assessment methods.

Method	Process method	Input-output method	Streamlined parametric analysis
Completeness[a]	Low	High	Low
Specificity[b]	High	Low	High
Reliability[c]	High	Low	Moderate
LCI data[d]	Athena, Ecoinvent, EPD, GaBi, USLCI	USEEIO	NA
LCA tools[e]	Athena Impact Estimator, SimaPro, BEES, EC3, Tally, OneClick LCA	EIO-LCA	Grasshopper3D

Note: EPD = Environmental Product Declaration.
USLCI = US Life Cycle Inventory.
BEES = Building for Environmental and Economic Sustainability.
EC3 = Embodied Carbon in Construction Calculator.
USEEIO = US Environmentally-Extended Input-Output model.
EIO-LCA = Economic Input Output Life Cycle Assessment.
NA = Not available.

a. Completeness means that the system boundary is fully represented by this method from upstream to downstream processes.
b. Specificity means that the energy intensity of a material is not represented by the industry average.
c. Reliability indicates that the data are collected directly from manufacturers, rather than relying on indirect or qualitative methods.
d. Life Cycle Inventory data. See Section 4 for details.
e. Life Cycle Assessment tools. See Section 5 for details.

Table 1. Embodied carbon assessment methods (continued).

Method	Hybrid method				Dynamic flow analysis
	Tiered method	Integrated method	Path exchange method	Matrix augmentation method	
Completeness	Moderate – High				Moderate
Specificity	High – Moderate				Moderate
Reliability	High – Moderate				Moderate
LCI data	NA	NA	EPiC	NA	NA
LCA tools	BIRDS	CMLCA	BDW	NA	NA

Note: NA = Not available.
BIRDS = Building Industry Reporting and Design for Sustainability [25].
CMLCA = Chain Management by Life Cycle Assessment.
EPiC = The Environmental Performance in Construction [22].
BDW = Building Design Workflow [23].

3.1.1. Process method

The process-based assessment is a bottom-up approach that assesses carbon emissions from specific processes of building construction. Direct emissions are quantified using the bill of materials and the embodied carbon coefficients of the materials. Indirect emissions from upstream processes can be difficult to identify and track. As a result, higher-order upstream processes in the supply chain, such as raw material extraction, are often excluded from the analysis. Improving the assessment of indirect emissions requires a deeper understanding of supply chain structures [24].

Carbon emissions in the production stage (C_p) can be calculated in two ways [27]:

$$\boldsymbol{C_p = \sum_i m_i f_{e,i}} \tag{1}$$

$$\boldsymbol{C_p = \sum_i q_i f_{m,i}} \tag{2}$$

where i denotes the material type used in production. m_i is the mass of a material (kg). $f_{e,i}$ is the energy emission factor (kg CO_2e/kg). q_i is the quantity of a material (m^3). $f_{m,i}$ is the material emission factor (kg CO_2e/m^3), which can be obtained from LCI databases.

Process method has the advantages of

- **Conciseness and clarity**. The analysis uses data specific to the process or product, as opposed to the input-output method, which uses average industry emissions to describe the environmental impact of products.
- **Adaptability.** The method can be combined with stochastic simulation and building information modeling.

Limitations of this method include:

- **Intensive data requirements.** Detailed process data, in terms of environmental impacts per unit of product or service, are required to perform the assessment.
- **Weak reproducibility and comparability.** Users can determine which processes to include or exclude in their analyses, which can lead to significant variation in assessment results. In addition, data collected from different sources can be inconsistent due to different product definitions and collection methods used to construct LCI databases. These variations underscore the need for standardized LCA methodologies and rigorous data validation to improve the reliability and comparability of results across LCA studies.
- **Truncation errors.** It is impossible to account for all emissions from upstream processes of building construction. There is also a risk of omitting emissions from some downstream processes (e.g., manufacturing the beam from raw steel) or non-material processes (e.g., services). Therefore, the system boundary is not as complete as the boundary defined in input-output method.

3.1.2. Input-output method

Economic input-output analysis is a top-down approach that translates economic activity in monetary terms into environmental terms through input-output models. The approach initially describes the complex dependence, constraints, and correlation between the production of inputs into outputs of various industrial sectors. It assumes that increasing the output of goods and services from any sector requires a proportional increase in each input received from all other sectors. The approach can be expressed as follows [27,32]:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}\boldsymbol{Y} \tag{3}$$

where X is an $n \times 1$ total output vector. Y is an $n \times 1$ final demand vector. I is the $n \times n$ identity matrix. A is an $n \times n$ direct input coefficient matrix. $(I - A)^{-1}$ is the Leontief inverse matrix, describing how changes in final demand affect the production of goods and services across various sectors of the economy.

The matrix A is defined as

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{a_{11}} & \cdots & \boldsymbol{a_{1n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{a_{n1}} & \cdots & \boldsymbol{a_{nn}} \end{bmatrix} \tag{4}$$

where a_{ij} $(i, j = 1,2, \ldots n)$ is the direct input coefficient, describing the dollar value of goods from sector i required by sector j to produce one dollar's worth of product. Matrix A is determined using the input-output table compiled and maintained by the US Bureau of Economic Analysis (BEA) [29,37].

Input-output analysis was later introduced into environmental research, correlating environmental data with sectoral economic data to assess both direct and indirect environmental impacts throughout the production supply chain [27]. This has led to the development of environmentally extended input-output tables, which represent life-cycle environmental flows per dollar of product [32-37]. The environmentally extended input-output tables were further refined to distinguish between environmental impacts resulting from domestic production and those resulting from import/export goods [37].

Figure 9 illustrates the steps for generating environmental impact results based on cost estimates for building damage and repair. The Economic Input-Output (EIO) LCA database mentioned in Step 2 is an environmentally extended input-output table developed by Hendrickson et al. (1998) [32].

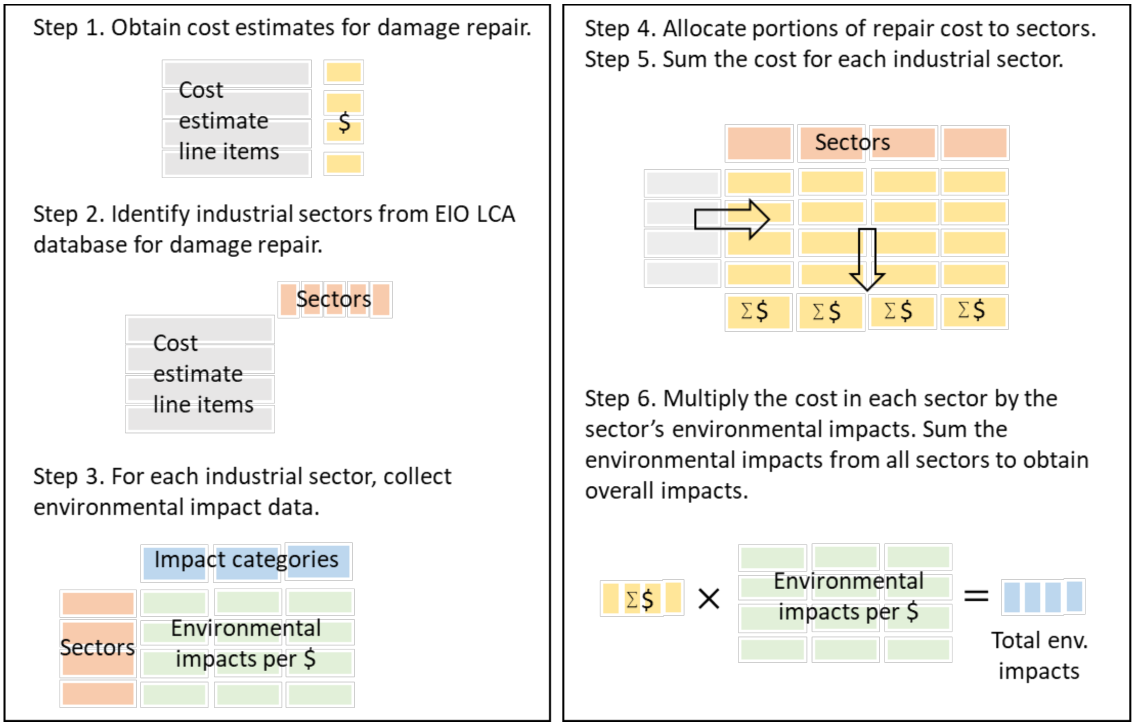

Fig. 9. Procedure for economic input-output analysis. Adapted from [31].

Input-output method has the following advantages:

- **A consistent accounting framework**. The method provides a consistent framework for environmental accounting, allowing comparisons between different studies and tracking performance within different sectors of the economy [32].
- **A complete system boundary.** Economic input-output models provide a comprehensive view of both direct and indirect environmental impacts. Rather than focusing on individual processes, these models define their system boundary by geographic areas, which can be a single region or multiple regions [32].
- **Fast and inexpensive**. Input-output method uses readily available data to assess the environmental impacts of a product or service. It saves the effort of collecting detailed process data and determining the mass or quantity of the product [32].

Limitations of this method include:

- **Homogeneity assumptions**. Economic input-output models assume that all products within a sector have the same emission intensity per monetary unit. Despite representing over 400 sectors in a typical model, the level of disaggregation is insufficient for the desired level of analysis. Consequently, these models lack the capacity to account for atypical products [32].

- **Outdated input-output tables**. Currently, the input-output table is updated every five years in line with Census surveys. Outdated data can compromise the accuracy of assessment results due to the influence of technological advances and policy changes on industrial sector emissions [29,34,37].

3.1.3. Hybrid method

Hybrid methods combine process method and input-output method to enhance the benefits and mitigate the weaknesses of each method. Based on the accounting framework, hybridization method, and data used, the hybrid method can be classified into the tiered method, integrated method, path exchange method, and matrix augmentation method [24], as shown in Fig.10.

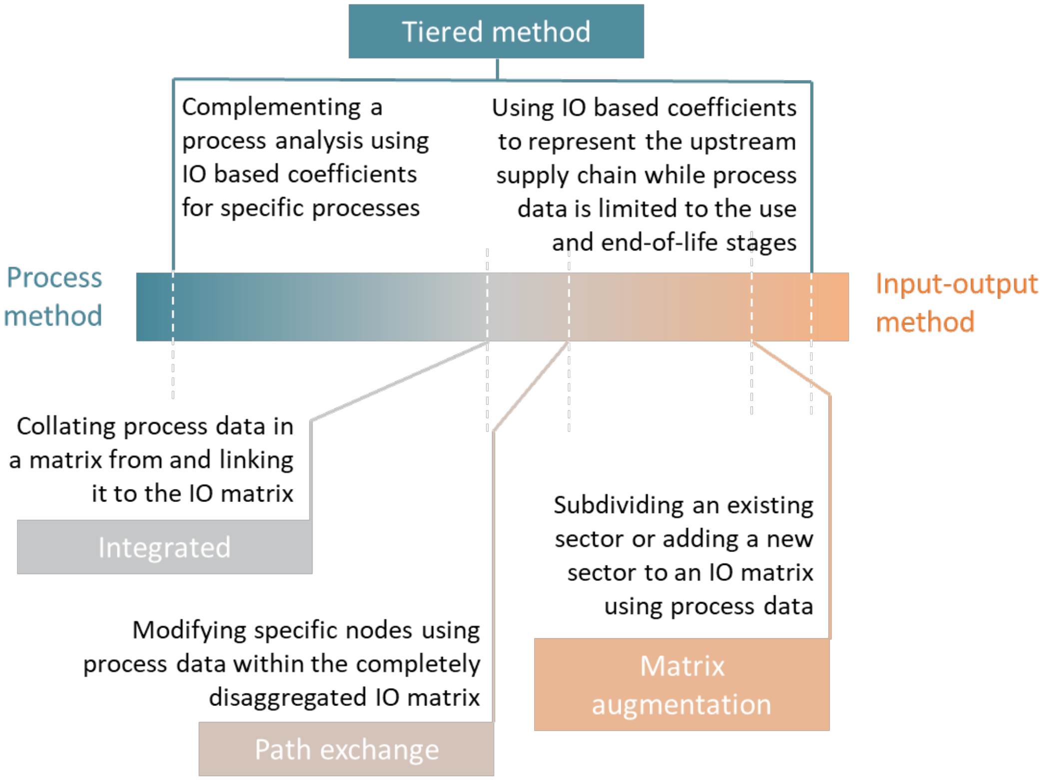

Fig. 10. The hybrid method spectrum. Adapted from [24].

Tiered method

Tiered method integrates data from input-output tables into a process-based framework to increase the completeness of the system boundary [38]. When upstream processes are not traceable, the process-based framework can be truncated and the remaining emissions can be counted using the input-output analysis. Since it relies on the user to determine the life cycle stage to which process or input-output data are applied, this method can lead to large variations in results. In particular, some studies may use process data only in the use and end-of-life stages, while others may use process data in all stages as long as they are available [24].

Integrated method

Integrated method combines process and input-output data in a single matrix framework using a set of vectors called upstream and downstream cutoff matrices [40]. The upstream cutoff matrix represents the upstream inputs from the input-output system to the process system. The downstream cutoff matrix represents the downstream use of goods and inputs from the process system to the input-output system. This method provides a consistent allocation and reduces the risk of double counting. However, the construction of the cut-off matrices is highly data and time intensive [24].

Path exchange method

Path exchange method decomposes the input-output matrix into energy paths and replaces the energy path data with more reliable process data. The energy paths, which represent the energy flows between sectors, are extracted by structural path analysis or sensitivity analysis [39]. Energy paths can also be interpreted as chains of transactions (nodes) leading to the final product or service. The goal of structural path analysis is to estimate the contributions of a supply chain to a given product or service. Finally, the method replaces node data with process data to provide a more accurate and comprehensive assessment of the supply chain's impact on the product or service [41,42]. However, the transformation of process data into energy path data is time-consuming and labor-intensive. The risk of double counting arises when the boundary between process and input-output data is not clear. To avoid double counting, it is essential to fully disaggregate the input-output matrix and subtract all aspects of the supply chain represented by process data from the disaggregated model [24].

Matrix augmentation method

The augmentation method modifies the input-output matrix by creating one or more sectors of the economy. It either divides an existing sector into subsectors or creates new sectors for a particular product or service. The product or service may exist within a large sector that does not adequately reflect its specialization, or may not yet be included in input-output tables (e.g. new products) [43].

3.1.4. Streamlined parametric analysis

The parametric approach uses correlation analysis (e.g., correlation test, sensitivity analysis, cluster analysis) or regression analysis (e.g., linear regression, quantile regression, random forest regression) to identify drivers of environmental impacts and quantify their influence on a building's environmental performance. Heeren et al. (2015)

analyzed 28 parameters that influence operation (ventilation, heating setpoint, cooling setpoint, occupancy density, lighting load, internal load, daylighting setpoint, building occupancy, hot water demand, shading control), design (building size, window ratio, shading, night setback temperature, thermal energy generation system), materials (construction material, thermal resistance, solar factor, building service life, material service life, transportation), and exogenous building characteristics (climate, energy mix) [44]. Using correlation analysis and Monte Carlo simulations based on assumed probability distribution functions for the 28 parameters, Heeren et al. (2015) found that energy mix, ventilation rate, heating setpoint, and construction material have the highest impact on the environmental performance of small office and residential buildings in Switzerland [44].

3.1.5. Dynamic flow analysis

The scope of LCA is often limited to individual buildings or specific assemblies. When studying environmental impacts on a large scale, dynamic flow analysis can be used to assess time-dependent energy and carbon flows across the building stock of a region or country [45,46]. In this context, the building stock change $\Delta K(t)$ is defined as the difference between the input flow $I(t)$ and the output flow $O(t)$ [45,47]:

$$\boldsymbol{\Delta K(t) = \frac{d\,K(t)}{d\,t} = I(t) - O(t)} \tag{5}$$

$$\boldsymbol{I(t) = \sum_{i}^{n} s_i(t) \cdot r_i} \tag{6}$$

$$\boldsymbol{O(t) = K(t-1) - K(t)} \tag{7}$$

where $K(t)$ is the number of buildings in year t, which is a function of population and floor area per capita. $s_i(t)$ is the usable floor area for material i (m^2). r_i is the material intensity per unit of floor area ($\mathrm{kg/m}^2$). The input flow $I(t)$ represents the total floor area in year t, including new construction. The output flow $O(t)$ describes the difference between the surviving units in two consecutive years, which is a function of the building lifetime. The large-scale environmental impacts are then assessed by combining the building stock model with the material inventory (i.e., material category, quantity, lifetime, and emission factor) for archetype buildings and accumulating the results over the analysis period (e.g., 60 years) [46].

Dynamic flow analysis has been used to assess the climate mitigation potential of different strategies [45]. However, the current approach does not consider end-of-life processes and the circularity potential of structures and their components.

3.2. Quantifying embodied carbon at the construction stage

The main sources of carbon emissions during the construction phase include the equipment used at the construction site and the transportation of materials from the manufacturer to the construction site. Building height can have a significant impact on emissions, as construction equipment for low-rise buildings differs significantly from that for high-rise buildings.

The embodied carbon due to equipment used (C_e) is calculated as

$$\boldsymbol{C_e = \sum_{k} E_k f_{e,k}} \tag{8}$$

where k denotes the energy type consumed on a construction site. E_k is energy consumption. $f_{e,k}$ is the energy emission factor.

The carbon footprint of equipment itself is considered in the manufacturing sector rather than the construction sector. In addition, sophisticated models have been developed to estimate emissions from various types of construction equipment, such as the Nonroad Engines, Equipment, and Vehicles (NONROAD) model [52], the MOtor Vehicle Emission Simulator (MOVES) [48], and the OFFROAD tool [49]. These models take into account the effects of temperature, deterioration, retrofitting, and load factor on the equipment, as well as temporal and geographic variations. It is worth noting that emissions can also be measured directly through dynamometer tests or monitored in real time using portable emission measurement systems [50].

The embodied carbon due to transportation (C_t) is calculated as

$$\boldsymbol{C_t = \sum_{i} m_i d_i f_{t,i}} \tag{9}$$

where d_i is the average distance of the construction material from manufacture to the construction site (m). $f_{t,i}$ is energy emission factor for a unit transportation distance and a unit mass.

Some studies use mapping tools to estimate distances between installation sites and factories, while others rely on general assumptions about transportation distances, often within city limits or based on generic data sources such as Ecoinvent. For example, Puettmann et al. (2021) assumed that materials in the US are transported by truck for distances less than 500 miles (805 km) and by a combination of truck and rail for distances greater than 500 miles (805 km) [51]. Note that employee commuting is a two-way trip of equal distance and should be counted twice.

3.3. Quantifying embodied carbon at the use stage

Embodied carbon emissions associated with building maintenance (C_r) can be calculated as follows:

$$\boldsymbol{C_r = \sum_i m_i f_{e,i} \frac{Y}{y_i}} \tag{10}$$

where Y is the lifespan of the building (years). y_i is the lifespan of the construction material i.

Carbon emissions from building maintenance are rarely considered in LCA studies [4,53]. However, in real projects, the replacement of building components (e.g., floor and wall finishes, photovoltaic systems on roofs) accounts for about 25 % of total embodied GHG impacts [54]. In addition, when natural hazard events occur during the life of a building and cause severe damage, emissions from repair and replacement can be significant [55,61,98]. Several methods have been proposed to quantify the environmental impacts of building repair and replacement following a disaster, including Hazus-based assessment, component-based assessment, and material-based assessment.

3.3.1. Hazus-based assessment

Hazus is a GIS-based software platform capable of estimating potential building and contents losses from earthquakes, tornadoes, floods, and hurricanes. It contains default building inventory and demographic databases for all regions of the United States [59]. Some studies use the probabilistic hazard analysis method, facilitated by the Hazus risk assessment tool, to calculate carbon emissions from potential building repairs [56-58].

Embodied carbon associated with building repair and replacement ($C_{r,j}$) is calculated as the sum of carbon emissions from demolition of irreparable components ($C_{dm,j}$), debris disposal ($C_{db,j}$), and building repair ($C_{rp,j}$) [58].

$$\boldsymbol{C_{r,j} = C_{dm,j} + C_{db,j} + C_{rp,j}} \tag{11}$$

where j is the damage state, denoted by s for slight damage, m for moderate damage, e for extensive damage, and c for complete damage. Table 2 provides repair assumptions for each Hazus damage state.

Table 2. Repair assumptions for concrete buildings subjected to earthquake damage [58, 60].

Damage state	Description	Repair actions	Carbon emission per floor area (kg/m^2)
Slight damage	Flexural or shear-type hairline cracks in the concrete surface of some columns	Bonding cracks with epoxy resin	4.1
Moderate damage	Large shear cracks and spalling in most columns of non-ductile frames	Patching shotcrete	27.7
Extensive damage	Shear failure or buckling failure of reinforcement in columns, partial collapse	Reinforced concrete jacketing for damaged columns	170.4
Complete damage	Brittle failure of non-ductile frame elements, collapse or nearly collapse	Demolition and reconstruction	446.7

The total emissions from buildings in a region is calculated as

$$\boldsymbol{C_r = \sum_j n_j C_{r,j}} \tag{12}$$

where n is the number of buildings that suffer a particular level of damage.

3.3.2. Component-based assessment

The Federal Emergency Management Agency's (FEMA) P58-4 methodology provides detailed guidance for assessing carbon emissions associated with earthquake damage and repair at the component level [63]. This methodology, which is based on probabilistic risk assessment, can be extended to assess environmental impacts for other types of natural hazards. The embedded database contains unit economic and environmental costs for repair materials and actions. The methodology consists of seven steps:

Step 1. Assembling a building performance model.

This includes defining the damageable structural and nonstructural components in the building, specifying the type of damage the components can sustain, and determining the consequences if that damage occurs to those components. The consequences are described by damage states, which have three to five levels depending on the component type.

Step 2. Defining earthquake hazard.

Depending on the research needs, earthquake hazard can be assessed in three ways: time-based assessment, where the hazard is defined by the site-specific probability for a given earthquake intensity; intensity-based assessment, where the hazard is defined by the intensity of earthquake ground shaking; and scenario-based assessment, where the hazard is defined by the magnitude and distance from the site for earthquakes of interest.

Step 3. Analyzing building response.

This involves predicting the structural response in terms of peak values of different demand parameters, at different earthquake intensities, and at different locations throughout the structure. Engineering demand parameters are structural response quantities that can be used to estimate damage to structural and nonstructural components and systems, such as interstory drift and beam plastic rotation [64].

Step 4. Developing collapse fragility functions.

Building collapse due to natural hazard events can significantly affect the life and annualized environmental impact of a building. This step requires the development of probability functions for partial or total structural collapse considering the effect of ground motion intensity.

Step 5. Calculating performance.

This step uses Monte Carlo simulations to generate hundreds to thousands of realizations, each with a unique combination of demand parameters, damage states, and consequences. Each realization represents a possible building performance outcome in response to earthquake shaking. The results are presented in a probabilistic distribution showing the probability that the consequences will not exceed certain values.

Step 6. Selecting environmental impact metrics.

Available metrics include GWP, primary energy use, ozone depletion potential, acidification potential, eutrophication potential, and photochemical smog potential. Embodied carbon is calculated as GWP and is expressed in carbon dioxide equivalent (CO_2e) units.

Step 7. Quantifying environmental impacts.

FEMA P58 has defined repair actions and associated GWP for each component damage state. The GWP of individual components are summed to produce a result for the whole building. The result can be reported as performance functions (i.e. probabilistic distributions) or as means or medians with dispersion.

3.3.3. Damage-based assessment

Some studies rely on the estimated percentage of building damage to calculate embodied carbon associated with building repairs [67-70]. Carbon emissions are calculated using the percentage of component damage along with material life cycle data. The percentage of component damage can be determined by laboratory tests or established models [62]. Interior damage can be estimated using damage ratios, which are assumed to be based on a large number of observations that correlate the percentage of damage to interior and exterior components [66].

Table 3 illustrates the damage state for a wood-frame building exposed to various levels of tornado winds. Carbon emissions from component repair are calculated as the percentage of damage multiplied by the initial embodied carbon of the component.

Table 3. Percentage of damage for a wood-frame building exposed to tornado winds [62].

Wind speed mph (m/s)	Percentage damaged					
	Roof shingles	Roof panels	Windows and doors	Exterior wall panels	Roof structure	Wall structure
50 (22.32)	0.3	0	0	0	0	0
75 (33.53)	2.13	0.6	0.54	0	0	0
100 (44.70)	16.5	22.51	33.85	0.81	0	0
110 (49.17)	30.76	48.28	70.29	5.51	0.16	0.09
120 (53.64)	48.37	72.54	92.03	20.8	2.68	3.14
130 (58.12)	66.51	88.14	98.47	46.61	16.63	18.79
140 (62.59)	80.69	95.51	99.76	72.43	46.53	46.03
150 (67.06)	89.99	98.5	99.94	89.04	75.63	71.4
160 (71.53)	95.29	99.58	99.98	96.5	91.59	87.53
180 (80.47)	99.16	99.97	99.99	99.76	99.46	98.59
200 (89.41)	99.88	100	100	99.98	99.95	99.87
250 (11.76)	100	100	100	100	100	100

Table 4 presents the assumptions for carbon emissions from the repair of reinforced concrete buildings due to earthquake damage. Emissions at each damage state are quantified as a percentage of the embodied carbon of initial construction materials.

Replacement due to full damage (100 %) requires removal, demolition, and disposal of damaged materials. Therefore, the number is increased by 15 % to account for these additional activities [67].

Table 4. Reinforced concrete buildings subjected to earthquake damage [67].

Damage state	Description	Damage index ($D_{P\&A}$)	Carbon emission as a percentage of initial construction
Without any damage	Slight cracks in nonstructural components	0 - 0.2	0
Slight damage	Slight cracks in structural components	0.2 - 0.4	2 %
Medium damage	Flexure shear cracks in the top or bottom ends of columns; Spalling of the concrete cover; Shear cracks in the middle part of columns connected to windowsills; Obvious damage in nonstructural components; Loosening of stirrups in the top or bottom ends of columns	0.4 - 0.6	10 %
Serious damage	Crushed concrete in column cores; Extensive loss of stirrups; Buckling of the main bars	0.6 - 0.9	50 %
Full damage	Extensive damage to columns; Extensive crushing of core concrete in columns and columns without any loading capacity; Partial or total building collapse, or close to collapse	0.9 - 1	115 %

Tables 5 and 6 present the assumptions used to assess the carbon emissions from reinforced concrete buildings due to fire damage [70].

Table 5. Reinforced concrete buildings subjected to fire damage (columns and beams) [70].

Damage state (DS)	Performance*	Carbon emission as a percentage of initial construction
DS1	0 < d300 < c/10	4.8 %
DS2	c/10 < d300 < c	23.6 %
DS3	c < d300 < d/4	39.8 %
DS4	d/4 < d300 < d/2	263.7 %

* d300 = depth of the 300℃ isotherm. c = thickness of the concrete cover over the rebar. d = side dimension of the cross section.

Table 6. Reinforced concrete buildings subjected to fire damage (floor slabs) [70].

Damage state (DS)	Performance*	Carbon emission as a percentage of initial construction
DS1	1/240 < Δ/l < 1/120	10 %
DS2	1/120 < Δ/l < 1/60	86.1 %
DS3	Δ/l > 1/60	121.5 %

* Δ/l = ratio between the vertical deformation and the square root of the span.

3.4. Quantifying embodied carbon at the end-of-life stage

There is a growing research interest in reducing waste disposal and increasing material salvaging. The embodied carbon due to waste disposal (C_w) can be computed as follows [71]:

$$\boldsymbol{C_w = \sum_i E_{d,i} + \sum_i q_{w,i} d_{w,i} f_{w,i} + \sum_i D_i} \tag{13}$$

where $E_{d,i}$ is carbon emissions associated with machinery during demolition. $q_{w,i}$ is the quantity of waste to be transported to landfills (m^3). $d_{w,i}$ is the average distance from the construction site to the landfill (m). $f_{w,i}$ is the emission factor for waste transportation. D_i is carbon emissions associated with the disposal of waste material *i*.

Instead of calculating embodied carbon using the equation above, a number of studies made assumptions based on statistical results or expert judgment. For example, many studies assume that demolition accounts for 0.2% of the total life cycle carbon emissions based on a case study by Scheuer et al. (2003) [72].

The embodied carbon due to material recycling, reuse, or remanufacturing (C_{rw}) can be computed as follows [71]:

$$\boldsymbol{C_{rw}} = \sum_{\boldsymbol{i}} \boldsymbol{E_{d,i}} + \sum_{\boldsymbol{i}} \boldsymbol{q_{rw,i} d_{rw,i} f_{rw,i}} + \sum_{\boldsymbol{i}} \boldsymbol{P_i} \tag{14}$$

where $q_{rw,i}$ is the quantity of waste to be transported to the recycling site (m^3). $d_{rw,i}$ is the average distance from the construction site to the recycling site (m). $f_{rw,i}$ is the emission factor for transporting the recycled material. P_i is carbon emissions associated with the processing of waste material *i*.

Researchers have developed more complex methodologies to account for downstream reuse (end-of-life), upstream reuse (initial), and multiple reuse scenarios [73]. These methods can improve the assessment and attribution of carbon impacts and help cities transition to a circular economy [73]. On the other hand, many studies relied on statistical results and expert judgment to determine recycling rates and corresponding carbon impacts.

3.5. Quantifying embodied carbon throughout a building's life cycle

3.5.1. Static and dynamic LCAs

The static LCA approach uses static parameters from LCI databases or input-output tables to calculate carbon emissions over the entire life cycle of a building. This approach is consistent with current standard practice for assessing the environmental impact of buildings. In contrast, the dynamic LCA approach considers the projected changes in the energy mix involved in the production and transportation of building materials, and in the construction, maintenance, and operation of buildings [53,74,75]. The increasing share of solar, wind, and other renewable energy sources in electricity generation has the potential to significantly impact the embodied carbon of buildings. In addition, renovation and retrofit initiatives can extend the life cycle of a building and modify its embodied carbon [53]. At the regional level, population change and variation in per capita floor area can strongly influence LCA results [45]. However, the application of dynamic LCA in the building sector is currently limited due to the lack of standardized methodologies and data to account for policy, technology, and other driving factors [16,74].

3.5.2. Attributional and consequential LCAs

Attributional and consequential LCAs represent two distinct approaches in assessing environmental impacts [76]. Attributional LCA quantifies the environmental flows associated with a life cycle and examines input and output flows within a product system. This approach aims to describe the environmental impacts directly attributable to the production of a unit of a product or service. In contrast, consequential LCA seeks to understand how these environmental flows may change in response to different decisions or scenarios. It aims to predict the changes in environmental impacts that will result from specific life cycle choices, including shifts in production output and consumption patterns.

The methodological differences between attributional and consequential LCA are particularly reflected in the choice of data used to model life cycle subsystems [76-78]. Attributional LCA typically uses average data that describe the typical environmental impacts associated with producing one unit of a good or service within a system. In contrast, consequential LCA uses marginal data that illustrate the impact of changing the production levels of goods and services on the environmental impacts of the system. Due to few available databases and limited studies on the subject, consequential LCA is less widely used than attributional LCA. However, consequential LCA offers better consistency and accuracy because it avoids using an economic or energy approach to allocate the environmental impacts of a system to many processes [78].

3.5.3. Uncertainty analysis

The main methods for assessing uncertainty are Monte Carlo simulation, sensitivity analysis, data quality evaluation, and fuzzy-related methods [81]. Sources of uncertainty in the LCA include:

- Data uncertainty, which includes emission factors for materials, machinery, fuels, and grid-supplied electricity.
- Travel distance uncertainty, which includes transportation of raw materials to manufacturing, transportation of manufactured products to construction sites, and transportation of demolished products to landfills.
- Material life uncertainty. The lifespan can vary from 60 to 100 years for concrete structures, from 35 to 50 years for steel structures, and from 10 to 20 years for timber structures, depending on initial construction quality and ongoing maintenance practices [79].
- Carbonation of concrete, a chemical reaction that can cause the concrete to absorb carbon dioxide from the atmosphere. Ignoring carbonation can overestimate the embodied carbon of concrete structures by 13–48%, depending on the type of cement binder [80].
- Biogenic carbon emissions associated with timber products. Timber structures can offset carbon emissions at the end of their life through reforestation or permanent biogenic carbon sequestration. See Section 6.3 for details.

- End-of-life scenarios, which involves landfill, incineration, recycling, or reuse of the construction material.

Many studies have assessed one or two of the above sources of uncertainty. Quantifying uncertainty within an LCA is challenging, but its importance is widely recognized [81].

4. LCI data for buildings and construction materials

The reliability and transparency of LCI data has improved significantly in recent years. One notable advance is the introduction of the EPD, a third-party verified document that details the life cycle environmental impacts of building materials from specific manufacturers. Prior to this development, transparent data directly from manufacturers was only available through commercial databases [16]. Public databases provide aggregated data from multiple sources (e.g., public and private submissions) that may lack details for validation [16]. In addition, a small number of structural engineering and architectural firms have developed in-house databases containing data from thousands of projects, but only data ranges are published [82].

4.1. Commercial LCI data

GaBi. Created in the early 1990s, GaBi is one of the earliest LCI databases for building and construction materials [16]. It contains more than 1,000 annually updated datasets for construction materials. The data is collected directly from companies, associations, and public bodies. The database has been integrated into many LCA software tools including Sphera's LCA for Experts (formerly GaBi), which supports all types of LCA studies.

Athena. Created in the early 1990s, the Athena database focuses on the manufacturing processes in Canada and the US. It contains data for construction materials, energy, transport, construction, demolition, maintenance, repair, and waste disposal. Some of the data is sourced from GaBi and the USLCI Database. The data is organized by regions, accounting for variations in transport, energy mix, and recycled material rates. In 2002, the database was integrated into several building product related LCA tools, the most recent of which is Athena Impact Estimator for Buildings (IE4B), which is a leading whole building assessment tool in North America [83].

Ecoinvent. Created in 2003, the Ecoinvent database has been utilized by a number of LCA tools, including SimaPro, GaBi, and Umberto. It contains data for more than 10,000 construction processes. Each category of construction materials is associated with a wide range of products [84,85]. A comparison for the three databases can be found in Table 7.

Table 7. Commercial LCI data for buildings and construction materials.

Database	Athena	Ecoinvent	GaBi
Geography	Canada, US	Worldwide	Worldwide
Scope	Regional or national average	National average	National average
Life cycle stages	A1-C4	A1-C4	A1-C4
Advantage	Reliable data sources and regional considerations	Reliable data sources and a good coverage of the building and construction sector	Reliable data sources
Limitation	Data only available for structural and envelope materials	Not U.S. based	Not U.S. based; limited construction sector datasets

4.2. Public LCI data

4.2.1. Federal LCA Commons

The Federal LCA Commons (FLCAC) is a mega-repository that includes the US Life Cycle Inventory (USLCI), the US Environmentally-Extended Input-Output (USEEIO) model, electricity baseline, other federal LCI datasets, and other LCI data that has been submitted for public use (e.g., industry, academia).

USLCI. The USLCI project was initiated by the US Department of Energy (DOE) in 2001 with the objective to provide publicly available LCI data. The National Renewable Energy Laboratory (NREL) and the Athena Institute were tasked to develop the database using a consistent protocol, thus allowing users to objectively review and compare data based on similar data collection and analysis methods. Launched in 2003, the database offers individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of energy and material flows linked to the production of a material, component, or assembly within the US [87].

USEEIO. The USEEIO is a combined economic-environmental model developed by the EPA. The model uses input-output tables from the BEA to generate environmental impact information for chemicals and fossil fuels. The environmental impact information includes land, water, energy and mineral use, air pollution, nutrients, and toxics. The model can separate domestic and foreign impacts, enabling the assessment of national total industry and environmental flows [36,37].

4.2.2. EPD documents

EPDs are not raw LCI data. They represent life cycle impact assessment (LCIA) results derived from an LCA model. Typically, the LCI data used in the assessment is not included in the EPD document. In some cases, the only information provided is the source database or the tool used to generate the EPD.

EPD. Regulated by ISO 21930 and a set of other rules [86], the EPD is a document that reports a product's environmental performance over its entire life cycle. EPDs use a combination of primary and secondary data for product assessment primarily on the life cycle stages of A1-A3. Primary data is obtained from a direct measurement or a calculation based on direct measurements at its original source. Secondary data is obtained from databases, published literature, and other verified sources of industry averages. Therefore, EPDs cannot be used to compare the environmental performance of two different materials (e.g., concrete and wood). Comparisons between EPDs should only be made if their impacts were calculated using the same methodologies and life cycle modules, and the products being compared are functionally equivalent [86]. ASTM International, UL SPOT, SCS Global Services, and NSF International are among the EPD databases developed for the United States.

North American Material Baselines. The Carbon Leadership Forum published the first material baseline for North American buildings in 2019, intended to help designers and decision makers to set reliable embodied carbon targets and understand the potential for reduction throughout the design and construction processes [88]. The material baseline, representing an estimate of industry-average GHG emissions, is appropriate for a rough estimate of a product type's embodied carbon before a specific product has been selected or as a reference value against which product-level comparisons can be made. The latest version, released in 2023, uses new methodologies to adapt the baseline to the change in policy, procurement, research, analysis tools, and reporting needs. Currently, the data only covers embodied carbon in the material production stage (A1-A3). The data is collected from multiple sources, including EPDs and the USLCI. A comparison for these databases is presented in Table 8.

Table 8. Public life cycle inventory databases for buildings and construction materials.

Database	USLCI	USEEIO	EPD	North American Material Baseline
Geography	US	US	Worldwide	US, Canada
Scope	Varied	National average	Manufacturer specific	Regional or national average
Life cycle stages	A1-A3, A1-B5, or A1-C4	A1-A3	A1-A3, A1-B5, or A1-C4	A1-A3
Advantage	Consistent protocol and transparent data collection methods	Complete system boundary and consistent accounting framework	Reliable data sources and transparent assessment procedure	An estimate of industry average GHG emissions
Limitation	Limited number of products	Difficult to validate the data and low level of details	Inconsistent accounting framework	Limited number of products

4.3. Data quality assurance

The International Standardization Organization (ISO) has played an important role in developing internationally recognized standards for LCA. In particular, the ISO 14044 series describes ten key criteria for ensuring data quality [11,13]:

- Time related coverage
- Geographical coverage
- Technology coverage
- Precision
- Completeness
- Representativeness
- Consistency
- Reproducibility
- Sources of the data
- Uncertainty of the information

The US EPA has formulated a pedigree matrix to assess data quality based on the ten criteria [13]. The matrix further divides the criteria into flow-level and process-level indicators. Flow-level indicators include source reliability, temporal correlation, geographic correlation, technological correlation, and data sampling methods. Process-level indicators include the extent of review (e.g., number of internal and external reviewers) and the completeness of the unit process. Each indicator is assigned a score ranging from 1 to 5, indicating the degree of compliance with the criterion.

5. Tools for embodied carbon assessment

LCA tools can be classified into three levels based on their usages: product comparison tools, whole building design decision support tools, and whole building assessment frameworks (i.e., certification programs).

5.1. Product comparison tools

A large number of tools have been designed to assess environmental impacts of specific materials, systems, or processes. For example, Envest 2, eTool, Elodie, and SBS are spreadsheet-based tools. BEES, EC3, LCA for Experts (formerly GaBi), SimaPro, openLCA, eLCA, EcoSoft, BELE, and BeCost are standalone tools based on component catalogs. Impact, Cocon-BIM, Lesoai, 360optimi, EQUER, and Elodie are plug-in tools for computer-aided design (CAD) software. Table 9 compares the tools employed in the United States.

SimaPro. Created in 1990, SimaPro utilizes process data from Ecoinvent and input-output data from the EU and DK input-output database, as well as other free databases, to analyze carbon footprint, water footprint, and other environmental impacts [89]. The tool is featured by a graphical presentation of the results, both in flow diagrams, tables, and graphs. It quantifies uncertainties through a combination of the parametric method and Monte Carlo analysis. However, creating models on SimaPro requires extensive LCA experience.

Building for Environmental and Economic Sustainability (BEES). BEES is a free, open-access tool developed by the National Institute of Standards and Technology (NIST) with the initial release in 1994. The tool is capable of analyzing cradle-to-grave emissions (A1-A5, B1-B5, C1-C4) for over 230 building products across over 30 product categories. The tool is featured by incorporating economic and social factors into decision making for environmentally preferable building products. This is achieved through customized weighting schemes and simultaneous computation for life cycle costs, social impacts, and environmental impacts. BEES is now legacy software. While it is still available for comparing products in a given product category, it is no longer actively supported [30].

Embodied Carbon in Construction Calculator (EC3). EC3 is a free, cloud-based, open-access tool that allows benchmarking, assessment, and reductions in embodied carbon [3]. The tool utilizes building material data from construction estimates and building information modeling (BIM), as well as the database for EPDs, to provide information regarding the embodied carbon impact of building materials. The tool focuses on the material production stage, supporting cradle-to-gate evaluation (A1-A3). However, the rest of stages are also important to the understanding of whole building life cycle emissions. Notably, EC3 reports EPD uncertainty and material variability along with the point estimates of emissions. However, the approach used to quantify the uncertainty needs further validating.

Economic Input-Output LCA (EIO-LCA). The EIO-LCA software, developed in the 1990s, utilizes input-output data from 428 US economic sectors and conducts calculations based on producer prices rather than consumer prices [32]. Producer prices represent the income received by producers for goods and services, excluding post-production costs such as transportation, wholesale, and retail margins, which are reflected in consumer prices. For instance, while a consumer may pay $1 for a cookie, the producer might only receive $0.55, with the remaining $0.45 allocated to post-production expenses. The most recent iteration, released in 2002, assesses life-cycle GHG emissions associated with manufacturing, resource extraction, and supply chains, but does not include emissions from the use or end-of-life stages. Moreover, EIO-LCA assumes that all production and supply chains are confined to the US, potentially leading to an underestimation of GHG emissions for certain products [90].

Table 9. Life cycle assessment tools used for building product comparison.

Tool	SimaPro	BEES	EC3	EIO-LCA
Geography	Worldwide	US	Worldwide	US
Element[a]	Process	Product	Product	Flow
LCI data	Ecoinvent, EU & DK input-output database, and other free databases	Ecoinvent, USLCI, manufacturers and retailers	EPDs	Input-output data from US Census
Availability	Subscription	Free	Free	Free
A1-A3 (materials)	Uses default LCI data	Uses default LCI data	Uses EDPs reported by manufacturers	Requires users to identify economic sectors and estimate material costs

A4 (transportation)	Uses default transportation distances from Ecoinvent	Uses transportation models from USLCI or information provided by manufacturers	Uses EDPs reported by manufacturers	Requires users to identify economic sectors and estimate transportation costs
A5 (construction)	Uses Ecoinvent data for natural gas and electricity; neglects for manual processes	Uses Ecoinvent data for natural gas and electricity; neglects for manual processes	Uses EDPs reported by manufacturers	Requires users to identify economic sectors and estimate costs for construction
B1-B5 (maintenance)	Allows users to define the frequency of maintenance	Allows users to define the frequency of cleaning and maintenance	Uses EDPs reported by manufacturers	Not available
B6 (energy use)	Requires users to estimate annual energy consumption	Not available	Not available	Requires users to identify economic sectors and estimate energy costs
C1-C4 (end of life)	Allows users to define multiple disposal scenarios	Assumes disposal in a landfill and truck transportation	Uses EDPs reported by manufacturers	Not available
D (beyond system boundary)	Allows users to define recycling ratios	Not available	Not available	Not available

[a] The smallest element analyzed in the tool.

5.2. Whole building design decision support tools

The whole building assessment tools rely on general building information, such as building size and structural framing system, to generate LCA results for a building. While a few tools allow for user-customized inputs, the level of customization is much lower compared with product comparison tools. However, these tools offer an efficient method for stakeholders to quantify environmental impacts, to comply with regulations or mandates (e.g., California Assembly Bill 2446, Federal Buy Clean Initiative), and to obtain green building certifications [20]. Table 10 provides an overview for the tools employed in the United States.

Athena IE4B. The Athena Impact Estimator is a free software tool that can be used to explore the environmental footprint of different material choices and core-and-shell system options. The tool is capable of modeling 95% of the building stock in North America and is applicable for new construction, renovation, and additions. The tool facilitates a cradle-to-grave assessment (A1-A5 and B1-B5) with seven environmental impact measures (GWP, acidification potential, human health respiratory effects potential, ozone depletion potential, photochemical smog potential, eutrophication potential, and fossil fuel consumption). The assessment can be customized to reflect electricity grids, transportation modes and distances, and product manufacturing technologies at the location of the building, as well as building service life and building type [83]. However, it does not allow the user to acquire environmental impacts of individual products or materials. Results are provided for the entire building at each life cycle stage.

Building Industry Reporting and Design for Sustainability (BIRDS) and BIRDS Neutral Environment Software Tool (BIRDS NEST). BIRDS was developed by NIST’s Engineering Laboratory in 2014 with the objective to support sustainability-related decision making at the whole building level. It uses LCA and life cycle costing together to evaluate the sustainability of building materials, systems, and operational energy use. The BIRDS web application included pre-processed databases that provide energy, environmental, and cost measurements for reference commercial and residential buildings [25,26]. While BIRDS ceased as of December 2023, the LCA framework and underlying data for residential buildings has been integrated into BIRDS NEST. BIRDS NEST is an application programming interface (API) that provides interoperability between DOE's OpenStudio and Athena Sustainable Materials Institute's IE4B[2], along with various other software tools [28].

---

[2] BIRDS NEST supplements IE4B’s building structure and envelope LCA calculations with building systems and dynamic operational energy use LCA calculations, returning a whole building LCA to OpenStudio through an OpenStudio "Measure," which will be available from NREL’s Building Component Library (BCL).

Tally and One Click LCA. Tally is a commercial plug-in tool for Autodesk Revit, capable of extracting data from Revit and calculating embodied carbon emissions of a building. A similar tool, One Click LCA, is a plug-in function for a variety of CAD, BIM, and energy software tools, but it focuses on European construction practice.

While the current whole building assessment tools are able to evaluate the environmental impacts for most of the materials utilized in a building’s core and shell, these tools may not adequately assess disparities in GHG emissions between onsite construction and prefabrication, accurately model the alterations in the delivery methods of materials to a project, and fully account for structural assemblies, interior and exterior elements, and systems in a building [20]. Moreover, the reliance on national or regional averaged data, the use of default assumptions, and the inconsistency in EPDs may introduce large uncertainties to assessment results [20].

Table 10. Life cycle assessment tools used for whole building design decision support.

Tool	Athena IE4B [20,83]	Tally [20]	OneClick LCA [20]
Geography	US, Canada	US	Worldwide
Compatibility	Excel	Autodesk Revit	Autodesk Revit and others
LCI data	Athena's self-compiled LCI database	GaBi	Ecoinvent, GaBi, EPDs
Availability	Free	Subscription	Subscription
A1-A3 (materials)	Selects from a limited list of reference cities; accounts for regional differences	Uses default LCI data from GaBi; allows users to select data from EC3 EPDs	Aligns LCI data with building's location by recalculating electricity-based emissions
A4 (transportation)	Uses default transportation modes and distances; calculates emissions from direct fuel consumptions	Allows users to adjust transportation modes and distances; calculates emissions from direct fuel consumptions	Allows users to adjust transportation modes and distances; calculates emissions from direct fuel consumptions
A5 (construction)	Uses default construction equipment and activities; performs internal calculation	Requires users to enter the total amount of energy mix used	Requires users to enter the total amount of energy mix used

B1-B5 (maintenance)	Uses default frequency and type of repair and replacement for building elements	Uses default frequency and type of repair and replacement for building elements	Allows users to define the frequency and type of repair and replacement
B6 (energy use)	Requires users to enter the consumed energy during building's lifetime; uses electricity emission factor from Ecoinvent and other energy emission factors from USLCI database	Requires users to enter the consumed energy during building's lifetime; uses electricity emission factor from Ecoinvent and other energy emission factors from GaBi	Requires users to enter the consumed energy during building's lifetime; uses electricity emission factor from IEA and other energy emission factors from Ecoinvent
C1-C4 (end of life)	Uses default disposal processes and transportation distances	Uses averaged recycling processes and transportation distances	Allows users to define material-specific disposal/reuse processes, extract data from EPDs, and to use default disposal/reuse information
D (beyond system boundary)	Incorporates default biogenic carbon sequestration and metals recycling data	Uses avoided burden approach	Allows users to specify concrete carbonation, biogenic carbon, and material reuse options

Note: IEA = International Energy Agency. EPD = Environmental Product Declaration.

5.3. Whole building assessment frameworks

Whole building assessment frameworks provide guidelines for a comprehensive assessment of a building's environmental performance. They may include some requirements for EPDs or whole building LCA calculations, but they are not LCA tools themselves. Common certification systems include LEED (US, Canada, Mexico, Brazil, Russia), Green Globe (Canada, US), BREEAM (UK, Netherlands), DGNB (Germany), HQE (France), ITACA (Italy), SNBS (Switzerland), CASBEE (Japan), GBEL/GBAS (China), GRIHA (India), IGBC (India), G-SEED (Korea), BEAM (Hong Kong), EEWH (Taiwan), Green Mark (Singapore), GBI (Malaysia), and Green Star (Australia, New Zealand, South Africa).

Leadership in Energy and Environmental Design (LEED). The LEED green building certification program was initiated by the U.S. Green Building Council in the 1990s, providing a framework for designing healthy, highly efficient, and cost-saving green buildings. The rating system entails design, construction, operation, and maintenance of buildings, as well as neighborhoods. One of the goals of LEED is to reduce carbon emissions and mitigate climate change [130].

Green Globes. The Green Globes certification system is administered by the U.S. Green Building Initiative. It assesses the environmental sustainability, health and wellness, and resilience of all types of commercial buildings. The certification system allows building owners and managers to tailor their sustainability efforts, selecting features that align with their building and occupants' needs. The accompanying software simplifies the import and monitoring of performance for individual buildings and enables easy comparison of building performance [131].

Table 11 elaborates the assessment criteria employed in these frameworks. In particular, energy efficiency, energy effectiveness, and renewable energy receive the highest weighting across most assessment frameworks. However, there are a few exceptions. DGNB prioritizes occupant health and wellbeing, and Green Mark places significant emphasis on materials (procurement of locally available materials, reuse of building components and materials, and use of low carbon materials). Note that these frameworks have been tailored to different building uses and occupancy types (e.g., office, residential, school, hospital, new and existing buildings) by modifying the weights for the indicators. However, researchers should further improve the flexibility of these frameworks by integrating local adaptation measures, such as regulations, local culture, and weather-resilient building design, into these frameworks [132]. For example, CASBEE tackles local issues arising from frequent natural disasters through its 'earthquake resistance' indicator. Additionally, the lack of consideration of affordability and financial viability can hinder the application of these frameworks to low-income communities [133]. Finally, the sustainable performance of buildings depends not only on the design but also on the use and management of buildings. Therefore, indicators for the use phase should be included in these frameworks [132].

Table 11. Sustainability assessment frameworks for buildings.

Certification system	LEED[a,d]	Green Globes[b,d]	BREEAM[c,d]	DGNB[d]	HQE[e]	ITACA[e]	CASBEE[d]
Energy	*×	*×	*×	×	×	×	*×
Greenhouse gases	×	×	×	×			×
Ecology (biodiversity)	×	×	×	×		×	×
Economy (initial cost, maintenance cost, lifecycle cost)		×		×			
Functionality (safety, resilience, durability, flexibility)		×		×			×
Health and wellbeing	×	×	×	*×	×	×	×
Indoor air quality	×	×	×	×	×	×	*×
Innovation	×		×				
Land use	×	×	×	×	×	×	×
Management	×	×	×	×	×	×	×
Materials	×	×	×	×	×	×	×
Pollution (light, air, water, or soil)	×	×	×				×
Regional priority	×						
Renewable technology	×	×	×			×	×

Transport	×	×	×				
Waste	×	×	×	×	×	×	×
Water	×	×	×	×	×	×	×

Note: (a) GBC 2024 [130]; (b) GBI 2022 [134]; (c) BRE 2011 [135]; (d) Varma and Palaniappan 2019 [136]; (e) Bruno Polli 2020 [137]; (f) Yeung et al. 2020 [138]; (g) Liu et al. 2019 [139]; (h) Kim 2023 [140]; (i) GRIHA 2021 [141].
× Indicator included in the assessment.
* Indicator with the highest priority/weight.

Table 11. Sustainability assessment frameworks for buildings (continued).

Certification system	GBEL[f]	BEAM[f]	EEWH[g]	G-SEED[h]	GRIHA[i,d]	IGBC[d]	Green Mark[d]	Green Star[d]
Energy	*×	*×	×	*×	*×	*×	×	*×
Greenhouse gases			×		×	×	×	×
Ecology (biodiversity)			×	×	×	×	×	×
Economy (initial cost, maintenance cost, lifecycle cost)					×			
Functionality (safety, resilience, durability, flexibility)	×							

Health and wellbeing	×				×	×	×	×
Indoor air quality	×	×	×	×	×	×	×	×
Innovation	×	×		×	×	×	×	×
Land use	×	×	×	×	×	×	×	×
Management	×	×		×	×		×	×
Materials	×	×	×	×	×	×	*×	×
Pollution (light, air, water, or soil)			×	×	×	×		×
Regional priority								
Renewable technology	×	×				×	×	×
Transport				×	×			×
Waste	×	×	×		×	×	×	×
Water	×	×	×	×	×	×	×	×

Note: (a) GBC 2024 [130]; (b) GBI 2022 [134]; (c) BRE 2011 [135]; (d) Varma and Palaniappan 2019 [136]; (e) Bruno Polli 2020 [137]; (f) Yeung et al. 2020 [138]; (g) Liu et al. 2019 [139]; (h) Kim 2023 [140]; (i) GRIHA 2021 [141].
× Indicator included in the assessment.
* Indicator with the highest priority/weight.

6. Case studies for embodied carbon assessment and reduction

This section reviews the case studies for reducing embodied carbon, with an emphasis on the resilience and sustainability of buildings. For new buildings, embodied carbon can be reduced through design optimization, material specification, and resilient design approaches. Design optimization involves careful selection and optimization of materials to minimize the quantity needed for new construction. Material specification involves the selection of low emission products and often requires developing predefined guidelines for materials, including written criteria and testing instructions. Resilient design aims to prevent damage and collapse of buildings from natural disasters. It reduces the materials and construction required to repair or replace a structure during its designed life. In addition, prefabrication, also known as modular construction, has been identified as an effective way to reduce embodied carbon. In modular construction, a building is constructed in a factory-controlled environment and then shipped to a construction site for installation.

For existing buildings, embodied carbon can be reduced by retrofitting and reusing building materials. By extending the life of existing buildings through retrofitting, emissions from demolition and new construction can be avoided. In addition, adaptive reuse, where existing buildings are repurposed to meet new functional needs of stakeholders, can prevent the demolition of mid-life buildings due to functional obsolescence.

6.1. Structural system selection

Studies indicate that improving material efficiency and decreasing self-weight of structural systems can help to reduce embodied carbon of buildings [107]. In addition, mass timber panels such as cross laminated timber and glued laminated timber have demonstrated their potential as a low carbon alternative to steel and concrete for gravity and lateral load bearing systems [108]. In contrast, timber-only structures may fail to meet certain strength and serviceability requirements. For example, the vibration and deflection issues have prevented the construction of long span timber-only floor systems. Instead, timber-concrete composite systems, in which a structural concrete top layer is applied to the timber beam or mass timber panel, have been found to provide sufficient floor mass and stiffness to prevent vibration and excessive deflection [109]. However, there is a lack of standard design methods for timber-concrete and timber-steel composite systems worldwide, as well as widely accepted models for simulating their performance [108].

The 2021 International Building Code allows mass timber to be used in office and residential buildings up to 18 stories in height, which may prompt the construction of tall wood structures in the future [110]. However, timber-framed structures require a greater volume of materials to ensure adequate load bearing capacity compared to reinforced concrete and steel frames. For example, an 18-story reinforced concrete building uses 180 mm thick concrete slabs, while a functionally equivalent mass timber building requires 540 mm thick wood slabs [101]. The increased slab thickness in the timber construction leads to greater floor-to-floor height requirements and thus greater material consumption [101]. Similarly, a 2-story steel frame needs 36 steel columns, while a functionally equivalent timber frame requires 128 columns [111]. However, the steel frame still results in greater embodied carbon due to higher carbon intensity of steel elements and self-weight increase in the upper structure of the building, which requires stronger and heavier columns to support the load.

To expand the use of timber–framed structures, a growing body of research is investigating the conditions under which timber buildings result in lower carbon effects compared to conventional concrete and steel buildings. Seismic risk and climatic conditions are the primary considerations. In particular, timber–steel composite frame and timber–concrete composite frame are found to provide desired strength and stiffness as well as environmental benefits when properly designed [108,112]. These studies typically do not consider carbon offsets due to replanting trees or permanent biogenic carbon sequestration. However, timber buildings act as temporary carbon sinks, actively capturing and storing carbon dioxide within its structure during their lifetime. The carbon storage effect of timber can be estimated as follows [100]:

$$\boldsymbol{C_s = 3.67VDF_c} \tag{15}$$

where V and D are the volume (m^3) and density (kg/m^3) of timber, respectively. F_c is the carbon fraction, indicating the fraction of a product made of roundwood. F_c is assumed to be 0.5 for pulp, 0.6 for lumber and other products, and 0.9 for wood pellet. The constant value 3.67 is used to convert the molecular weight of carbon to the molecular weight of CO_2 (44/12).

The stored carbon is accounted for in the LCA calculation at end of life. The amount of emission depends on the strategies employed to dispose of the wood, including reuse, recycling, energy recovery, and landfilling. Energy recovery is a strategy that uses wood as a fuel to provide thermal energy to a boiler [101]. On the other hand, newly planted trees that replace those harvested for construction can capture and sequester carbon. Therefore, some researchers suggest that replanting can offset the carbon impact of timber buildings at the end of their life cycle [16,17]. More optimistically, some researchers suggest that future technologies may enable permanent biogenic carbon sequestration, allowing timber buildings to contribute to a long-term climate cooling effect [16,17,102].

While timber structures can reduce embodied carbon, in certain climate zones they can increase heating requirements during the operational stage compared to heavy masonry and reinforced concrete structures [103,104]. Similarly, advanced thermal insulation and innovative facade systems can significantly improve the operational efficiency of a building but are often associated with high embodied carbon intensity [23]. The influence of building materials on indoor climate and operational energy demand is beyond the scope of this study. However, this highlights the need to examine the inherent trade-offs between operational and embodied performance for different materials and construction methods. Table 12 summarizes the studies on structural system selection.

Table 12. Life cycle assessment for structural system selection.

Study	Building type	Method	Simulation results
Helal et al. (2023) [23]	A 52-story office building	Parametric analysis	Building material (i.e., 32/40/50 MPa RC and steel), typology (i.e., shear wall, cantilever, and belt and braced tube), and geometry (i.e., width, depth, aspect ratio, and slenderness ratio) can affect embodied carbon to some degree. In particular, RC frames result in significantly less embodied carbon than steel frames.
Dicko et al. (2023) [113]	A 4-story apartment building	Process-based method	Redesigning the RC building with a timber frame and a low-carbon concrete foundation can reduce GHG emissions by up to 97% when low carbon energy sources are also employed. In particular, the use of a timber frame reduces construction emissions from 3.01 to -0.41 kg CO_2e/m^2/year.
Morales-Beltran et al. (2023) [112]	A 9-story residential building	Process-based method	The RC building emits two times more carbon than the hybrid steel–timber building (CLT floors and GLT frames). Additionally, using CLT instead of RC floor systems can potentially reduce embodied carbon due to the reduced weight of CLT structures. This can result in the use of smaller foundations and thinner shear walls, requiring less concrete and RC bars and thus contributing to an overall reduction in embodied carbon.
Zhang et al. (2023) [114]	A 10-story hotel	Process-based method	The hybrid concrete–timber building (GLT frames and concrete shear walls) results in a weight reduction of 30%, base shear decreases of 37% and 37% in X and Y directions, a maximum interstory drift reduction of nearly 50%, and 65% less carbon emissions compared to the RC building.

Huang et al. (2023) [111]	A 2-story house	Parametric analysis	The timber-framed structure results in the lowest embodied carbon emissions, despite having the highest volume of material used in the frame construction. The timber–steel composite frame is in between due to lower material consumption and lower weight. The steel frame has the highest embodied carbon due to the high weight and the high embodied carbon intensity of steel.
Greene et al. (2023) [102]	A 4-story office building	Process-based method	Mass timber design leads to 80-99% reduction in embodied carbon relative to the functionally equivalent steel building. The amount of reduction depends on end-of-life treatment of mass timber products.
Almulhim and Taher (2023) [105]	A 4-story apartment building	Process-based method	The two-way ribbed slab system can reduce 13–15% of the life cycle environmental impact relative to the two-way solid system, the flat slab system can reduce 17–19%, the flat plate system can reduce 21–22%, and the one-way rib system can reduce 27-28%.
Robati and Oldfield (2022) [101]	A 18-story mixed-use commercial building	Process-based method	With a carefully planned end-of-life strategy, mass timber mid-rise buildings have the potential to benefit from lower embodied carbon emissions, as compared to concrete buildings, across their full lifecycle.
Duan et al. (2022) [106]	A 11-story residential building	Process-based method	The 50-year life cycle GHG emissions of the CLT building is 15% lower than that of the RC building. Replacing RC walls with CLT walls (the hybrid CLT building) can reduce life cycle GHG emissions by 11%. If only production and construction stages are considered, 47% and 37% of embodied GHG emissions can be reduced by CLT and hybrid CLT buildings relative to the RC building.

Rinne et al. (2022) [104]	A 5-story apartment building	Process-based method	The timber building results in the lowest carbon footprint in stages A1-A4, but greater carbon footprint in stages B1-B6 compared to the timber-concrete composite structure and the RC structure due to the use of gypsum boards, which have to be replaced from time to time. Additionally, the use of light timber reduces heat absorption capacity of the building, increasing heating demands.
Puettmann et al. (2021) [51]	Mixed-use commercial buildings with different heights (18, 12, and 8 stories)	Process-based method	Mass timber buildings can reduce 22-50% of carbon emissions compared to functionally equivalent concrete buildings. The regional difference in the reduction (Pacific Northwest, Northeast, and Southeast US) is caused by different building code requirements, production differences, and electricity grid differences.
Yang et al. (2021) [103]	A 3-story apartment	Process-based method	Compared to ordinary buildings made of RC, timber buildings can reduce carbon emissions in the production stage by 64.5%. From a life-cycle perspective, 11.0% of carbon emissions (embodied and operational) can be saved by using timber buildings.
Mirdad et al. (2021) [108]	Floor system with a variety of span lengths	Process-based method	Using thicker mass timber panels results in lower embodied carbon values compared to adding concrete thickness to meet a given span requirement. Increasing timber thickness also contributes to smaller size of lateral load resisting systems and foundations, further reducing the embodied carbon of the entire structure.
Chen et al. (2020) [115]	A 12-story mixed-use building	Process-based method	The total weight of the mass timber building is about 67% of its RC equivalent. The embodied carbon of the mass timber building is 21% lower than that of the RC building. If carbon is permanently stored in the mass timber building, the reduction of embodied carbon can reach 69.5%.

Paik et al. (2019) [116]	A high-rise mixed-use building	Process-based method	The total carbon footprint of the void slab system is 34% less than that of the RC slab due to the reduced amount of concrete required and the lower self-weight of the void slab system (comprising T-shaped steel deck plates, lightweight expanded polystyrene void formers, and anchors).
Gan et al. (2017) [117]	A 60-story composite core-outrigger building	Process-based method	Compared to the composite and pure RC buildings, the pure steel building has 50-60% less overall weight but produces 25-30% more embodied carbon. This is because large amounts of highly carbon intensive steel sections are often required to construct the lateral load-resisting system in the steel building.
Choi et al. (2016) [118]	A 35-story building with 6 stories underground	Process-based method	Replacing RC columns with steel–concrete composite columns can reduce total carbon emissions from columns by 41%. The difference between the two column types is more pronounced in the lower floors where larger axial loads appear. The RC columns require a larger amount of concrete to withstand the loads (high strength concrete is not considered), while steel-concrete composite columns require higher strength of steel shapes, which does not lead to substantial increase in material consumption.
Cho et al. (2012) [107]	A 35-story steel building	Process-based method	Using a braced frame system can result in approximately 16% less lifecycle GHG emissions than the cantilever and belt system. In addition, the Chevron-braced system produces 5.28% less lifecycle GHG emissions than the X-braced system due to a 28.3% reduction in steel usage.

Note: RC = reinforced concrete; CLT= cross-laminated timber; GLT = glued-laminated timber; GHG = greenhouse gases; GWP = Global Warming Potential.

6.2. Material specification

Material specifications are important to encourage the use of more sustainable materials in construction, such as low emission concrete, natural products, and recycled materials. Table 13 summarizes the studies on material specification.

Low emission concrete

The use of low emission concrete can significantly reduce the carbon footprint of buildings [163]. As the compressive strength of concrete increases, the required amounts of concrete and steel reinforcement for structural elements decrease significantly, although the required amount of cement increases [119]. By replacing cement with fly ash or other low-emission binder, high-strength concrete can be a plausible carbon reduction strategy for tall buildings [120].

Natural products

Straw bales are a promising low-carbon alternative to conventional thermal insulation and structural materials [121]. Their mechanical, hygrothermal, energy, and acoustic performance has been extensively studied. Since their performance varies by dimension, density, fiber orientation, and crop type (e.g., wheat, corn, rice, barley, oats, rye, and sorghum), guidelines for their production and standards for their use in building construction are needed [122]. Similarly, bamboo and earthen materials (e.g., adobe bricks, rammed earth, and earth plasters) all have significant potential to improve structural sustainability, but their use is limited in current construction practices due to a lack of guidelines and standards [123].

Recycled materials

Reusing and recycling practices help reduce use of large quantities of new materials and high-emission materials in construction projects. Materials with higher recycled content typically have lower embodied carbon compared to their counterparts with no recycled content. Moreover, industrial wastes like fly ash and blast furnace slag have been used as substitutes for Portland cement to reduce environmental impacts [124,125].

Table 13. Life cycle assessment for material specification.

Strategy	Study	Building type	Method	Simulation results
High strength concrete	Gan et al. (2019) [119]	A 40-story RC building	Process-based approach	In general, increasing concrete strength by every 5 MPa can reduce 4.50% of the plain concrete used and 3.75% of the steel reinforcement.
	Tae et al. (2011) [120]	A 35-story RC apartment building	Process-based approach	Using high-strength concrete can reduce carbon emissions by 4.12-52.06%, depending on lifespan and maintenance assumptions.
Bamboo	Liu et al. (2023) [126]	A 2-story residential building	Process-based method	The carbon emission of the engineering bamboo-based building in the whole life cycle is 30.4% lower than that of the RC building.
	Zhang et al. (2021) [127]	A 3-story single-family house	Hybrid method	The total life cycle emission of the steel-bamboo frame scheme was 17.6% lower than that of the RC frame scheme.
Recycled concrete aggregates	Welsh-Huggins et al. (2019) [124]	A 4-story modern code-designed RC frame building	Process-based approach	Replacing virgin coarse aggregate with recycled concrete aggregate can worsen seismic performance, making the overall life-cycle sustainability calculus unfavorable in terms of GHG emissions.
Fly ash/ industrial wastes/ eco-cement	Bheel et al. (2022) [128]	Concrete mixes	Process-based approach	Replacing 40% natural fine aggregates and 15% Portland cement in concrete with sugarcane bagasse ash and coal bottom ash respectively can increase concrete compressive and tensile strengths, decrease workability, and lead to 4% reduction in embodied carbon.

Fly ash/ industrial wastes/ eco-cement	Welsh-Huggins et al. (2019) [124]	A 4-story modern code-designed RC frame building	Process-based approach	Replacing cement with fly ash can be an effective strategy to improve building sustainability over the entire life cycle, reducing GHG emissions during both construction and service life, without compromising seismic performance.
	Teng and Pan (2019) [125]	A 30-story RC residential building	Process-based approach	Up to 22.8% of the embodied carbon can be reduced through replacing the ordinary Portland cement by blast furnace slag cement, and 9.8% of the embodied carbon can be reduced when 25% of the cement was replaced by fly ash.
	Sandanayake et al. (2017) [129]	A 15-story RC commercial building	Process-based method	A GHG emission reduction of 12% can be achieved by adopting sustainable materials such as fly ash and blast furnace concrete.

Note: RC = reinforced concrete; GHG = greenhouse gases.

6.3. Resilient design

The structure type with the lowest embodied carbon in non-seismic regions may not retain this advantage in seismic regions (e.g., unreinforced masonry structures) [164]. Increased lateral strength requirements in seismic regions can significantly increase material and reinforcement usage, making the previously low-carbon option less advantageous [164]. In contrast, for some types of structures (e.g., reinforced concrete structures), the increased up-front embodied carbon may be offset by avoided damage, making them a low-carbon option in seismic regions [56,92,93]. Similarly, in regions prone to tornadoes and hurricanes, improved structural integrity can minimize damage and reduce the frequency and extent of repair or reconstruction, thereby reducing the long-term embodied carbon of the building [61,62]. Table 14 summarizes the case studies on resilient design.

Table 14. Embodied carbon assessment for resilient design.

Hazard	Study	Building type	Method	Simulation results
Earthquake	Welsh-Huggins and Liel (2018) [92]	Thirty modern reinforced concrete building with varying lateral strengths and ductility capacities (4- and 12-story space and perimeter frames)	Process-based LCA, FEMA P58 performance based assessment	In highly seismic regions, the enhanced lateral strength can significantly reduce the life-cycle embodied carbon losses enough to offset the higher upfront embodied carbon from constructing the larger structural members.
	Hossain and Gencturk (2016) [93]	A 4-story 3-bay special moment-resisting reinforced concrete frame	PEER PBEE methodology, emission assumptions from the literature	Although the environmental impact of repair activities was considerably high for the low-cost low-performance design, it produced only about 40% of the impact of the high-cost high-performance design over the 50-year lifetime of the buildings because of the lower initial and end-of-life environmental impacts.
	Comber et al. (2012) [56]	A planned 75,000 sf 5-story concrete office building	Input-output based LCA, Hazus AEBM methodology	The annualized impact of the standard shear wall system is 22% less than that of the concrete moment frame system, and the annualized impact of the isolated shear wall system is 94% less than that of the standard shear wall system.

Tornado	Adhikari et al. (2020) [62]	Three archetype wood-framed, hip roof residential buildings with 1 or 2 stories	Component-level performance analysis, Athena Impact Estimator	The design that achieves the lowest life cycle cost may not yield the lowest life cycle carbon footprint. Therefore, a multi-objective optimization method is required to balance resilience, sustainability, and cost considerations when designing and retrofitting residential buildings.
Hurricane	Matthews et al. (2016) [61]	A one-story, slab-on-grade, wood-framed, hip roof single family home with varying wind- and water-resistant construction materials and installations	Process-based LCA, component-level performance analysis	Minor changes in component configuration and materials can reduce carbon emissions of a house by approximately 40–60% when considering coastal flood damage repairs over a 30 year building life.

Note: LCA = life cycle assessment; FEMA = Federal Emergency Management Agency; PEER = Pacific Earthquake Engineering Research; PBEE = performance-based earthquake engineering; AEBM = Advanced Engineering Building Module.

6.4. Structural retrofits

Strengthening existing buildings through retrofitting methods can protect them from severe damage and collapse during natural disasters. This allows these buildings to reach their intended lifespan, avoiding extensive repair and replacement that would cause additional environmental impacts. In addition, existing buildings have embodied a significant amount of carbon during their initial construction. Extending their life through structural retrofits can help offset their carbon debt. Moreover, updating existing buildings to meet new functional requirements can reduce the need for demolition and new construction, promoting sustainability and conserving resources. Table 15 lists the studies that assess the environmental impacts of seismic retrofits.

Table 15. Embodied carbon assessment for structural retrofits.

Study	Building type	Method	Simulation results
Keskin et al. (2021) [94]	A 9-story RC hospital constructed 46 years ago	Athena Impact Estimator for Buildings, process-based LCA	The environmental impact from retrofitting is only one-tenth of that of new construction.
	A 7-story RC apartment built in 2001	Athena Impact Estimator for Buildings, process-based LCA	Concrete and steel jacketing result in 16% and 35% embodied carbon emissions respectively during the construction stage. Steel jacketing leads to 30% less carbon emissions during the use stage and 170% less embodied carbons at the end of life due to a high recycling rate. Overall, steel jacketing contributes to 16% less embodied carbon emissions compared to concrete jacketing.
Giresini et al. (2021) [95]	A 4-story masonry office building	The force-based method, process-based LCA	When increasing the diameter of steel tie rods, carbon emission rises from 20 to 50 kgCO2 eq/m^2 as the building's seismic performance improves from 70% to 130% (the baseline is 100%). When increasing the number of carbon fiber reinforced polymer strips, carbon emission rises from 20 to 50 kgCO2 eq/m^2 as the seismic performance improves from 55% to 137%.
Hashemi et al. (2019) [96]	A multi-story limited-ductility RC building with a soft story	Process-based approach, PBEE PEER methodology	The carbon emissions from FRP solutions are not significant due to the small amount of materials required to achieve the given level of strengthening.
Ribakov et al. (2017) [97]	A 5-story RC residential building with large open spaces on the ground floor	Eco-Indicator 99 methodology, two-stage, nested, mixed, and balanced ANOVA test	Under the simulated El Centro, Kobe, and Hachinohe earthquakes, using high-damping rubber bearing isolators or seismic isolation columns for base isolation can improve the overall life cycle performance of the building compared with the status quo.

Wei et al. (2016) [58]	A 3-story, 2-bay pre-1980 RC building	Process-based LCA, probabilistic seismic hazard analysis	The benefit of seismic retrofit outweighs its environmental impact.
Belleri and Marini (2016) [98]	A 3-story RC residential building constructed after the second world war	The Performance Assessment Calculation Tool	Buildings located in a high-seismicity region present an expected additional annual embodied carbon due to seismic risk, which almost equals the annual operational carbon after thermal refurbishment.
Vitiello et al. (2016) [99]	A 3-story RC building constructed in the 1970s	SimaPro 7.3 LCA software package, IMPACT 2002+, probabilistic seismic hazard analysis	Strengthening shear walls results in the highest environmental impact. The isolation strategy has the lowest impact. The FRP retrofit option and the RC jacketing of columns are in between.
Chiu et al. (2013) [67]	Eight low-rise RC school buildings with insufficient seismic performance	The capacity spectrum method, simplified assumptions for carbon emissions	The environmental payback period for seismic retrofit (14.4 years) is shorter than the building's remaining service period (20 years).
Comber et al. (2012) [56]	A 49,000 ft^2 (4,552 m^2) tilt-up concrete shear wall building with wood roof diaphragm constructed in 1963	Input-output based LCA, Hazus AEBM methodology	Increased materials usage for better performance objectives can sometimes result in a net reduction in life-cycle impacts. The environmental impact reductions achieved through enhanced seismic performance are comparable to those obtained through energy efficiency upgrades in highly seismic regions.

Note: RC = reinforced concrete; PEER = Pacific Earthquake Engineering Research; PBEE = performance-based earthquake engineering; FRP = fiber reinforced polymers; ANOVA = analysis of variance; LCA = life cycle assessment; AEBM = Advanced Engineering Building Module.

7. Future research needs

Figure 11 illustrates the need for future research, ranked by frequency of appearance in 33 review articles. The research needs can be categorized into LCA Practice, LCA Methodology, and LCA Applications.

LCA Practice:

- Develop guidelines for consistent and standardized LCA practices
- Ensure the completeness of each LCA by including life cycle stages A–C
- Improve data quality, transparency, and regional specificity
- Improve the methodology for uncertainty analysis
- Develop LCA methods and tools to meet stakeholder needs
- Improve the accuracy of Input-Output method

LCA Methodology:

- Adapt LCA to a hybrid approach
- Adapt LCA to a dynamic approach
- Integrate LCA and life cycle cost analysis
- Integrate LCA and Building Information Modeling
- Include natural hazard impacts in the embodied carbon calculation
- Include human activities in the embodied carbon calculation

LCA Applications:

- Use LCA to enhance carbon mitigation efforts
- Analyze carbon mitigation strategies for different climate zones
- Incorporate LCA results into building certification systems such as LEED

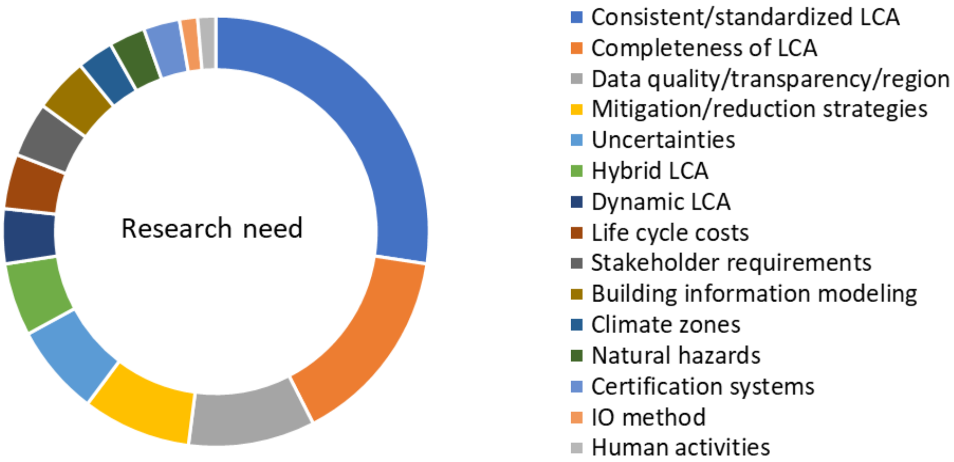

Fig. 11. Research gaps for life cycle assessment.

The following subsections elaborate on the research needs most relevant to the current study, from each of the high-level categories.

7.1. LCA Practice: Consistent and standardized LCA

A consistent framework for LCA is essential for comparing assessment results across different studies and drawing meaningful conclusions regarding building design. The following parameters are important to the establishment of a consistent framework for LCA.

Functional unit

While only a few studies have discussed the consistency problem with functional units, it is important to note that an inadequate definition for functional units can affect the comparability of LCA results [142]. Products with equivalent functions can be compared through LCA. However, defining equivalent functions for materials, systems, and buildings can be challenging. Typically, two buildings with the same usable floor area are considered functionally equivalent, and thus using per unit floor area as the functional unit seems reasonable. However, some researchers argued that building function is also affected by factors such as building type, technical and regulatory requirements, use patterns, and service life, and therefore these factors should be considered when defining a functional unit [142].

System boundary

There is a large discrepancy in defining system boundaries across LCA studies. Most studies only assess embodied carbon emissions in the product stage, while a few studies evaluate the emissions in the construction, use, and end-of-life stages [4,12]. Although it is feasible to separate assessment results for each stage and compare the stages with sufficient data samples – a method that several review articles have utilized for benchmarking purposes [54,144] – this segmented approach can lead to carbon reduction efforts focusing on individual life cycle stages rather than the entire life cycle. For example, timber structures have the greatest carbon impact at the end-of-life stage, while steel structures have the greatest impact at the production stage. Focusing on certain stages rather than the entire life cycle may mislead carbon reduction efforts.

Analysis period

The results of LCA are highly sensitive to the assumed lifespan of buildings, which can range from 1 to 150 years, depending on regional factors and the life cycle stages considered [94]. For example, an assumption of 1 year implies that the assessment only covers the production stage. However, this discrepancy becomes more pronounced under certain conditions. Some studies argued that the entire life cycle of timber structures can be as long as 300 years, accounting for 80 years of tree growth or regrowth, 70 years of building service life, and 150 years of biodegradation in landfills [143]. In regions prone to natural hazards, inadequate structural performance can lead to irreparable damage or collapse of a building, significantly impacting its expected lifespan [55,65].

Databases and tools

Enhanced standardization across tools and databases is essential to ensure results that are consistent and comparable. Incorporating verified, local manufacture EPDs can increase the accuracy of assessment. Accounting for the influence of local electric grid decarbonization can improve the assessment of the trade-off between embodied and operational carbons [20]. Moreover, research is needed to create quantitative benchmarking datasets for individual materials and processes [6].

Modeling approach

The process-based approach may provide a low estimate for life cycle embodied carbon due to data constraints and truncation bias. In contrast, the input-output based approach may provide a high estimate for embodied carbon due to the extended system boundary (both direct and indirect environmental impacts are counted) and the risk of double counting. Nässen et al. (2007) [145] and Säynäjoki et al. (2017) [146] reported that the input-output analysis leads to two times higher estimates than the process analysis for the building sector in Finland.

7.2. LCA Methodology: Adapting LCA to a hybrid approach

By integrating detailed process data with broader economic input-output data, the hybrid approach captures a wide range of emissions sources and interactions, providing a robust assessment of a building's total carbon footprint.

Hybrid life cycle inventory

Only a few databases are currently available for conducting hybrid analyses, and these databases are not tailored for US practices. Future research should expand the availability of data by integrating high-quality process data with comprehensive input-output data to enhance the robustness and applicability of hybrid analysis in the US context [22,24].

Automatic calculation

The adoption of the hybrid approach in LCA studies has been limited due to its increased complexity and time demands compared to other approaches. Automating the calculation process would enhance the accessibility of hybrid analysis for researchers and practitioners. For instance, the process-based approach has been employed in many LCA software tools and BIM systems (e.g., SimaPro, One Click LCA, Athena, GaBi). The recent introduction of computational tools into hybrid analysis represents a notable advancement [23,24], highlighting the need for further research in this area.

7.3. LCA Methodology: Adapting LCA to a dynamic approach

Adapting LCA to a more dynamic approach can enhance its usefulness in evaluating the environmental performance of buildings and other complex systems [74]. The challenges to the development of dynamic approach include the lack of dynamic characterization methods, insufficient data to account for dynamic variations and spatial variability, and uncertainty regarding future scenarios [142].

Dynamic characterization factors

Addressing these challenges requires future research to develop dynamic characterization factors and dynamic parameters for LCI databases. A characterization factor is a quantitative measure that represents the relative importance of a specific intervention (e.g., land use changes, vehicle regulations) to the GWP. To implement a dynamic approach, one could multiply emission amounts by a characterization factor that decreases from 1 (present) to 0 (future), discounting emission impacts over time [74].

Future scenarios

The dynamic approach should reflect the evolving nature of key factors such as fuel mix[3], electricity grid efficiency[4], building operations, and emissions from industrial processes [74]. It should help users to identify potential future impacts and make more informed decisions during the planning and design phases of buildings [16,147].

7.4. LCA Methodology: Building damage in natural hazard-prone regions

Natural hazard impacts are rarely considered in LCA studies due to the perceived low probability of hazard events, and thus perceived low contribution to the total life cycle environmental impact. However, in hazard-prone regions, the repair and replacement of buildings following hazard events can result in significant environmental impacts. Climate change exacerbates the impacts by increasing the frequency and intensity of certain natural hazard events.

Design for disaster resilience

Section 6.1 has discussed the environmental impacts of designing new buildings for disaster resilience. Although there is no standard approach for resilient design, functional recovery, a new design method, aims to have buildings reoccupied and restored to provide their original intended services within a specified timeframe, aligning with the overall goal of resilience [148]. The approach is still under development. Further research is essential to better understand the environmental, economic, and social implications of functional recovery design [149,150], as this can inform the development of new design requirements to ensure that they effectively balance resilience and sustainability.

---

[3] The NETL-NIST collaboration provides dynamic operational energy LCA data (https://www.osti.gov/servlets/purl/1961183).

[4] The NREL's Cambium offers dynamic electricity GWP values (https://scenarioviewer.nrel.gov/).

Tall buildings

The environmental impact of buildings per unit floor area is found to increase with building height due to increased requirements for wind and earthquake design [23]. Research is needed to identify and develop structural systems that can minimize embodied carbon for tall buildings while maintaining or enhancing wind and earthquake resilience [23,107].

Affordability

Accounting for natural hazard impacts in LCA is crucial, particularly for low-income communities that are more likely to be exposed to degraded environments and have limited resources for disaster preparation and recovery [133].

Uncertainties

Accounting for natural hazard impacts will inevitably introduce more uncertainties into LCA. The sources of uncertainty include the occurrence and magnitude of a hazard event at a specific site, the building's response to the event, the mapping of building response to damage, the lifespan of a building, the material quantities needed for repairs, and the environmental impacts linked to the production of each unit of material or repair action. To account for so many sources of uncertainty, a probabilistic approach is recommended for quantifying environmental impacts associated with post-disaster repairs [65].

7.5. LCA Applications: Structural retrofits and adaptive reuse

As noted by Giesekam et al. (2014) [151], demolition is still a preferable option worldwide due to design barriers, financial barriers, and temporary barriers to the retrofitting and repurpose of old buildings. A significant number of structures are demolished each year in the US before reaching the end of their design life due to functional obsolescence [152], highlighting the need to adapt old structures for new purposes and design new buildings with adaptive capabilities [151].

LCA for seismic retrofits

Section 6.2 has discussed the environmental impacts of retrofitting existing buildings for better structural performance. However, current assessment frameworks such as LEED do not consider natural hazard events and building management during the use stage [132,133]. This is partly due to the fact that LCAs are typically conducted at the design stage, where data for the use and management of buildings are not available. Correspondingly, there is limited research investigating the tradeoff between carbon emissions resulting from retrofits and carbon savings achieved by avoiding damage and repairs. Future research is needed to evaluate the environmental impacts of structural retrofits, taking into account the variability in natural hazard risks and the differences in building codes and standards across regions [95,98].

Design for adaptability, durability, and disassembly

Designing for adaptability means that buildings are adaptable throughout their lifespan, allowing for changes in use, enabling minor shifts in space planning, and facilitating additions to the quantity of space [153]. Moreover, designing for durability can extend the useful lifetime of materials and technology in a building, complementary to adaptability [154]. This involves selecting materials, assemblies and systems that require less maintenance, repair, and replacement. Finally, designing for disassembly can ease the process of dismantling products so that their constituent elements can easily be reused or recycled [153,155].

LCA for adaptive reuse

Existing LCA tools are inadequate to assess the case when the components of a building are derived from previous structures or when its components are intended for future reuse. While software such as Athena and SimaPro offer credits for recycling and reusing beyond the buildings' life, these credits do not accurately reflect the environmental benefits because the recycling process can result in the production of different materials or lower quality of the same materials [94,155]. For example, concrete can only be reused as a filler material or concrete aggregates. This underscores the need for improved methodologies and tools to account for the life cycle impacts of reused building components, perhaps accompanied with guidance on the expected applications for reuse of certain materials.

8. Standards and codes

8.1. International standards for life cycle assessment

A set of standards have been developed to increase transparency in assessing and reporting the GHG emissions of products. The International Organization for Standardization (ISO) 14040 specifies a four-stage framework for conducting a LCA [11]. The ISO 14044 specifies the principles and guidelines for carrying out an LCA study. The two standards have been widely adopted in current LCA tools. The Publicly Available Specification (PAS) 2050 further specifies the requirements for LCA, including the standard methods for estimating GHG emissions, system boundaries for emission assessment, data quality rules, and the approaches to allocating emissions to co-products [156]. In particular, PAS 2050 requires that the impact of GHG emissions be assessed over a 100-year period after the product is manufactured. The specification also elaborates the method to assess the carbon footprint of products that are recycled and reused multiple times.

In 2011, the European Standard (EN) 15978 provided indicators, calculation rules, and system boundaries for the assessment of GHG emissions, resource consumption, and water use, among others, related to the environmental performance of buildings [157]. The standard also introduces emission factors into the assessment. Emission factors are constants that translate human activities into environmental impacts. In 2012, the EN 15804 provided core Product Category Rules (PCR) for environmental declarations concerning construction product and construction service (The European Commission 2012). Based on these rules, the ISO 14025 defines the EPD, a document that reports a product's environmental performance over its entire life cycle [8]. The development of EPD marks an important step towards regulating buildings' embodied carbon assessment.

In 2016, a complementary specification PAS 2080 was published, providing guidance on reporting, benchmarking, and target setting for low carbon infrastructure [158]. In 2017, the ISO 21930 updated the principles, specifications and requirements to develop an EPD for construction products and services, construction elements and integrated technical systems used in any type of construction works [159]. Between 2018 and 2019, the ISO 14064 series were released, which specify requirements for the design, development, management, monitoring, quantifying, documenting, reporting, and verification at the organizational level.

In 2021, the EN 15643 incorporated three new stages into LCA: A0 (pre-construction stage), B8 (building user activities), and D2 (exported utilities). The pre-construction phase includes developing a strategic project plan, designing the structure, obtaining necessary permits or entitlements, and assembling the labor and resources essential for construction. Building user activities refer to GHG emissions associated with the user's utilization of the buildings or infrastructure, such as emissions from vehicles using a road or the impact of commuting to an office building. Exported utilities are applicable to infrastructure that generates more energy or other utilities than it uses over the course of the year [160]. However, building repair and replacement due to natural hazard events has not yet been considered in standard LCA practices [91].

8.2. Building codes for embodied carbon assessment and reduction

The International Building Code (IBC) already regulates the use and performance of building materials. However, the code emphasizes occupant health and wellness without regard to embodied carbon emissions. The ASHRAE 189.1 Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential, now part of the International Green Construction Code, has introduced a prescriptive embodied carbon amendment. The amendment requires a certain percentage of products to have EPDs and a certain percentage of products to comply with emission limits [161]. In addition, the New Building Institute is actively proposing amendments for the performance specifications of nearly 40 products within IBC [161]. These proposed amendments target widely used building materials with high carbon emissions, aiming to enhance the environmental sustainability of construction practices.

Furthermore, California adopted the nation's first Green Building Standards Code, requiring that commercial buildings over 100,000 sf and school buildings over 50,000 sf reduce their embodied carbon emissions in three ways for new construction, alterations, and additions to these buildings [162]. For new construction, the project should demonstrate a minimum 10% reduction in GWP compared to a code-compliant building of similar size, function, complexity, type of construction, material specification, and location. Alternatively, the project should certify that the materials used in construction do not exceed the maximum GWP specified in the code document. For an alteration or addition to an existing building, a minimum 45% combined of the existing building’s primary structural elements (foundations; columns, beams, walls, and floors; and lateral elements) and existing building enclosure (roof framing, wall framing and exterior finishes) should be maintained [162]. Moreover, California’s Carbon Intensity of Construction and Building Materials Act (CA AB2446) requires the California Air Resources Board to develop a framework to measure and achieve a 20% reduction in the carbon intensity of new building construction by 2030 and a 40% reduction no later than 2035.

9. Conclusions

In the United States, regulations aimed at reducing energy consumption and GHG emissions from buildings have focused primarily on operational carbon. Building codes have generally excluded the assessment and reduction of embodied carbon, which represents a significant and growing portion of total emissions. As awareness of the importance of embodied carbon increases, there is a growing consensus that strategies to reduce operational energy use should be complemented by efforts to address embodied energy and GHG emissions. This holistic approach is essential to achieving more comprehensive and sustainable reductions in the overall environmental footprint of buildings. By integrating both operational and embodied considerations, regulations can better support the transition to low-carbon buildings and ultimately contribute to broader climate goals.

This report provides an overview of the methods used to assess embodied carbon emissions at each stage of a building's life cycle, including process method, input-output method, hybrid method, and parametric analysis. The advantages and limitations of each method are discussed to help LCA researchers and practitioners select the appropriate method for their specific needs. Further research is needed to adapt LCA to a hybrid approach, which can fill data gaps and improve the accuracy of environmental assessments. Additionally, adapting LCA to a dynamic approach can account for variations in energy use and emissions over time, informing strategic planning for future changing conditions. This report also highlights the importance of considering the impact of natural hazards during the use phase of buildings. Three methods for quantifying the environmental impact of building repairs are discussed, including the Hazus-based approach, the component-based approach, and the damage-based approach. These methods require different levels of detail on building design.

In addition, this report compares LCA databases and tools commonly used in the US, and reviews the case studies that evaluate four carbon reduction strategies: structural system selection, material specification, resilient design, and structural retrofits. Structural system selection aims to minimize embodied carbon through careful selection of building frames and by designing for resource efficiency and longevity. Material specification involves developing predefined guidelines for materials to reduce the use of high-emission products. Resilient design involves designing new buildings that can withstand and adapt to changing environmental conditions, thereby extending their lifespan and reducing the need for frequent repairs or replacements. Structural retrofits focus on strengthening existing buildings or adapting them to new functional needs, thereby reducing carbon footprint by reusing existing structures rather than demolishing and rebuilding. Further research is needed to incorporate the effects of natural hazards into LCA, ensuring that the effort to reduce carbon emissions do not compromise the ability of buildings to withstand natural hazards and vice versa. Additionally, improving carbon reduction for existing buildings with LCA can help identify the most carbon-intensive components, evaluate retrofit options, and achieve net zero emission goals in the building sector.

Finally, this report provides an overview of international standards and building codes related to the embodied carbon of buildings. These standards and codes are crucial for setting benchmarks and guiding industry practices towards more sustainable construction. Further research is needed to develop standardized protocols for functional units, system boundaries, analysis periods, databases and tools, and modeling approaches. Standardization is essential to ensure comparability between studies and to increase the reliability of LCA results.

A limitation of this study is that the review is based on an analysis of peer-reviewed research articles, with conference proceedings and technical reports largely excluded. In addition, this study focuses on LCA as the predominant method for assessing the environmental impact of individual buildings. Other methods such as dynamic flow analysis and multicriteria analysis are only briefly discussed.

Regulatory efforts to reduce the embodied carbon of buildings have increased in recent years [7,9,10,54,161,162]. The goal of this report is to promote a more holistic approach to decarbonizing the built environment. By highlighting innovative strategies and best practices, this report provides a useful resource for industry professionals, policy makers and researchers seeking to reduce carbon emissions and mitigate climate change. This report also underscores the need to integrate resilient and sustainable design principles to ensure that efforts to reduce carbon emissions are aligned with broader climate and societal goals.

References

[1] United Nations Environment Programme. (2023). 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. ISBN: 978-92-807-3984-8.

[2] Davies, D., and Kestner, D. (2020). The Embodied Carbon in Construction Calculation Tool (EC3). STRUCTURE magazine, July 2020. https://www.structuremag.org/wp-content/uploads/2020/06/272007-C-Technology-Davies.pdf

[3] Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., and Passer, A. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy* 258: 114107. https://doi.org/10.1016/j.apenergy.2019.114107

[4] Pomponi, F., and Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment—What does the evidence say? *J. Environ. Manag*. 181, 687–700. https://doi.org/10.1016/j.jenvman.2016.08.036

[5] Department of Energy (2022). Historical Model Energy Code Improvement. https://public.tableau.com/app/profile/doebecp/viz/HistoricalModelEnergyCodeImprovement/CombinedHistoricalCodeImprovement_1

[6] Hu, M., and Esram, N.W. (2021). The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation. *Sustainability* 13(23): 12961. https://doi.org/10.3390/su132312961

[7] Office of the Federal Chief Sustainability Officer (2021). Federal Buy Clean Initiative. https://www.sustainability.gov/buyclean/

[8] British Standards Institution (2011). EN 15978: 2011 Sustainability of Construction Works—assessment of environmental performance of buildings—calculation method.

[9] Environmental Protection Agency (2023). Reducing Embodied Carbon of Construction Materials through the Inflation Reduction Act. https://www.epa.gov/greenerproducts/reducing-embodied-carbon-construction-materials-through-inflation-reduction-act

[10] California Air Resources Board (2022). Assembly Bill No. 2446. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB2446

[11] International Standard Organization (2006). ISO 14040: Environmental management-life cycle assessment-principles and framework.

[12] Pan, W., Li, K., and Teng, Y. (2018). Rethinking system boundaries of the life cycle carbon emissions of buildings. *Renewable and Sustainable Energy Reviews*, 90, 379-390. https://doi.org/10.1016/j.rser.2018.03.057

[13] Edelen, A., and Ingwersen, W. (2016). Guidance on Data Quality Assessment for Life Cycle Inventory Data. EPA/600/R-16/096, Life Cycle Assessment Research Center, Systems Analysis Branch/ Sustainable Technology Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency.

[14] Environmental Protection Agency (2024). Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[15] Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157896.

[16] Breton, C., Blanchet, P., Amor, B., Beauregard, R., and Chang, W.S. (2018). Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches. Sustainability 10: 2020. https://doi.org/10.3390/su10062020

[17] Hawkins, W., Cooper, S., Allen, S., Roynon, J., and Ibell, T. (2021). Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. Structures 33, 90-98. https://doi.org/10.1016/j.istruc.2020.12.013.

[18] Canada Green Building Council (2022). Zero Carbon Building – Design Standard, Version 3. ISBN: 978-1-7781454-1-4. https://www.cagbc.org/wp-content/uploads/2022/06/CAGBC_Zero_Carbon_Building-Design_Standard_v3.pdf

[19] Twinn, R., Desai, K., and Box, P. (2019). Net zero carbon buildings: A framework definition. https://ukgbc.org/wp-content/uploads/2019/04/Net-Zero-Carbon-Buildings-A-framework-definition.pdf

[20] Greer, F., Raftery, P., Brager, G., and Horvath, A. (2023). A perspective on tools for assessing the building sector's greenhouse gas emissions and beyond. *Environ. Res.: Infrastruct. Sustain*. 3, 043001. https://doi.org/10.1088/2634-4505/ad064d

[21] Islam, S., Ponnambalam, S.G., and Lam, H.L. (2016). Review on life cycle inventory: methods, examples and applications. *Journal of Cleaner Production* 136: 266e278.

[22] Crawford, R. H., Stephan, A., and Prideaux, F. (2019). Environmental Performance in Construction (EPiC) Database, The University of Melbourne, Melbourne. https://doi.org/10.26188/5dc228ef98c5a.

[23] Helal, J., Stephan, A., and Crawford, R.H. (2023). Integrating embodied greenhouse gas emissions assessment into the structural design of tall buildings: A framework and software tool for design decision-making. *Energy and Buildings*, 297, 113462. https://doi.org/10.1016/j.enbuild.2023.113462.

[24] Crawford, R.H., Bontinck, P., Stephan, A., Wiedmann, T., and Yu, M. (2018). Hybrid life cycle inventory methods – a review. *Journal of Cleaner Production*, 172, 1273-1288. https://doi.org/10.1016/j.jclepro.2017.10.176

[25] Kneifel, J., O'Rear, E., Grubb, S., Greig, A. and Suh, S. (2019). Building Industry Reporting and Design for Sustainability (BIRDS) Commercial Database Technical Manual: Update. NIST Technical Note 1975, Revision 2, National Institute of Standards and Technology, Gaithersburg, MD, https://doi.org/10.6028/NIST.TN.1975r2

[26] Kneifel, J., O'Rear, E., Webb, D., Greig, A.L., and Suh, S. (2018). Building Industry Reporting and Design for Sustainability (BIRDS) Building Code-Based Residential Database Technical Manual: Update. NIST Technical Note 1999, National Institute of Standards and Technology, Gaithersburg, MD, https://doi.org/10.6028/NIST.TN.1999

[27] Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev. Econ. Stat.* 52, 262-271. https://dx.doi.org/10.2307/1926294

[28] National Academies of Sciences, Engineering, and Medicine (2021). An Assessment of Selected Programs at the National Institute of Standards and Technology Engineering Laboratory: Fiscal Year 2020. Washington, DC: The National Academies Press. https://doi.org/10.17226/26051.

[29] Bureau of Economic Analysis (2024). Input-Output Accounts Data. https://www.bea.gov/industry/input-output-accounts-data

[30] Kneifel, J., Greig, A.L., Lavappa, P., and Polidoro, B. (2018). Building for Environmental and Economic Sustainability (BEES), Online 2.0 Technical Manual. NIST Technical Note 2032, National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.6028/NIST.TN.2032

[31] Huang, M., and Simonen, K. (2019). Comparative Environmental Analysis of Seismic Damage in Buildings. *Journal of Structural Engineering* 146(2): 05019002. https://doi-org.proxy-um.researchport.umd.edu/10.1061/(ASCE)ST.1943-541X.0002481

[32] Hendrickson, C., Horvath, A., Joshi, S., and Lave, B. (1998). Use of Economic Input-Output Models for Environmental Life Cycle Assessment. *Environ. Sci. Technol.* 32(7), 184A–191A. https://doi.org/10.1021/es983471i

[33] Suh, S., and Huppes, G. (2000). Gearing input-output model to LCA, part i: General framework for hybrid approach. CML-SSP Working Paper, CML, Leiden University, Leiden, The Netherlands.

[34] Bare, J.C. (2011). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual. EPA/600/R-12/554. https://pre-sustainability.com/legacy/download/TRACI_2_1_User_Manual.pdf

[35] Suh, S., and Lippiatt, B.C. (2012). Framework for hybrid life cycle inventory databases: a case study on the Building for Environmental and Economic Sustainability (BEES) database. *The International Journal of Life Cycle Assessment*, 17(5), 604-612.

[36] Yang, Y., Ingwersen, W. W., Hawkins, T. R., Srocka, M., and Meyer, D. E. (2017). USEEIO: A New and Transparent United States Environmentally-Extended Input-Output Model. *J. Clean. Prod.* 158, 308–318. https://doi.org/10.1016/j.jclepro.2017.04.150

[37] Ingwersen, W. W., Li, M., Young, B., Vendries, J., and Birney, C. (2022). USEEIO v2. 0, the US environmentally-extended input-output model v2. 0. *Scientific Data*, 9(1), 194.

[38] Bullard, C. W., Penner, P. S., and Pilati, D. A. (1978). Net energy analysis: Handbook for combining process and input-output analysis. Resources and energy, 1(3), 267-313.

[39] Guan, J., Zhang, Z., and Chu, C. (2016). Quantification of building embodied energy in China using an input–output-based hybrid LCA model. Energy and Buildings 110, 443-452. https://doi.org/10.1016/j.enbuild.2015.11.032.

[40] Suh, S., and Huppes, G. (2000). Gearing input-output model to LCA, part i: General framework for hybrid approach. CML-SSP Working Paper, CML, Leiden University, Leiden, The Netherlands.

[41] Lenzen, M., and Crawford, R. (2009). The path exchange method for hybrid LCA. *Environmental science & technology*, 43(21), 8251-8256.

[42] Crawford, R. H., Bontinck, P. A., Stephan, A., and Wiedmann, T. (2017). Towards an automated approach for compiling hybrid life cycle inventories. *Procedia Engineering*, 180, 157-166.

[43] Joshi, S. (1999). Product environmental life-cycle assessment using input-output techniques. *Journal of industrial ecology*, 3(2-3), 95-120.

[44] Heeren, N., Mutel, C.L., Steubing, B., Ostermeyer, Y., Wallbaum, H., and Hellweg, S. (2015). Environmental impact of buildings - what matters? *Environ. Sci. Technol*. 49 (16), 9832–9841. https://doi.org/10.1021/acs.est.5b01735.

[45] Hingorani, R., Dittrich, N., Köhler, J., and Müller, D.B. (2023). Embodied greenhouse gas emissions in structural materials for the German residential building stock — Quantification and mitigation scenarios. *Building and Environment* 245: 110830. https://doi.org/10.1016/j.buildenv.2023.110830.

[46] Lausselet, C., Urrego, J. P. F., Resch, E., and Brattebø, H. (2021). Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. *Journal of Industrial Ecology*, 25(2), 419-434.

[47] Müller, D.B. (2006). Stock dynamics for forecasting material flows—case study for housing in the Netherlands. *Ecol. Econ.*, 59 (1), 142-156.

[48] Environmental Protection Agency (2023). Overview of EPA's MOtor Vehicle Emission Simulator (MOVES4). EPA-420-R-23-019. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10186IV.pdf

[49] California Air Resources Board (2010). Appendix D. Mobile Source Emission Inventory: OSM and Summary of OFF-ROAD Emissions Inventory. http://www.arb.ca.gov/regact/2010/offroadlsi10/offroadappd.pdf

[50] Heidari, B., and Marr, L.C. (2015). Real-time emissions from construction equipment compared with model predictions. *Journal of the Air & Waste Management Association*, 65(2): 115–125. https://doi.org/10.1080/10962247.2014.978485

[51] Puettmann, M., Pierobon, F., Ganguly, I., Gu, H., Chen, C., Liang, S., Jones, S., Maples, I., and Wishnie, M. (2021). Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration. *Sustainability* 13(24): 13987. https://doi.org/10.3390/su132413987

[52] Environmental Protection Agency (2009). EPA NONROAD model updates of 2008 "NONROAD2008". Presented at International Emission Inventory Conference, U.S. Environmental Protection Agency, Baltimore, Maryland, April 14–17. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100AKH1.pdf

[53] Kang, G., Cho, H., and Lee, D. (2019). Dynamic Lifecycle Assessment in Building Construction Projects: Focusing on Embodied Emissions. *Sustainability*, 11, 3724. doi:10.3390/su11133724

[54] Moncaster, A.M., Rasmussen, F.R., Malmqvist, T., Wiberg, A.H., and Birgisdottir, H. (2019). Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies. *Journal of Cleaner Production*, 235, 378-393. https://doi.org/10.1016/j.jclepro.2019.06.233.

[55] Hasik, V., Chhabra, J.P.S., and Warn, G.P., and Bilec, M.M. (2018). Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair. *Engineering Structures*, 175, 123-137. https://doi.org/10.1016/j.engstruct.2018.08.011.

[56] Comber, M.V., Poland, C., Sinclair, M. (2012). Environmental Impact Seismic Assessment: Application of Performance-Based Earthquake Engineering Methodologies to Optimize Environmental Performance. Structures Congress, Jul 11, 2012, page 910-921. https://doi.org/10.1061/9780784412367.081

[57] Feese, C., Li, Y., and Bulleit, W.M. (2015). Assessment of Seismic Damage of Buildings and Related Environmental Impacts. *J. Perform. Constr. Facil.*, 29(4): 04014106.

[58] Wei, H., Skibniewski, M.J., Shohet, I.M., and Yao, X. (2016). Lifecycle Environmental Performance of Natural-Hazard Mitigation for Buildings. *J. Perform. Constr. Facil.*, 30(3): 04015042. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000803

[59] Federal Emergency Management Agency (2022). Hazus Inventory Technical Manual, Hazus 6.0. https://www.fema.gov/sites/default/files/documents/fema_hazus-6-inventory-technical-manual.pdf

[60] Hossain, K. A., and Gencturk, B. (2014). Life-cycle environmental impact assessment of reinforced concrete buildings subjected to natural hazards. *J. Archit. Eng.*, 22(4): A4014001. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000153

[61] Matthews, E.C., Friedland, C.J., and Orooji, F. (2016). Integrated environmental sustainability and resilience assessment model for coastal flood hazards. *Journal of Building Engineering*, 8, 141–151.

[62] Adhikari, P., Mahmoud, H., Xie, A., Simonen, K., and Ellingwood, B. (2020). Life-cycle cost and carbon footprint analysis for light - framed residential buildings subjected to tornado hazard. *Journal of Building Engineering*, 32, 101657.

[63] Federal Emergency Management Agency (2018). Seismic Performance Assessment of Buildings. Volume 4 – Methodology for Assessing Environmental Impacts. https://www.atcouncil.org/docman/fema/248-fema-p-58-4-seismic-performance-assessment-of-buildings-volume-4-methodology-for-assessing-environmental-impacts/file

[64] Applied Technology Council (2004). ATC-58 Project Task Report Phase 2, Task 2.2: Engineering Demand Parameters for Structural Framing Systems. https://www.atcouncil.org/pdfs/atc582t23.pdf

[65] Chhabra, J.P.S., Hasik, V., Bilec, M.M., and Warn, G.P. (2018). Probabilistic Assessment of the Life-Cycle Environmental Performance and Functional Life of Buildings due to Seismic Events. *J. Archit. Eng.,* 24, 04017035.

[66] Murphree, J. (2004). Florida Public Hurricane Loss Projection Model:Development Calibration and Validation of Vulnerability Matrices. MS Thesis, Florida Institute of Technology, Department of Civil Engineering.

[67] Chiu, C.K., Chen, M.R., and Chiu, C.H. (2013). Financial and Environmental Payback Periods of Seismic Retrofit Investments for Reinforced Concrete Buildings Estimated Using a Novel Method. *J. Archit. Eng.*, 2013, 19(2): 112-118.

[68] Hossain, K. A., and Gencturk, B. (2014). Life-cycle environmental impact assessment of reinforced concrete buildings subjected to natural hazards. *J. Archit. Eng*., 22(4): A4014001. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000153

[69] Angeles, K., Patsialis, D., Taflanidis, A.A., Kijewski-Correa, T.L., Buccellato, A., and Vardeman II, C. (2020). Advancing the Design of Resilient and Sustainable Buildings: An Integrated Life-Cycle Analysis. *J. Struct. Eng*., 147(3), 04020341. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002910

[70] di Filippo, R., Possidente, L., Tondini, N., and Bursi, O.S. (2023). Quantitative integration of fire risk with life cycle analysis of building: The case of thermal insulation. *Journal of Building Engineering*, 76, 107124. https://doi.org/10.1016/j.jobe.2023.107124

[71] Blay-Armah A, Mohebbi G, Bahadori-Jahromi A, Fu C, Amoako-Attah J, Barthorpe M. (2023). Evaluation of Embodied Carbon Emissions in UK Supermarket Constructions: A

Study on Steel, Brick, and Timber Frameworks with Consideration of End-of-Life Processes. *Sustainability* 15(20):14978. https://doi.org/10.3390/su152014978

[72] Scheuer, C., Keoleian, G.A., and Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings*, 35(10), 1049-1064. https://doi.org/10.1016/S0378-7788(03)00066-5.

[73] De Wolf, C., Hoxha, E., and Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society* 61: 102322. https://doi.org/10.1016/j.scs.2020.102322.

[74] Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., and Bilec, M.M. (2013). Dynamic life cycle assessment: Framework and application to an institutional building. *Int J Life Cycle Assess*,18, 538–552. doi:10.1007/s11367-012-0528-2.

[75] Negishi, K., Lebert, A., Almeida, D., Chevalier, J., Tiruta-Barna, L. (2019). Evaluating climate change pathways through a building's lifecycle based on Dynamic Life Cycle Assessment. *Building and Environment*, 164, 106377. https://doi.org/10.1016/j.buildenv.2019.106377.

[76] Finnveden, G., and Potting, J. (2014). Life Cycle Assessment. *Encyclopedia of Toxicology*, 3, 74-77. http://dx.doi.org/10.1016/B978-0-12-386454-3.00627-8

[77] Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E. (2021). Attributional & Consequential Life Cycle Assessment: Definitions, Conceptual Characteristics and Modelling Restrictions. *Sustainability* 13(13):7386. https://doi.org/10.3390/su13137386

[78] Schaubroeck, T. (2023). Relevance of attributional and consequential life cycle assessment for society and decision support. *Front. Sustain*. 4:1063583. https://doi.org/10.3389/frsus.2023.1063583

[79] Certified Commercial Property Inspectors Association (2024). Estimated Life Expectancy Chart for Commercial Building Systems and Components. https://ccpia.org/estimated-life-expectancy-chart-for-commercial-building-systems-and-components/

[80] Collins, F. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. *Int J Life Cycle Assess* 15, 549–556. https://doi.org/10.1007/s11367-010-0191-4

[81] Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., and Thurairajah, N. (2022). Uncertainties in whole-building life cycle assessment: A systematic review. *Journal of Building Engineering*, 50, 104191. https://doi.org/10.1016/j.jobe.2022.104191.

[82] De Wolf, C., and Ochsendorf, J. (2014). Participating in an embodied carbon database. Structural Engineer, 92(2), 30-31.

[83] Athena Sustainable Materials Institute (2023). User Manual and Transparency Document Impact, Estimator for Buildings v.5.5. https://calculatelca.com/wp-content/uploads/2023/12/IE4B_v5.5_User_Guide_Dec_2023.pdf

[84] Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., and Wernet, G. (2007). Overview and methodology. EcoInvent Data v2. Final EcoInvent Rep. No. 1, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland. https://inis.iaea.org/collection/NCLCollectionStore/_Public/41/028/41028087.pdf?r=1

[85] Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J.,Vadenbo, C.O., and Wernet, G. (2013). Overview and methodology: Data quality guideline for the

ecoinvent database version 3. https://vbn.aau.dk/ws/portalfiles/portal/176769045/Overview_and_methodology.pdf

[86] Lewis, M., Huang, M., Waldman, B., Carlisle, S., and Simonen, K. (2021). Environmental Product Declaration Requirements in Procurement Policies: An analysis of EPD definitions in Buy Clean and other North American procurement policies. Carbon Leadership Forum, University of Washington. Seattle, WA.

[87] National Renewable Energy Laboratory (2009). U.S. Life Cycle Inventory Database Roadmap. DOE/GO-102009-2881, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. https://www.energy.gov/eere/buildings/articles/us-life-cycle-inventory-database-roadmap-brochure

[88] Waldman, B., Hyatt, A., Carlisle, S., Palmeri, J., and Simonen, K. (2023). 2023 Carbon Leadership Forum North American Material Baselines, Baseline Report, (version 2). University of Washington. Seattle, WA. http://hdl.handle.net/1773/49965

[89] Goedkoop, M., Oele, M., Leijting, I., Ponsioen, T., and Meijer, E. (2016). Introduction to LCA with SimaPro. https://presustainability.com/legacy/download/SimaPro8IntroductionToLCA.pdf

[90] West Coast Climate and Materials Management Forum (2024). EIO-LCA Economic Input Output Life Cycle Assessment. https://westcoastclimateforum.com/content/eio-lca-economic-input-output-life-cycle-assessment-0

[91] Last, N., Kneifel, J., Costello, A., Houska, C., and Morris, K.C. (2024). Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry. [Unpublished manuscript].

[92] Welsh-Huggins, S.J., and Liel, A.B. (2018). Evaluating Multiobjective Outcomes for Hazard Resilience and Sustainability from Enhanced Building Seismic Design Decisions. *J. Struct. Eng*. 144(8): 04018108.

[93] Hossain,K.A., and Gencturk, B. (2016). Life-Cycle Environmental Impact Assessment of Reinforced Concrete Buildings Subjected to Natural Hazards. *Journal of Architectural Engineering*, 22(4), A4014001.

[94] Keskin, F.S., Martinez-Vazquez, P., and Baniotopoulos, C. (2021). An Integrated Method to Evaluate Sustainability for Vulnerable Buildings Addressing Life Cycle Embodied Impacts and Resource Use. *Sustainability*, 13(18):10204. https://doi.org/10.3390/su131810204

[95] Giresini, L., Casapulla, C., and Croce, P. (2021). Environmental and Economic Impact of Retrofitting Techniques to Prevent Out-of-Plane Failure Modes of Unreinforced Masonry Buildings. *Sustainability*, 13(20):11383. https://doi.org/10.3390/su132011383

[96] Hashemi, M.J., Al-Attraqchi, A.Y., Kalfat, R., and Al-Mahaidi, R. (2019). Linking seismic resilience into sustainability assessment of limited-ductility RC buildings. *Engineering Structures*, 188, 121-136. https://doi.org/10.1016/j.engstruct.2019.03.021.

[97] Ribakov, Y., Halperin, I., and Pushkar, S. (2017). Seismic Resistance and Sustainable Performance of Retrofitted Buildings by Adding Stiff Diaphragms or Seismic Isolation. *J. Archit. Eng.,* 24(1): 04017028.

[98] Belleri, A., and Marini, A. (2016). Does seismic risk affect the environmental impact of existing buildings? *Energy and Buildings*, 110, 149-158. https://doi.org/10.1016/j.enbuild.2015.10.048.

[99] Vitiello, U., Salzano, A., Asprone, D., Di Ludovico, M., and Prota, A. (2016). Life-Cycle Assessment of Seismic Retrofit Strategies Applied to Existing Building Structures. *Sustainability* 2(8), 1275. https://doi.org/10.3390/su8121275

[100] Chang, Y.S., Kim, S., Kim, K.M., Yeo, H., and Shim, K.B. (2018). Quantification of Carbon Reduction Effects of Domestic Wood Products for Valuation of Public Benefit. *Journal of the Korea Wood Science and Technology*, 46(2):202-210. https://doi.org/10.5658/WOOD.2018.46.2.202

[101] Robati, M., and Oldfield, P. (2022). The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. *Building and Environment* 214: 108944. https://doi.org/10.1016/j.buildenv.2022.108944.

[102] Greene, J.M., Hosanna, H.R., Willson, B., and Quinn, J.C. (2023). Whole life embodied emissions and net-zero emissions potential for a mid-rise office building constructed with mass timber. *Sustainable Materials and Technologies* 35: e00528. https://doi.org/10.1016/j.susmat.2022.e00528.

[103] Yang, X., Zhang, S. and Wang, K. (2021). Quantitative study of life cycle carbon emissions from 7 timber buildings in China. *Int J Life Cycle Assess* 26, 1721–1734. https://doi.org/10.1007/s11367-021-01960-8

[104] Rinne R, Ilgın HE, and Karjalainen M. (2022). Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. *International Journal of Environmental Research and Public Health*, 19(2): 774. https://doi.org/10.3390/ijerph19020774

[105] Almulhim, M.S.M., and Taher, R. (2023). Environmental impact assessment of residential building structural systems: A case study in Saudi Arabia. *Journal of Building Engineering*, 72, 106644. https://doi.org/10.1016/j.jobe.2023.106644.

[106] Duan, Z., Huang, Q., Sun, Q., and Zhang, Q. (2022). Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross laminated timber alternatives in China*. Journal of Building Engineering*, 62, 105357. https://doi.org/10.1016/j.jobe.2022.105357.

[107] Cho, Y.S., Kim, J.H., Hong, S.U., and Kim, Y. (2012). LCA application in the optimum design of high rise steel structures. *Renewable and Sustainable Energy Reviews*, 16(5), 3146-3153. https://doi.org/10.1016/j.rser.2012.01.076.

[108] Mirdad, M. A. H., Daneshvar, H., Joyce, T., and Chui, Y. H. (2021). Sustainability design considerations for timber-concrete composite floor systems. *Advances in civil engineering*, 2021, 1-11.

[109] Yeoh, D., Fragiacomo, M., De Franceschi, M., and Heng Boon, K. (2011). State of the art on timber-concrete composite structures: literature review. *Journal of Structural Engineering*, 137(10), 1085–1095.

[110] Bland, K.E. (2021). States, Cities Adopting Tall Mass Timber Provisions: A Variety of Approaches. STRUCTURE magazine, 48-49. https://www.structuremag.org/wp-content/uploads/2021/10/282111-C-CodeUpdates-Bland.pdf

[111] Huang, B., Xing, K., and Rameezdeen, R. (2023). Exploring Embodied Carbon Comparison in Lightweight Building Structure Frames: A Case Study. *Sustainability* 15: 15167. https://doi.org/10.3390/su152015167

[112] Morales-Beltran M, Engür P, Şişman ÖA, Aykar GN. (2023). Redesigning for Disassembly and Carbon Footprint Reduction: Shifting from Reinforced Concrete to Hybrid Timber–Steel Multi-Story Building. *Sustainability* 15(9):7273. https://doi.org/10.3390/su15097273

[113] Dicko, A.H., Roux, C., and Peuportier, B. (2023). Achieving Net Zero Carbon Performance in a French Apartment Building? Energies 16(22):7608. https://doi.org/10.3390/en16227608

[114] Zhang X, Huang W, Khajehpour M, Asgari M, Tannert T. (2023). Seismic Performance and LCA Comparison between Concrete and Timber–Concrete Hybrid Buildings. *Buildings* 13(7):1714.

[115] Chen, Z., Gu, H., Bergman, R.D., and Liang, S. (2020). Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings. *Sustainability* 12(11):4708. https://doi.org/10.3390/su12114708

[116] Paik, I., Na, S., and Yoon, S. (2019). Assessment of CO2 Emissions by Replacing an Ordinary Reinforced Concrete Slab with the Void Slab System in a High-Rise Commercial Residential Complex Building in South Korea. *Sustainability* 11(1):82. https://doi.org/10.3390/su11010082

[117] Gan, V.J.L., Chan, C.M., Tse, K.T., Lo, I.M.C., and Cheng, J.C.P. (2017). A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. *Journal of Cleaner Production* 161, 663-675. https://doi.org/10.1016/j.jclepro.2017.05.156.

[118] Choi, S.W., Oh, B.K., Park, J.S., and Park, H.S. (2016). Sustainable design model to reduce environmental impact of building construction with composite structures. *Journal of Cleaner Production*, 137, 823-832. https://doi.org/10.1016/j.jclepro.2016.07.174.

[119] Gan, V.J.L., Cheng, J.C.P., and Lo, I.M.C. (2019). A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. *Journal of Cleaner Production*, 229, 582-597. https://doi.org/10.1016/j.jclepro.2019.05.035.

[120] Tae, S., Baek, C., and Shin, S. (2011). Life cycle CO2 evaluation on reinforced concrete structures with high-strength concrete. *Environmental Impact Assessment Review*, 31(3), 253-260. https://doi.org/10.1016/j.eiar.2010.07.002.

[121] Koh, C.H., and Kraniotis, D. (2020). A review of material properties and performance of straw bale as building material. *Construction and Building Materials*, 259, 120385. https://doi.org/10.1016/j.conbuildmat.2020.120385.

[122] Fąfara, M., Łukaszewski, L., Owczarek, E., and Źrebiec, I. (2022). Life Cycle Assessment (LCA) and environmental comparison the selected construction methods of residential buildings in traditional and straw cubes technology – a case study. *Archives of Civil Engineering*, 68(3), 241-255.

[123] Ben-Alon, L., Loftness, V., Harries, K.A., DiPietro, G., Hameen, E.C. (2019). Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. *Building and Environment*, 160, 106150. https://doi.org/10.1016/j.buildenv.2019.05.028.

[124] Welsh-Huggins, S.J., Liel, A.B., and Cook, S.M. (2019). Reduce, Reuse, Resilient? Life-Cycle Seismic and Environmental Performance of Buildings with Alternative Concretes. *Journal of Infrastructure System*, 26(1), 04019033.

[125] Teng, Y., and Pan, W. (2019). Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong. *Journal of Cleaner Production* 238: 117791. https://doi.org/10.1016/j.jclepro.2019.117791.

[126] Liu, Y., Zhang, J., Xu, J., Wang, Y., Li, B., and Zhang, S. (2023). Carbon emission-based life cycle assessment of rural residential buildings constructed with engineering bamboo: A case study in China. *Journal of Building Engineering*, 76, 107182. https://doi.org/10.1016/j.jobe.2023.107182.

[127] Zhang, X., Xu, J., Zhang, X., and Li, Y. (2021). Life cycle carbon emission reduction potential of a new steel-bamboo composite frame structure for residential houses. *Journal of Building Engineering* 39: 102295. https://doi.org/10.1016/j.jobe.2021.102295.

[128] Bheel, N., Khoso, S., Baloch, M. H., Benjeddou, O., and Alwetaishi, M. (2022). Use of waste recycling coal bottom ash and sugarcane bagasse ash as cement and sand replacement material to produce sustainable concrete. *Environmental Science and Pollution Research*, 29(35), 52399-52411.

[129] Sandanayake, M., Zhang, G., Setunge, S., Luo, W., and Li, C. (2017). Estimation and comparison of environmental emissions and impacts at foundation and structure construction stages of a building – A case study. *Journal of Cleaner Production*, 151, 319-329. https://doi.org/10.1016/j.jclepro.2017.03.041.

[130] U.S. Green Building Council (2024). LEED rating system. https://www.usgbc.org/leed

[131] U.S. Green Building Initiative (2024). Green Globes® Certification. https://thegbi.org/greenglobes/

[132] Ferreira, A., Pinheiro, M.D., de Brito, J., and Mateus, R. (2023). A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings. *Journal of Building Engineering*, 66: 105825. https://doi.org/10.1016/j.jobe.2023.105825.

[133] Charoenkit, S., and Kumar, S. (2014). Environmental sustainability assessment tools for low carbon and climate resilient low income housing settlements. *Renewable and Sustainable Energy Reviews*, 38, 509-525. https://doi.org/10.1016/j.rser.2014.06.012.

[134] U.S. Green Building Initiative (2022). NEW CONSTRUCTION 2021 (ES + BEQ) TECHNICAL REFERENCE MANUAL, Version 1.0. https://thegbi.org/wp-content/uploads/2022/11/Green_Globes_NC_2021_ES__BEQ_Technical_Reference_Manual.pdf

[135] The Building Research Establishment Ltd. (2011). The world's foremost environmental assessment method and rating system for buildings. https://tools.breeam.com/filelibrary/BREEAM_Brochure.pdf

[136] Varma, C.R.S., and Palaniappan, S. (2019) Comparison of green building rating schemes used in North America, Europe and Asia. *Habitat International*, 89: 101989. https://doi.org/10.1016/j.habitatint.2019.05.008.

[137] Bruno Polli, G.H. (2020). A Comparison about European Environmental Sustainability Rating Systems: BREEAM UK, DGNB, LiderA, ITACA and HQE. *U.Porto Journal of Engineering*, 6(2),46-58. https://doi.org/10.24840/2183-6493_006.002_0005

[138] Yeung, H. C., Ridwan, T., Tariq, S., and Zayed, T. (2020). BEAM Plus implementation in Hong Kong: assessment of challenges and policies. *International Journal of Construction Management*, 22(14), 2830–2844. https://doi.org/10.1080/15623599.2020.1827692Liu et al. 2019

[139] Liu, T.Y., Chen, P.H., and Chou, N.N.S. (2019). Comparison of Assessment Systems for Green Building and Green Civil Infrastructure. *Sustainability* 11(7):2117. https://doi.org/10.3390/su11072117

[140] Kim, M. (2023). The Early Case for Stabilization and Sustainability of Korean G-SEED Based on Collaborative Governance: A Theoretical Review. *Buildings* 13, 2631. https://doi.org/10.3390/buildings13102631

[141] GRIHA (2021) Introduction to National Rating System - GRIHA, An evaluation tool to help design, build, operate, and maintain a resource-efficient built environment. https://www.grihaindia.org/sites/default/files/pdf/Manuals/GRIHA_Volume_1_Inside_Pages.pdf

[142] Nwodo, M.N., and Anumba, C.J. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*, 162, 106290. https://doi.org/10.1016/j.buildenv.2019.106290.

[143] Peñaloza, D., Erlandsson, M., and Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. *Construction and Building Materials*, 125, 219-226. https://doi.org/10.1016/j.conbuildmat.2016.08.041.

[144] Dong, Y., Ng, S.T., and Liu, P. (2021). A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Building and Environment*, 204, 108162. https://doi.org/10.1016/j.buildenv.2021.108162.

[145] Nässén, J., Holmberg, J., Wadeskog, A., and Nyman, M. (2007). Direct and indirect energy use and carbon emissions in the production phase of buildings: An input–output analysis. *Energy*, 32(9), 1593-1602. https://doi.org/10.1016/j.energy.2007.01.002.

[146] Säynäjoki, A., Heinonen, J., Junnonen, J. M., and Junnila, S. (2017). Input–output and process LCAs in the building sector: are the results compatible with each other? *Carbon Management*, 8(2), 155–166. https://doi.org/10.1080/17583004.2017.1309200

[147] Asdrubali, F., Baggio, P., Prada, A., Grazieschi, G., and Guattari, C. (2020). Dynamic life cycle assessment modelling of a NZEB building. *Energy*, 191, 116489. https://doi.org/10.1016/j.energy.2019.116489.

[148] Sattar, S., Ryan, K., Arendt, L., Bonowitz, D., Comerio, M., Davis, C., Deierlein, G. and Johnson, K. (2021), Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time. NIST SP 1254, National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1254

[149] Fung, J.F., Zhang, Y., Johnson, K.J., Cook, D.T., and Sattar, S. (2022). A Framework to Evaluate the Cost-Effectiveness of Recovery-Based Design. NIST SP1277, National Institute of Standards and Technology, Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1277

[150] Fung, J.F., Zhang, Y., Johnson, K.J., Cook, D.T., and Sattar, S. (2023). Multidisciplinary research to advance the development of functional recovery for community resilience. Disaster Prevention and Resilience, 2, 13. DOI: 10.20517/dpr.2023.15

[151] Giesekam, J., Barrett, J., Taylor, P., and Owen, A. (2014). The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings*, 78, 202-214. https://doi.org/10.1016/j.enbuild.2014.04.035.

[152] O’Connor, J. (2004). Survey on actual service lives for North American buildings. In Woodframe housing durability and disaster issues conference, Las Vegas, pp. 1-9. https://cwc.ca/wp-content/uploads/2013/12/DurabilityService_Life_E.pdf

[153] Russell, P., and Moffatt, S. (2001). Assessing Buildings for Adaptability: IEA Annex 31 Energy-Related Environmental Impact of Buildings. https://www.iea-ebc.org/Data/publications/EBC_Annex_31_Assessing_Building.pdf

[154] Bertin, I., Saadé, M., Roy, R.L., Jaeger, J., and Feraille, A. (2022). Environmental impacts of Design for Reuse practices in the building sector. *Journal of Cleaner Production*, 349: 131228. https://doi.org/10.1016/j.jclepro.2022.131228.

[155] Tingley, D.D., and Davison, B. (2012). Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment*, 57, 387-395. https://doi.org/10.1016/j.buildenv.2012.06.005

[156] British Standard Institute (2008). PAS 2050 - Assessing the life cycle greenhouse gas emissions of goods and services. ISBN 9780580509780. http://www.carbonconstruct.com/pdf/pas_2050.pdf

[157] British Standard Institute (2011) Sustainability of Construction Works, Assessment of Environmental Performance of Buildings, Calculation Method (BS EN 15978). https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

[158] British Standard Institute (2016). PAS 2080 - Testing and certification in carbon management in infrastructure.

[159] International Standard Organization (2017). ISO 21930: Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services.

[160] Royal Institution of Chartered Surveyors (2023). Whole life carbon assessment for the built environment, version 2. Parliament Square, London, ISBN 978178325034.

[161] National Building Institute (2023). Embodied Carbon Building Code. https://newbuildings.org/resource/embodied-carbon-building-code/

[162] State of California (2024). Supplement for Title 24, Part 11, California Green Building Standards Code. https://www.iccsafe.org/wp-content/uploads/errata_central/2022-CA_Green_July24-Supp_COMPLETE.pdf

[163] Cho, S.H. and Chae, C.U. (2016). A Study on Life Cycle CO2 Emissions of Low-Carbon Building in South Korea. *Sustainability* 8(6):579. https://doi.org/10.3390/su8060579