



Circular Design and Embodied Carbon in Living Buildings: The Missing Potential

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Abstract: While the built environment negatively contributes to resource use, waste generation, and climate change, this same sector has the potential to provide innovative solutions to these complex global challenges. Circular economy (CE) strategies have the potential to provide these solutions, yet systems and incentives related to CE and the built environment are disparate and at varying stages of development. Green building rating systems, such as the Living Building Challenge, have the potential to change the market and drive innovation, but these systems need to evolve and change in alignment with the emergence of new and promising strategies, such as CE. The objective of this study was to elucidate whether implementing CE practices could help further reduce embodied carbon and life cycle carbon dioxide equivalent (CO₂-eq.) emissions in buildings that are already environmentally conscious to further drive market innovation. This study analyzed the potential reduction in the embodied carbon of an existing Living Building, the Frick Environmental Center, by applying various CE strategies and using life cycle assessment. The investigated strategies include (1) using materials that are biodegradable and have lower embodied carbon, (2) using salvaged alternatives for embodied carbon-intensive building products, (3) extending the lifespan of selected building materials, and (4) carbon sequestration. Given that the case study building is already LEED Platinum and Living Building certified, the results elucidated the extent of potential environmental impact savings in buildings that are already certified due to having lower environmental impacts than the industry average. The CE strategies resulted in a 30% reduction in the building's embodied carbon (excluding end-of-life) compared with the base case. Results exemplify whether a significant decrease in the buildings' embodied carbon/life cycle CO₂-eq. emissions can be achieved as a result of implementing modest changes in design. **DOI: 10.1061/JAEIED.AEENG-1445.** © 2023 American Society of Civil Engineers.

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Introduction

A circular economy (CE) aims to decouple economic growth from resource consumption by cycling products and materials back into production, either by returning materials to generate new products, or by releasing benign substances to the environment through degradation (Circular Designs 2020). Built on the cradle-to-cradle principle (McDonough and Braungart 2009), the Ellen MacArthur Foundation (EMF) proposed one of the most used CE frameworks that distinguishes between restoring and regenerating resources

through biological or technical cycles (EMF 2015). Biological cycles include biological and renewable materials (e.g., natural fibers) that can eventually be returned to their source through benign biodegradation (Braungart 2020; EMF 2015; Kalmykova et al. 2018; Morsetto 2020). Technical cycles refer to finite materials that should be designed to remain in the production system through maintenance and repair, reuse, remanufacturing, and recycling (EMF 2015; Kalmykova et al. 2018; Morsetto 2020). Key enablers for keeping materials circulating in technical cycles are design for disassembly (Cruz Rios and Grau 2020; Durmisevic 2019; Rios et al. 2015; Stahel 2019), circular business models (Bocken et al. 2016; Cruz Rios and Grau 2020; Michelini et al. 2017; Stahel 2019), and material tracking technologies (Copeland and Bilec 2020; Luscuere and Mulhall 2018; Swift et al. 2015). These enablers can be implemented into the built environment in order to reduce the demand for the key materials used in buildings, including steel, plastics, aluminum, and cement (EMF 2019), and, correspondingly, to decrease embodied carbon as well as global carbon emissions.

The built environment is a major contributor to environmental impacts (Pomponi and Moncaster 2017). About 38% of annual global carbon dioxide (CO₂) emissions are from the building sector, of which 28% is from building operations (i.e., use phase and energy-related emissions) with the remaining largely from building material manufacturing and construction (UNEP 2020). Buildings consume about 41 billion tons of resources annually and contribute to a significant amount of waste generation (Mollaei et al. 2021; EPA 2020). With the built environment, we typically refer to two types of carbon: operational carbon and embodied carbon. Operational carbon generally occurs in the operational phase of a building and refers to the emissions due to building energy

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consumption. Embodied carbon is the carbon emitted from the other phases of the building, often referred to as the preuse stage (e.g., raw material extraction, production, transportation, design, and construction), use stage (e.g., maintenance, repair, replacement), and end-of-life stage (e.g., deconstruction or demolition) (UL 2020; WorldGBC 2019). Accordingly, the embodied carbon and operational carbon together indicate the life cycle CO₂-eq. emissions of a building. Over the past decade, research on building operational carbon was more prevalent than research on embodied carbon (Pomponi and Moncaster 2016). However, reducing the embodied carbon in the built environment is acknowledged as an important path for reducing building sector CO₂ emissions (USGBC 2019a). It should be emphasized that, by definition, embodied carbon does not include emissions from operational emissions but does include CO₂ equivalent (CO₂-eq.) emissions generated from all activities including material replacements throughout the lifespan of a building (Waldman et al. 2020). Therefore, as illustrated in Fig. 1, while operational carbon is associated with Stage B6 only, embodied carbon includes the rest of the building life cycle stages excluding B7 and D (CLF 2020; WorldGBC 2019).

As buildings become more energy efficient and the use phase of buildings improves with low/zero carbon buildings and renewable energy, the relative importance of embodied carbon increases (Kayaçetin and Tanyer 2020; Malmqvist et al. 2018; Pan and Teng 2021). Given the growing interest in calculating embodied carbon and proposing ways to reduce it, the International Energy Agency's Energy in Buildings and Communities (IEA-EBC) Programme conducted a 5-year research project that aimed to provide guidance for researchers in calculating and mitigating embodied carbon (IEA-EBC 2016; Seo et al. 2016). The IEA-EBC grouped potential mitigation strategies under three categories as substitution of materials (e.g., using biobased materials), reduction of resource use (e.g., reusing old building structures or using durable products for longer lifespan), and reduction of construction stage impacts (e.g., energy efficiency or site waste management) (Nehasilova et al. 2016, pp. 94–95). Similarly, Pomponi and Moncaster's review paper identified key elements for embodied carbon mitigation, including using construction materials with lower embodied carbon, promoting better design, reusing embodied carbon-intensive materials, and adopting strong policy drivers (Pomponi and Moncaster 2016). As can be seen from these findings, shifts in

material selection are key strategies in potential embodied carbon reduction. More broadly, Densley Tingley et al. argued that construction materials can be considered as input flows of embodied carbon and cradle-to-cradle embodied carbon reductions can be achieved by implementing CE principles (Densley Tingley et al. 2018). The current study elucidates the potential to reduce embodied carbon by implementing various CE practices in a building that is already certified due to having lower environmental impacts than the industry average as detailed in the subsequent sections.

CE strategies can be employed to reduce the embodied carbon of the construction sector, as CE aims to reduce raw material consumption and waste generation by returning materials back into production or use (Arora et al. 2021; Babbitt et al. 2018; Geisendorf and Pietrulla 2018; Kalmykova et al. 2018; Schroeder et al. 2019). According to the EMF, applying CE strategies (also called circular design) to the built environment could reduce global CO₂ emissions by 2 gigatons (Gt) in 2050, and by 3 Gt beyond 2050 (EMF 2019; Material Economics 2018). As outlined in the 2019 Circularity Gap Report, considering the global material footprint, only 8.4 Gt of materials consisted of cycled inputs, yet 84.4 Gt of materials were extracted resources, resulting in the global economy being only 9% circular in 2019 (Circle Economy 2019). The performance of the global material footprint has not improved in 2020, as our global economy was only 8.6% circular last year (Circle Economy 2021a). EMF reported that the built environment consumes approximately half of the world's extracted materials on an annual basis (EMF 2019). Considering these numbers and the current state of raw materials extraction rate, it is critical to implement strategies, including key CE strategies of narrowing, slowing and/or closing resource loops in resource-intensive sectors such as building and construction (Circle Economy 2021a; EMF 2019; Stahel 2019). It should be highlighted that many circular design strategies overlap with the strategies listed in the previous paragraph that are proposed to reduce embodied carbon (Pomponi and Moncaster 2016). As the CE concept is gaining momentum for the built environment, there are numerous papers that review existing literature on CE applications in the building and construction industry (Benachio et al. 2020; Hart et al. 2019; Joensuu et al. 2020; Munaro et al. 2020; Norouzi et al. 2021; Pomponi and Moncaster 2017).

There are a few publications in the literature that examine the potential environmental benefits of applying CE strategies in the built environment by using life cycle assessment (LCA). LCA is

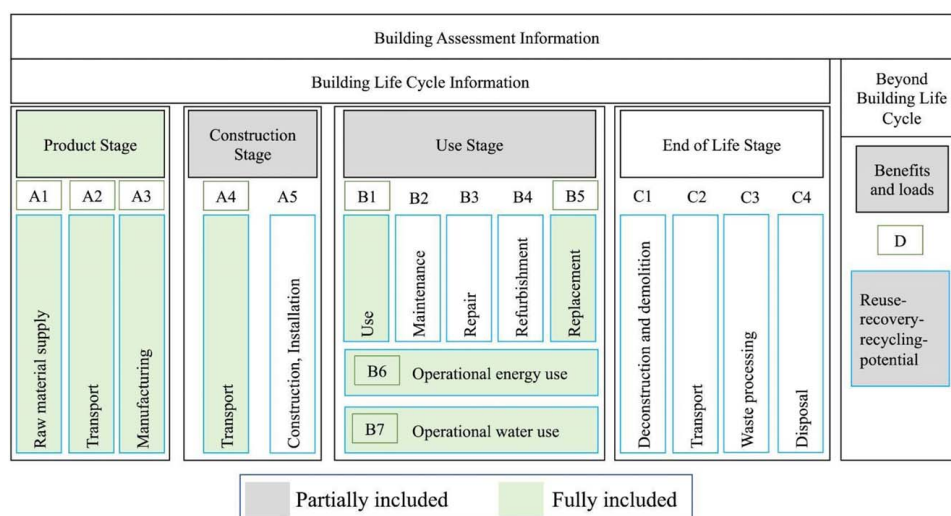


Fig. 1. Building life cycle stages and system boundaries. (Adapted from Gardner et al. 2020.)

a methodology for evaluating the environmental impacts of products, processes, and/or services throughout their life cycles (i.e., raw materials acquisition, manufacturing, use, end-of-life) by quantifying all inputs and outputs associated with each life cycle stage (ISO 2006a,b). For instance, using LCA, Minunno et al. compared the environmental performance of two modular buildings, one of which was designed for disassembly and reuse, and the other was traditionally built. They concluded that up to 88% reduction in CO₂-eq. emissions were achieved employing design for disassembly and reuse compared with regular practices (Minunno et al. 2020). Similarly, Eberhardt et al. analyzed potential CE savings on a conventional Danish office building considering different scenarios for design for disassembly and material choice optimization. They found a major improvement in the building's environmental performance (i.e., lower impact) due to design for disassembly and reported that the choice of building materials greatly affects the building's embodied impacts (Eberhardt et al. 2019). Another study by Buyle et al. assessed seven alternative internal wall assemblies and found that demountable wall assembly was the least impactful alternative for the environment considering the whole life cycle of a building (Buyle et al. 2019). In another study, Cruz Rios et al. evaluated the benefits of reusing a material with high embodied energy compared with its single-use alternative. They analyzed whether design for disassembly followed by reuse of steel frames has lower embodied impacts than a single-use wood frame in buildings (Cruz Rios et al. 2019). Although LCA is used as an assessment tool, it should be noted that there is a lack of guidance on how to apply LCA in circular buildings (Hossain and Ng 2018; van Stijn et al. 2021). Accordingly, there are publications that aim to create new and preliminary frameworks to assess CE strategies in existing buildings (van Stijn et al. 2021; Zimmermann et al. 2020).

Voluntary green building certification programs such as the Living Building Challenge (LBC) by the International Living Future Institute (ILFI) (ILFI 2021a) and Leadership in Energy and Environmental Design (LEED) by the US Green Building Council (USGBC) (USGBC 2021) help drive sustainable design and construction practices in the built environment. As a result, LEED and LBC certified buildings tend to have lower environmental impacts than the industry average (ILFI 2021b; USGBC 2018). For reference, the developer of LEED, the USGBC, aims to reduce embodied carbon, protect human and ecological health, and advance the CE in materials and resources used in the built environment (USGBC 2019b). More specifically, LEED addresses the following CE elements explicitly: (1) prioritizing regenerative resources, (2) extending lifetime, and (3) using waste as a resource (Circle Economy 2021b). Similarly, the LBC certification touches upon circular design strategies such as design for deconstruction, reuse, and recycling of building materials. LBC also requires a carbon offset for the embodied carbon of building materials but does not address other CE and carbon mitigation strategies such as extending product durability and carbon sequestration.

This paper aims to investigate whether increasing circularity with modest changes in building design can help further reduce the embodied carbon in a certified Living Building that has achieved LEED Platinum. CE scenarios analyzed include (1) using materials that are biodegradable and have lower embodied carbon, (2) using salvaged alternatives for embodied carbon-intensive building products, (3) extending the lifespan of selected building materials, and (4) carbon sequestration. LCA is used to quantify the environmental implications of applying CE strategies as explained in the materials and methods section. The Frick Environmental Center (Pittsburgh, Pennsylvania) was selected as the case study building as detailed in the next section along with the

CE strategies that are evaluated. Lastly, results and limitations of the current study are discussed, and ideas are shared for future research. Results are intended to inform researchers, engineers, and building designers on the potential benefits of implementing CE practices into the building and construction industry, more specifically its impact on reducing the embodied carbon and life cycle CO₂-eq. emissions of buildings.

Materials and Methods

Methodology

The LCA was used in order to assess the outcomes of implementing various CE principles on the embodied carbon levels of the Frick Environmental Center. The LCA has four phases: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment, and (4) interpretation. These will be discussed in detail in the subsequent sections (ISO 2006a,b). Environmental impacts were modeled using the ecoinvent 3 (ecoinvent 2020) and US Life Cycle Inventory (US LCI) (NREL 2020) databases accessed from the SimaPro Professional v7 software (PRé Sustainability 2020).

Case Study Description

The case study building is the Frick Environmental Center, which is a public building in Pittsburgh, Pennsylvania and serves as a venue for numerous events. This building is three-story, has 15,000 ft² net floor area (or 16,440 ft² gross floor area), and has extensive sustainable features such as being net-positive for energy and water. Accordingly, the site has onsite solar panels, geothermal wells, a rainwater collection, a storage and purification system, and temperature, humidity, and CO₂ monitoring systems (Gardner et al. 2020; ILFI 2018). It is also designed with passive design strategies such as benefiting from summer breezes and winter sun due to the building orientation and using a natural ventilation system as a primary approach for conditioning, among others (ILFI 2018). The center received numerous awards from the American Institute of Architects, the American Concrete Institute, and Urban Land Institute Pittsburgh, among others (Pittsburgh Parks 2020). The Frick Environmental Center is a certified Living Building by ILFI (ILFI 2018) and achieved LEED Platinum by the USGBC (USGBC 2017).

The current study builds on the work of Gardner et al., in which the authors conducted a cradle-to-grave LCA for the Frick Environmental Center with a functional unit of "whole Living Building with a lifetime of 100 years" (Gardner et al. 2020). The scope of this study included preuse (raw material extraction, manufacturing, and processing when available), use (material replacements, energy consumption, and onsite emission), and end-of-life phases in the analysis and excluded the construction stage due to the lack of available data. A holistic inventory was compiled using as-built drawings to complete the quantity takeoffs and material specifications for the materials and systems used in the building. This paper quantified the impacts largely using the ecoinvent 3 database (ecoinvent 2020) and the impact assessment method, Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) (Bare 2012). Results indicated that the embodied carbon of materials (i.e., preuse and replacements only) accounted for 62% of life cycle CO₂-eq. emissions before considering the offset by the onsite photovoltaic (PV) electricity generation, and material replacements accounted for 46% of the building's embodied carbon. This finding is consistent with the studies that show how

Table 1. Strategies to reduce embodied carbon in buildings considering literature, circular economy principles, and Living Building Challenge standard

Embodied carbon mitigation strategies related to building design (Pomponi and Moncaster 2016)	CE (EMF 2015)	LBC (ILFI 2019)	FEC	
			Already in place (ILFI 2018)	Current study
Use of materials with lower embodied carbon	X	^a		A
Better design (e.g., design for deconstruction)	X	X	X	
Reduction, reuse, and recovery of embodied carbon-intensive construction materials	X	X	X	B, C
Refurbishment of existing buildings instead of new built	X	X		
Decarbonization of energy supply/grid	X	X	X	
Inclusion of waste, byproduct, used materials into building materials	X		X	
Increased use of local materials		X	X	
More efficient construction processes/techniques		X	X	
Carbon mitigation offsets, emissions trading, carbon tax	X	X	X	
Extending the building's and building materials' life	X			D
Carbon sequestration	X	^a		E
Increased use of prefabricated elements/off-site manufacturing				
Demolition and rebuild				

Note: CE = Circular economy; LBC = Living Building Challenge; FEC = Frick Environmental Center.

^aThe LBC focuses on sourcing local materials and materials that are free of harmful chemicals, but not *necessarily* on materials with low embodied carbon.

the largest impacts result from material replacements in energy-efficient buildings or buildings with longer lifetimes (Cellura et al. 2014; De Wolf et al. 2017; Francart and Malmqvist 2020). For reference, Röck et al. reviewed over 650 building LCA case studies and reported that in energy-efficient buildings the materials account for 50%–90% of CO₂-eq. emissions (Röck et al. 2020).

Given that embodied carbon contributes significantly to buildings' greenhouse gas emissions (Waldman et al. 2020), and this is found applicable for the Frick Environmental Center (Gardner et al. 2020), the current work implements various CE strategies to investigate potential savings in embodied carbon using LCA methodology.

Goal and Scope Definition

The goal of this study is to evaluate whether CE strategies can help to further reduce the embodied carbon in Living Buildings. In order to examine potential scenarios, different approaches that are applicable for this purpose were compiled from the literature (Table 1). To start with, in a review paper, Pomponi and Moncaster identified the main embodied carbon mitigation strategies found in the built environment literature (Pomponi and Moncaster 2016) (first column in Table 1). Although there is not yet a consensus in the literature on CE strategies (Kirchherr et al. 2017; Korhonen et al. 2018; Saidani et al. 2019), considering the main CE goals of increasing product durability, recovery, and use of biobased products (EMF 2015), numerous overlaps between embodied carbon mitigation strategies and CE strategies can be identified (second column in Table 1). As stated previously, the case study building in the current work is a certified Living Building, therefore, strategies that are covered in the LBC are also included in Table 1 (third column) for cross comparison (ILFI 2019). While many CE and embodied carbon mitigation strategies have some commonality with the LBC standard, there is not an overwhelming focus on product or building durability or the inclusion of byproducts into building materials in the LBC (ILFI 2019). The LBC does require the embodied carbon associated with the building materials and construction to be neutralized through carbon offsets, but at this point material replacements are not included (Gardner et al. 2020; ILFI 2019). Considering the Frick Environmental Center, the strategies that are already in place were also included in Table 1 (fourth column).

Finally, circular design scenarios that were modeled in this study for potential embodied carbon mitigation are presented in Table 1 (fifth column) and are expanded in the following subsection. Circular strategies that would increase the building circularity while resulting in modest changes (e.g., structural grid would not be modified) in building design were selected for analysis. The strategies that were selected are more focused on the material selection phase. For instance, salvaged beams were selected instead of new ones, a different type of flooring was chosen, concrete was procured from companies that practice carbon sequestration, solar panels with recovered silicon cells were bought, and companies with optimized maintenance services or circular business models to extend product lifetime were chosen. While ideally the buildings should be designed with CE principles from the early design phases (e.g., design for deconstruction), the strategies that were selected here in the current study can be applied to buildings in late design phases to increase their circularity through material selection and procurement.

Different from Gardner et al., the system boundary considered in the current work is cradle-to-gate, meaning that the end-of-life phase of the building's life cycle is not included in the analysis. In order to ensure consistency in LCA data (e.g., inventory, results, assumptions), the functional unit is selected as compatible with Gardner et al. as the whole Living Building with a lifetime of 100 years (Gardner et al. 2020). Detailed life cycle stages that are included in the current analysis are presented in Fig. 1.

Circular Design Scenarios and Assumptions

In order to assess whether CE strategies can contribute to mitigating the embodied carbon in Living Buildings, five scenarios under four main strategies (fifth column in Table 1) were modeled as detailed herein. Given that the case study building was already certified, significant shifts in design could change the basics in which the certifications were achieved, or they could affect the causal relations between design choices. Therefore, it should be highlighted that relatively small changes in design were assumed and modeled in the current study to make sure these changes did not impact the physical properties, function, and aesthetics of the existing building. This approach could also elucidate whether significant improvement in the buildings' embodied carbon can be achieved as a result of implementing small changes in design. Best-case scenarios for each strategy were assumed, meaning that materials with

possible longer lifespans were selected and a 100% reuse rate was considered for salvaged materials, which indicates perfect substitution. The LCAs for each scenario were conducted by keeping everything constant except the inventories of substituted/replaced materials and assumed scenarios as expanded in the following subsections.

Use of Materials with Lower Embodied Carbon (Scenario A)

The strategy *use of materials with lower embodied carbon* analyzed the impact of substituting materials with their biodegradable alternatives on the overall embodied carbon of the case study building. Two scenarios were evaluated: hemp insulation in place of mineral wool (Scenario A1) and linoleum flooring in place of carpet (scenario A2).

Reduction, Reuse, and Recovery of Embodied

Carbon-Intensive Construction Materials (Scenarios B and C)

The strategy *reduction, reuse, and recovery of embodied carbon-intensive construction materials* included two different scenarios related to the structural assembly and the energy system of the Frick Environmental Center. The first scenario analyzed the impact of substituting new materials with salvaged alternatives (Scenario B), and the second scenario evaluated substituting silicon parts with reused ones in PV panels (Scenario C). As stated previously, a 100% reuse rate was considered, meaning that for each material that is recovered, the production of the same amount of virgin material is avoided. However, in reality, this assumption may not be as thorough as accounted here as a rebound effect may occur. Given that there is no consensus in the published body of the literature on how to account for a rebound effect in LCAs (Croes and Vermeulen 2021; Font Vivanco and van der Voet 2014), potential rebounds were not considered and best-case scenarios were modeled in the current study. Accordingly, the following was developed to calculate the environmental impacts of salvaged/reused materials:

$$\text{Environmental impact} = [(1 - RR) \times x] - [RR \times x] \quad (1)$$

where RR = reuse rate of the material; and x = value of the associated environmental impact (e.g., global warming) for the new material that is not reused. This equation was applied for both scenarios that were evaluated under this strategy.

Extending the Building's and Building Materials' Life (Scenario D)

As previously discussed, in energy-efficient buildings, the largest impacts result from material replacements (Cellura et al. 2014; De Wolf et al. 2017; Francart and Malmqvist 2020). Taking this into consideration, in order to identify materials that require a high number of replacements, the lifespan assumptions from the whole building LCA were examined and products that have a shorter warranty compared with their expected lifespans were listed. Gardner et al. extracted the lifespan data from product warranties that were compiled for LEED and LBC certification purposes (Gardner et al. 2020). In the current study, instead of using warranty data, it was assumed that the products would last as long as their expected service lives. This would be the best-case scenario for maintenance and repair purposes. Accordingly, this strategy evaluated the impact of extending the lifespan of the acoustic ceiling tiles (ACTs) (Scenario D1) and thermoplastic polyolefin (TPO) membrane (Scenario D2) on the building's embodied carbon.

Carbon Sequestration (Scenario E)

There are numerous technologies available in the market for carbon capture, utilization, and storage (Kocs 2017). Concrete is one of the

most abundant materials used in the building and construction industry, which consists of cement, aggregates, and water (Howden 2020). Although cement comprises only 10%–15% of concrete by volume, previous LCA literature showed that it is the major contributor to many environmental impacts—especially global warming—of concrete (Knoeri et al. 2013; Manjunatha et al. 2021; Ventura et al. 2021). For reference, cement production is the fifth major source of greenhouse gas emissions in the United States, which released 40.9 million metric tons of CO₂-eq. emissions in 2019 (EPA 2021). In order to evaluate the potential for reducing the overall embodied carbon of the Frick Environmental Center, a CO₂ utilization technology, *CarbonCure*, was considered in the current study (CarbonCure 2021b). *CarbonCure* injects postindustrial CO₂ into concrete during the mineralization phase to reduce the need for cement. This process also helps to permanently embed CO₂ in concrete as a form of mineral (i.e., calcium carbonate) (CarbonCure 2021a). This technology results in a material that performs equivalent to regular concrete, which makes this scenario applicable (CarbonCure 2021a, b).

Life Cycle Inventory Analysis

The LCI analysis is the data collection step in LCAs where all input and output data for the full system are detailed. In the current study, relevant LCI was extracted from Gardner et al. as they conducted a full LCA for the same building (Gardner et al. 2020). The authors created a comprehensive list of inventory with a full list of materials and their quantities for the Frick Environmental Center (Gardner et al. 2020). The remaining inventories were collected from the ecoinvent 3 database (ecoinvent 2020), peer-reviewed sources (Gorree et al. 2000; Zampori et al. 2013), and manufacturers (CarbonCure 2021a). In the following subsection, the unit processes for both the base case and the circular design scenarios are further discussed for each strategy.

Scenario A1 (Use of Biodegradable Materials and Materials with Lower Embodied Carbon): Hemp Insulation

Substitution of inorganic mineral fibers with their natural alternatives for building thermal insulation was a suggested approach by the literature (Islam et al. 2022; Korjenic et al. 2011). Given that natural fibers are manufactured from agricultural sources, they are environmentally sustainable and have a lower impact on human health compared with inorganic fibers (Sassoni et al. 2014). Accordingly, in Scenario A1, hemp was assumed to be used instead of mineral wool as an insulation material as it is a natural alternative, has lower embodied carbon, and is biodegradable (Karche and Singh 2019).

As per the quantity takeoff provided by Gardner et al., there is 1,054 ft³ of black locust lumber wall in the Frick Environmental Center, in which mineral wool is used as an insulation material. As a first step, the case study building's wood-black locust envelope assembly was remodeled in SimaPro Professional v7 software. Table S1 in the *Supplementary Information (SI)* file presents the amount and units of each material as well as the assumptions made for modeling 1 ft³ wall with mineral wool as an insulation material (base case). Then, in order to model the circular design scenario, inventory data for hemp was extracted from Zampori et al., where the authors evaluated the cradle-to-gate environmental implications of using hemp as a thermal insulator for building applications instead of a mineral-based one (Zampori et al. 2013). They considered an insulation mat that consists of 85% hemp and 15% polyester fiber in a wall that has similar technical properties (e.g., wall and insulation thickness, thermal characteristics) to the Frick Environmental Center (Gardner et al. 2020; Zampori

et al. 2013). The lifespan of the wall was assumed as 25 years for both scenarios, meaning that it needs to be replaced three times (plus one installment) during the building's lifetime of 100 years.

Scenario A2 (Use of Biodegradable Materials and Materials with Lower Embodied Carbon): Linoleum Flooring

Minne and Crittenden compared five different flooring options including carpet, hardwood, linoleum, vinyl, and ceramic in terms of their environmental and economic performances (Minne and Crittenden 2015). They normalized the environmental and economic impacts and created a single score in order to compare the overall performance of these options. As per their findings, over the expected service life of a building, carpet showed the worst (environmental score was 30.74 points, cradle-to-grave) and linoleum showed the best (environmental score was 6.62 points, cradle-to-grave) overall performance (Minne and Crittenden 2015). Considering this finding, in Scenario A2, linoleum was assumed to be used instead of carpet. As per the material quantities presented by Gardner et al., 3,523 ft² of carpet was used in the Frick Environmental Center. A cradle-to-grave LCA for linoleum flooring was conducted by Gorree et al., from where extraction and production data were collected and the alternative scenario was modeled (Gorree et al. 2000). The lifespan of the linoleum flooring was assumed as 40 years (Flooring Inc. 2022; Mattison et al. 2013), meaning that it would need to be replaced twice (plus one installment) during the building's lifetime of 100 years.

Scenario B (Reduction, Reuse, and Recovery of Embodied Carbon-Intensive Construction Materials): Salvaged Steel Beams

In Scenario B, it was assumed that recovered steel beams from existing buildings that were being deconstructed were reused instead of using new beams (Densley Tingley and Allwood 2014). Considering the cut-off allocation approach, which suggests that impacts resulting from material production were allocated to the primary user (ecoinvent 2021; Malabi Eberhardt et al. 2020), the salvaged steel beams that enter the building were assumed to be free of the burdens of production and with the credits for reuse. As a salvaged material was assumed to substitute the entire production of new material of the same type (i.e., perfect substitution), using Eq. (1), the environmental impact of a 100% salvaged material equals -x, which means the environmental impact savings are equal to the environmental impact of new material. According to Gardner et al., the Frick Environmental Center has 137,550.11 lb of steel beams with a lifespan of 75 years (Gardner et al. 2020). Although the lifetime of the steel beams was assumed as 75 years and the whole building's lifespan was 100 years, replacement of these materials would not be realistic. Therefore, only the impacts resulting from installment was considered for this scenario.

Scenario C (Reduction, Reuse, and Recovery of Embodied Carbon-Intensive Construction Materials): Remanufacturing PV Modules

In Scenario C, it was assumed that recovered silicon cells from existing modules were used to remanufacture new PV modules (Table S2 in the SI) (Deng et al. 2021). Similar to Scenario B, considering the cut-off allocation approach, utilization of burden-free silicon cells was assumed, which also helped to avoid the production of new silicon for PV panels. Using Eq. (1), the environmental impact savings for this scenario was equal to the environmental impact of using new silicon cells. According to Gardner et al., the Frick Environmental Center has a total of 470.40 lb of panels in PVs with a lifespan of 25 years (Gardner et al. 2020), the

replacement was three times (plus one installment) during the building's lifetime of 100 years.

Scenario D1 (Extending the Building Materials' Life): Acoustic Ceiling Tiles

In Scenario D1, it was assumed that the ACTs would last as long as their expected service lives of 75 years (UL 2016), instead of assuming a 25-year lifetime as included in Gardner et al. (Gardner et al. 2020). Considering the full quantity takeoff data, the Frick Environmental Center has a total of 3,645 lb of ACTs (Gardner et al. 2020), and with the assumed lifespan of 75 years, they will need to be replaced once (plus one installment) during the building's lifetime of 100 years.

Scenario D2 (Extending the Building's and Building Materials' Life): Thermoplastic Polyolefin Roof

Similar to Scenario D1, in Scenario D2, it was assumed that the TPO roof would last throughout its whole expected lifespan of 33 years (WNC Roofing 2020) instead of lasting 20 years (Gardner et al. 2020). According to Gardner et al., the Frick Environmental Center has a total of 3,322 lb TPO roof (Gardner et al. 2020), and with the assumed lifespan of 33 years, it should be replaced twice (plus one installment) during the building's lifetime of 100 years.

Scenario E (Carbon Sequestration): CarbonCure Concrete

In Scenario E, it was assumed that the concrete used in the Frick Environmental Center was prepared using CarbonCure technology, which promises a reduction of 15 kg CO₂-eq. emissions per 1 m³ of concrete (CarbonCure 2021b). The full quantity takeoff data suggest that a total of 4,374,498.89 lb concrete is used in the building's structural assembly (Gardner et al. 2020).

Life Cycle Impact Assessment

The life cycle impact assessment step is where inputs and outputs (namely resources and emissions) are summarized into usable impact categories. Given that this study analyzed the potential savings in embodied carbon as a result of implementing CE strategies, only the CO₂-eq. emissions were considered. Characterization factors for each flow were exported from the TRACI 2.1 impact assessment method (Bare 2012), and were multiplied with the material quantities as described in Gardner et al. (Gardner et al. 2020). It should be highlighted that, in order to calculate the embodied carbon, CO₂-eq. emissions resulting from material replacements were included while the energy consumption and onsite emissions within the use phase were excluded.

Results and Discussion

In line with Gardner et al., materials were grouped under architectural (e.g., flooring, walls, ceiling) and structural (e.g., beams and concrete) assemblies and energy systems (e.g., PV panels) categories (Gardner et al. 2020), and the LCA results were organized accordingly. Individual calculations for each scenario are presented in Section S3 in the SI. The CE strategies that were modeled resulted in a total of 29% reduction in the building's embodied carbon. The largest savings were found to be associated with using recovered silicon cells for solar panels. Despite assuming relatively small modifications in building materials, changes in material selection helped to reduce the embodied carbon approximately by 8%. Fig. 2 shows the life cycle CO₂-eq. emissions (excluding end-of-life) per assembly/system for both base case and alternative CE scenarios considering the functional unit of the whole Living

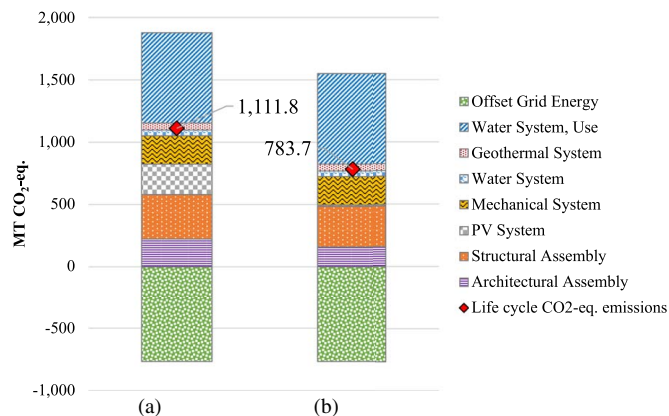


Fig. 2. Life cycle CO₂-eq. emissions (excluding end-of-life, MT CO₂-eq.) per assembly/system: (a) before; and (b) after implementing circular economy strategies.

Building with a lifetime of 100 years. Total values for both scenarios are embedded in the figure. In addition, Table S3 in the SI includes values for each assembly/system that are used to create the base case column ('before') in Fig. 2 (Gardner et al. 2020). Embodied carbon calculations for the base case and alternative scenarios are described in SI, including Tables S5 (mineral wool insulation) and S6 (PV modules).

Embodied carbon emissions savings disaggregated by the evaluated CE strategies are presented in Table 2 (for the whole building). It should be acknowledged that a single value without an uncertainty range may not represent the true value of an environmental impact, because each inventory used to calculate the life cycle CO₂-eq. emissions has an uncertainty (Bałdowska-Witos et al. 2020). Therefore, Monte Carlo uncertainty analysis is conducted using Monte Carlo simulations in SimaPro Professional v7 software to estimate the maximum and the minimum boundaries of environmental impacts associated with the design scenarios (confidence interval: 95% and sample size: 1000). However, in scenarios A1 (hemp insulation), A2 (linoleum flooring), and E (CarbonCure), single carbon intensity values were used from the published literature (CarbonCure 2021b; Gorree et al. 2000; Zampori et al. 2013), and these were coupled with material weights extracted from Gardner et al. (2020) to analyze the potential emission savings. Therefore, standard deviations around these scenarios cannot be established, which makes authors unable to run uncertainty analysis. Fig. 3 shows uncertainty analysis results for the rest of the scenarios, that is, D1 (ACTs), D2 (TPO roof), B (salvaged steel beams), and C (salvaged PV panel), in which the error bars represent the maximum and the minimum boundaries of CO₂-eq. impacts per scenario.

Table 2. Embodied carbon of the whole building before and after implementing circular economy strategies (MT CO₂-eq.) and percentage reduction achieved

Scenario	Embodied carbon (MT CO ₂ -eq.)			
	Before	After	Reduction	Reduction (%)
A (A1, A2)	1,153	1,109	44.15	3.83%
B	1,153	1,136	17.52	1.52%
C	1,153	919	234.7	20.35%
D (D1, D2)	1,153	1,131	22.49	1.95%
E	1,153	1,141	12.40	1.08%

Note: MT = metric ton.

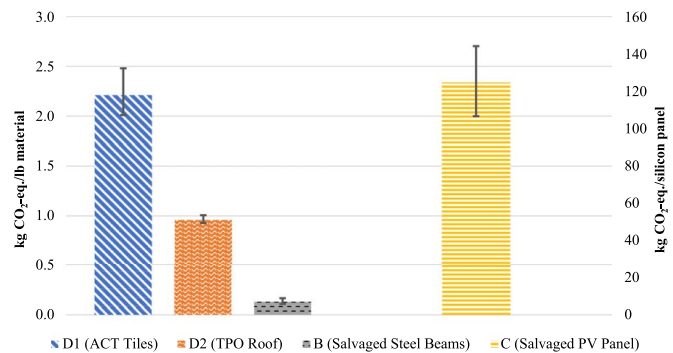


Fig. 3. Monte Carlo uncertainty analysis results for each scenario available [Note: secondary vertical axis belongs to Scenario C (Salvaged PV Panel) only.]

As previously mentioned, Scenario C (i.e., remanufacturing PV modules with recovered silicon cells) contributed to reducing the building's embodied carbon by 20%. This is followed by scenarios A, B, D, and E, respectively. This result is expected because the solar panels accounted for a significant share of embodied carbon in highly sustainable buildings. For example, in another Living Building in Pittsburgh, the Center for Sustainable Landscapes (CSL) located at the Phipps Conservatory and Botanical Garden, the solar panels accounted for 49% of the building's embodied carbon, most of which comes from the silicon cells (Hasik et al. 2017). Therefore, reusing recovered silicon cells was identified as the most effective CE strategy to reduce embodied carbon in the current study. Recent studies demonstrated the technical and economical feasibility of recovering silicon cells from existing PV modules. One study showed that manufacturers could save more than 20% in manufacturing costs, despite a slight decrease in efficiency when compared with standard panels (Deng et al. 2019, 2021). Another study developed a simple pretreatment process to successfully recover these cells without breaking them (Lee et al. 2018). Mahmoudi et al. estimated that the infrastructure required for PV recovery and remanufacturing will be economically feasible in the United States by 2027 (Mahmoudi et al. 2021), accordingly, evaluating Scenario C here adds an environmental perspective to the aforementioned argument.

More specifically, using biodegradable materials that have lower embodied carbon (hemp and linoleum) and extending the lifespan of products reduced the embodied carbon of architectural components by 30% and the building's life cycle CO₂-eq. emissions (excluding end-of-life) by 6% compared with the base case. Considering structural assemblies, using low carbon concrete from CarbonCure and salvaged steel beams reduced the embodied carbon of structural components by 8% and the building's life cycle CO₂-eq. emissions (excluding end-of-life) by 3% compared with the base case. Lastly, remanufacturing PV systems with salvaged silicon panels reduced the PV system's embodied carbon by 96% and the building's life cycle CO₂-eq. emissions (excluding end-of-life) by 21% compared with the base case. Fig. S1 in the SI shows the potential reductions in embodied carbon based on analyzed CE scenarios and material categories. It should be highlighted that the extent of embodied carbon savings for the whole building—which range from 1% to 20% in the current case study—is representative for a building type that is already certified due to having lower environmental impacts than the industry average. Authors expect these reductions to be relatively lower in conventional buildings, as their initial embodied carbon would likely be higher. In order to exemplify the environmental savings

associated with implementing CE strategies to the case study building (i.e., 328.1 MT CO₂-eq.), the equivalence of emissions was calculated using data for different types of vehicles. According to the US Dept. of Energy, annual emissions per electric vehicle driven in Pennsylvania are 1,537 kg CO₂-eq. and per gasoline vehicle are 5,187 kg CO₂-eq. (DOE 2021). Taking these numbers into consideration, life cycle CO₂-eq. emissions savings correspond to driving 213 all-electric vehicles or 63 gasoline vehicles in a year. From a broader perspective, these hypothetical savings can be used as a reference for other Living Buildings.

There are 24 certified Living Buildings in the United States with different properties such as location, project area, number of occupants, and the version of LBC. Table S7 in the SI is a list of all the certified Living Buildings in the United States along with additional information on their properties extracted from the ILFI's website (ILFI 2021a). If all these buildings would implement these CE strategies and achieve similar savings, the overall reduction in life cycle CO₂-eq. emissions would be about 7,874 MT CO₂-eq., which is equivalent to emissions resulting from driving 1,518 gasoline vehicles in one year. It should be highlighted that this analogy has limitations since properties such as location and project area of the listed Living Buildings are different. For example, there are certified Living Buildings in Washington and Texas (Table S7). The solar power potential in Washington is the lowest among all the US states, indicating that offsets through PV utilization would not be as high as offsets achieved in Texas (Grant et al. 2020). In addition, the number and technical properties of PV panels in those buildings may not be the same. Therefore, note that this analogy is a hypothetical one, which solely aims to show the potential extent of savings.

Finally, LCA for CE strategies in the built environment such as design for deconstruction, reuse, and biobased materials are still relatively new to the literature, and there is a lack of standards on how to perform closed-loop LCAs. As a result, the few existing studies have fundamental differences in methodology (e.g., scope, functional unit, system boundaries) that makes it hard to compare different studies and draw meaningful conclusions. However, similar to the results presented in this paper, the authors have found that CE strategies can significantly reduce embodied carbon in buildings. For example, Cascione et al. (2022) illustrates the importance of using LCA for decision making and for the optimization of building components in early design. They compared cradle-to-cradle environmental impacts of a circular biobased wall panel prototype (which was designed for deconstruction) with conventional, noncircular steel frame panels (which were assembled using regular techniques). Similar to Scenario A1 examined in the current paper, Cascione et al. (2022) used hemp waste fibers in their wall panel prototype, which resulted in 28% reduction in the total kg CO₂-eq. impacts per m² wall assembly over one service life (Cascione et al. 2022). Another study was conducted by Stijn et al., in which authors used LCA and material flow analysis methodologies to develop environmental design guidelines for circular building components with a case study of a circular kitchen. They evaluated four design scenarios including (1) a kitchen made from biobased, biodegradable materials, (2) a kitchen made from reused materials, (3) a kitchen that optimizes lifespans and materials, and (4) a modular kitchen in which components are reused by the manufacturer. Considering cradle-to-cradle system boundaries, Scenario 4 showed the largest decrease (50% reduction) in CO₂-eq. emissions compared with the base case. Scenarios 3, 1, and 2 followed Scenario 4 with a 28%, 19%, and 2% reduction, respectively (Stijn et al. 2020; van Stijn et al. 2021). It should be noted that the scenarios examined by Stijn et al. are similar to the scenarios analyzed in the current study, which are among

the most common CE design strategies being studied. Considering architectural assemblies only, the CE design strategies examined in the current study resulted in 59% decrease in embodied carbon compared with the base case with individual savings per scenarios ranging from 40% (D2) to 79% (A2) (Table S4). The CE is gaining traction in the built environment and standards are being created to address closed-loop strategies in the LCA methodology. As a result, future studies on the topic will allow us to better compare different CE strategies and their effectiveness in reducing building's embodied carbon.

Limitations

The authors acknowledge that some limitations exist with the current work as expanded in the current section. One of the major limitations is using LCA to estimate potential benefits resulting from implementing the selected CE strategies. For instance, it is challenging to quantify qualitative points (such as the quality loss from reused materials) and find a way to account for that in LCAs. Evaluating the environmental implications of buildings in which recovered materials are used needs robust measurements in order to account for all the potential benefits of the reusing/recovering approach, and it was suggested that LCA may not be an appropriate tool for this purpose (De Wolf et al. 2020). Another limitation is related to allocation methods, including the difficulty in allocating materials between different building cycles. In the current study, perfect substitution was assumed when using recovered materials in the building and the potential rebound effect was excluded from the analysis, which can serve as a limitation. In addition, the assumed cut-off allocation method here may restrain accounting for the benefits of designing for future deconstruction and reuse. As De Wolf et al. suggested, in order to account for the benefits of reusing building materials, "a trans-scalar sustainability performance method" should be developed (De Wolf et al. 2020). More broadly, numerous authors argued that, in order for the LCA method to support CE, instead of considering a single life cycle, it should consider multiple life cycles and/or continuous loops for materials that are reused/recovered in buildings (Eberhardt et al. 2019; Ghisellini et al. 2016; Niero et al. 2016).

In the current study, only small changes in the building design were hypothetically modeled to estimate potential savings in embodied carbon and life cycle CO₂-eq. emissions (excluding end-of-life). That being said, a holistic evaluation was not conducted, which is another limitation. More specifically, in Scenario A1, LCA results for hemp were directly extracted and used from the literature. Similarly in Scenario A2, LCA data for linoleum was directly incorporated into current calculations. This can be considered as a limitation because the software/database that was used by those authors may not be consistent with the current software/database used, which may bring some discrepancy in the impact assessment phase. Lastly, the residual lifespan of materials was not taken into account while calculating embodied carbon/life cycle CO₂-eq. emissions. As aforementioned, the lifespan of the case study building was assumed as 100 years and material replacements were calculated accordingly. For instance, ACTs had a lifespan of 75 years, and with one round of replacement over the building's lifetime, 50 years of service life for ACTs would be demolished.

Future Steps

As discussed in the current study, implementing the concept of CE in the built environment can help reduce associated CO₂ emissions. Although this study was based on an already existing building and

CO₂-eq. emissions could still be reduced by applying small changes in design, additional steps can be taken to mitigate the environmental impacts of the buildings and construction industry even more. This includes designing buildings with CE in mind from early stages, such as using durable materials or designing for disassembly. In addition, incorporating CE principles into the green building rating systems (GBRS) can help standardize this concept among certification schemes that are implemented around the world. Another point that requires further research is creating standards to better assess the benefits of CE in the built environment, such as a special version of an LCA or any other environmental impact assessment tool. Promoting circular business models such as recovering solar panels (as assessed in the current work) or maximizing the durability of building products through repair and maintenance can have an impact on a broader scale and hence help in transforming the building and construction sector's environmental implications. Finally, developing concepts such as material passports and material recovery technologies to enable urban mining for existing buildings and new constructions can be an efficient way to compile information of the material stock of buildings and to track flows in the built environment.

Conclusions

This paper explored whether relatively small design changes toward improving the circularity of an existing (LEED Platinum and Living Building certified) building could further reduce the embodied carbon and life cycle CO₂-eq. emissions. Results show that about 30% reduction could be achieved in both by incorporating various CE scenarios such as using materials with lower embodied carbon, reduction/reuse/recovery of embodied carbon-intensive materials, extending the lifespan of the selected building materials, and carbon sequestration, compared with the base case. Among these, the greatest environmental impact reduction was found to be associated with the reduction/reuse/recovery of embodied carbon-intensive materials strategy, specifically with using recovered silicon cells to remanufacture new PV modules. Although potential savings on embodied carbon and life cycle CO₂-eq. emissions that were analyzed are associated with small changes in design, organizations such as ILFI or USGBC can benefit from the results of this study. For instance, they could include credit categories that require similar (i.e., small) modifications in the building's design to further reduce environmental impacts and could grant points accordingly. Future work should expand on incorporating CE principles from the design phase of a building, creating standards for measuring the benefits of CE, and further developing technologies to track materials to keep them in the system as long as possible.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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mentioned are for informational purposes only and are not an endorsement.

Supplemental Materials

Tables S1–S7 and Fig. S1 are available online in the ASCE Library (www.ascelibrary.org).

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