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Embodied Carbon and Resilient Building Design

Course Number: SU-02-816

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Course Author: Roman Titov

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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).

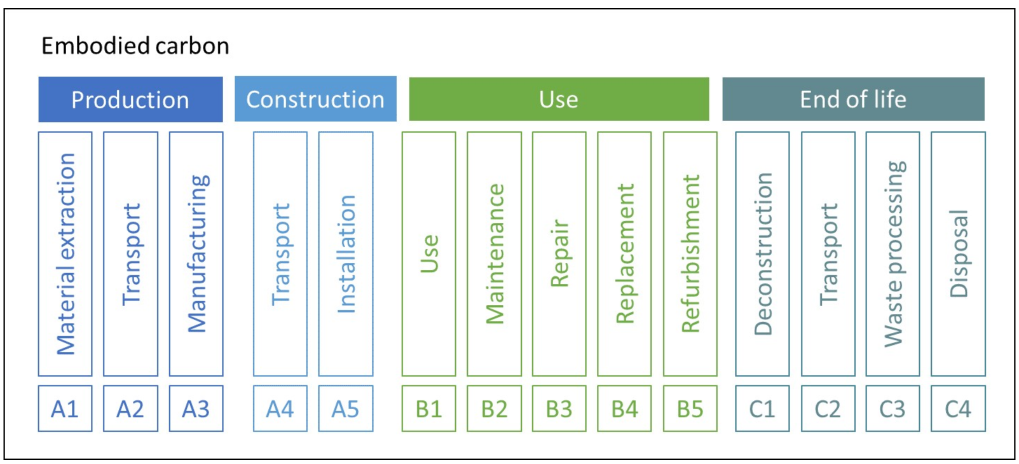

Fig. 1. Building's embodied carbon assessment through the range of process stages. Adapted from [20].

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.

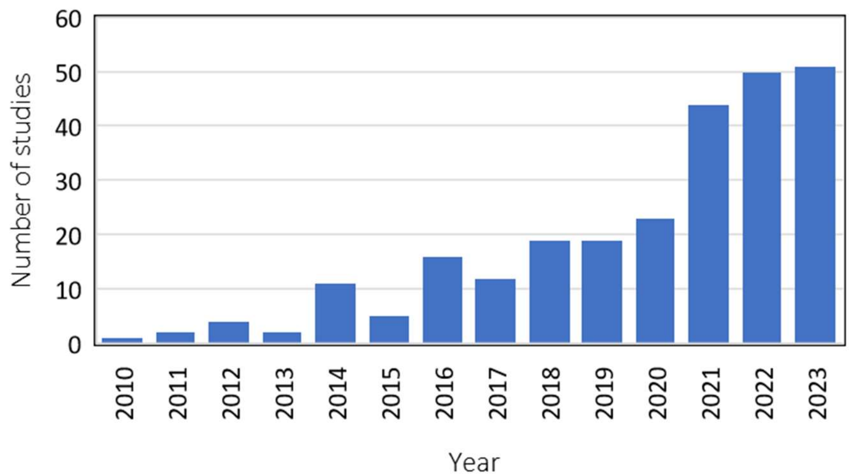

Fig. 2. Publication years of the studies included in this review.

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.