Incorporating Hazard Vulnerability and Carbon Uptake into Building Life Cycle Assessment

MIT CSHub Research Brief
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MIT CONCRETE SUSTAINABILITY HUB

Bridging sustainability and resilience concepts

Residential buildings are widely recognized as a major contributor of **greenhouse gas** (GHG) emissions [1]. Thus, buildings are becoming a central topic for discourse around climate mitigation and adaptation.

To aid the increasing demand for 'green' buildings, various institutions offer building certification systems, such as the U.S. Green Building Council's (USGBC's) **Leadership in Energy and Environmental Design (LEED)** program. The material's related emissions in such programs focus on environmental impacts associated with initial design and construction rather than the embodied impacts generated during the entire building life cycle. Ignoring impacts that occur during building use and end-of-life removes the incentive to construct buildings that are more durable, more hazard-resilient, and more efficient to operate.

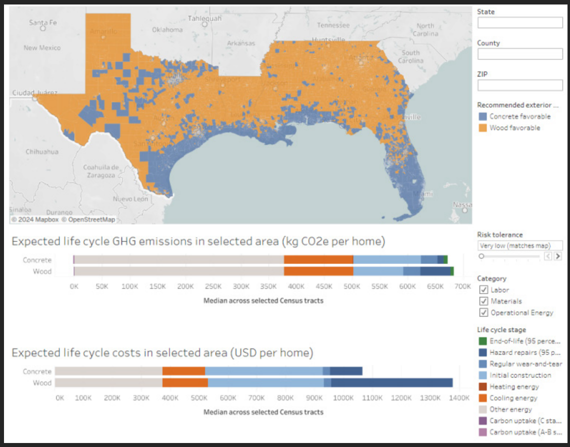
To address concerns around hazard resilience, an increasing number of institutions offer building certification systems focused on this issue, such as the Institute for Business and Home Safety's (IBHS's) **FORTIFIED program** for buildings in hurricane-prone communities. Similar to LEED, this program is based on prescriptive measures, albeit a separate set from those covered in LEED. As a result of the differences in the ways sustainability and resilience measures are designated by these programs, it can be difficult to pursue both in practice, despite sustainability and resilience being essential components of each other.

A similar trend follows for sustainability and resilience assessments. **Life cycle assessment** (LCA) – a common tool for sustainability experts – theoretically captures environmental impacts arising from the entire building life cycle. However, present LCA studies ignore hazard repair and replacement demands in estimating building embodied emissions. On the other hand, loss estimation – a common tool for resilience experts – deals with a variety of different metrics (e.g., dollar value of expected damages, number of households expected to displace) but falls short of translating those metrics to environmental metrics (e.g., GHG emissions associated with repairing expected damages).

In this study, we bring these two perspectives together to better represent the outcomes of construction material choice in single-family dwellings in hurricane-prone communities. By forging a comprehensive model for building LCA, we incorporate hazard vulnerability into the discussion of what makes a home 'green'. The results of this study demonstrate that a construction material with higher initial GHG emissions can still result in lower life cycle emissions. If used in a climate where it enhances durability, hazard resilience, and energy efficiency, its long-term benefits can outweigh its initial impact.

Key Takeaways:

- Most recent studies of building environmental impacts are limited to only embodied emissions from initial construction.
- The majority of building life cycle emissions occur during the use stage, which includes repair, replacement, and operational energy usage.
- CSHub's model results show that durable, hazard-resilient materials lead to higher emissions in the initial construction stage while also contributing to lower life cycle emissions, thanks to savings in the repair and replacement stages.
- This case study highlights concrete as the favorable material option in coastal and more southern communities, where hurricane wind exposure is relatively higher, and wood as the favorable material option in inland and more northern communities.
- Life cycle emissions as well as exterior wall core material recommendations, can be explored by ZIP code using the CSHub Hazard-informed Building LCA Dashboard.



The MIT CSHub Hazard-informed Building LCA Dashboard allows users to model how hazard-related life cycle impacts and costs are impacted by exterior wall choices.

Improving building life cycle assessment

In studies of building embodied emissions, use-stage emissions are the "most neglected" [2]. Pomponi and Moncaster conducted a review of 77 such studies and found that 90% account for the **production (A1-3) stage**, 50% account for the **construction (A4-5) stage**, and 30% account for the **end-of-life (C) stage**, while only 20% account for the **use (B) stage**. Even in studies that consider B-stage emissions, we identified two major gaps pertinent to evaluating decisions like construction material choice: neglect of hazard vulnerability and either neglect or overstatement of carbon uptake.

Figure 1 presents the building life cycle stages considered in this study. The objective of this study is to conduct a regional assessment of the outcomes of construction material choice in single-family dwellings in hurricane-prone communities. To achieve this, we extended the **Building Attribute-to-Impact Algorithm** (BAIA), developed by researchers at the MIT Concrete Sustainability Hub (CSHub), to incorporate hazard vulnerability and carbon uptake into the LCA of single-family dwellings.

Particularly when a building is damaged, that damage needs to be repaired. Repair requires both additional construction activities and additional materials, both of which are associated with emissions. As such, buildings that require more repairs have an emissions burden that is not included in current building LCA.

The BAIA operational energy and materials models allow us to estimate replacement schedules, energy costs and emissions, and labor and material costs and emissions. This, in turn, allows us to compute the environmental impacts associated with the initial construction, repair, replacement, and operational energy usage of each building.

In addition to BAIA, we made use of the U.S. Federal Emergency Management Agency's (FEMA's) **HAZUS loss estimation model** to assign damage functions and compute expected damages in terms of a percentage of total replacement of each building.

Complete lists of characteristics input to HAZUS and BAIA can be found in **Appendix A**. For the purposes of this study, we generated 5,000 iterations of each design and evaluated each iteration under 100 wind loading scenarios. These iterations vary by:

- Number of stories (1, 2, or 3)
- Living area (small, medium, or large)
- Roof shape (gable or hip)
- Roof cover (asphalt shingles, concrete tiles, or metal cladding)
- Window area (low, medium, or high)

To improve the statistical resolution of the analysis, we carried out paired samplings across two exterior wall core materials: concrete and wood. Paired samples were identical in all attributes except for the exterior wall core material for that iteration. Moreover, more durable and hazard-resilient construction materials provide longer service lives [3]. As a conservative assumption and to focus on the impact of repair in the building life cycle, the functional unit in this analysis considers the same survival rate (a Weibull distribution with mean 66 years) for concrete and wood homes.

To account for carbon uptake, we applied the same framework as the **C-Up model** [4]. In this framework, the carbon uptake of a structure is summed across each surface on each building component. The potential for carbon uptake relies on whether this building component is concrete or mortar as well as its compressive strength, mix design, and exposure conditions.

Comparing building life cycle emissions

We compared building life cycle emissions for three example Census Tracts in Miami-Dade, FL. **Figure 2** shows life cycle results for a Census Tract at a 'mid-level' of hurricane wind exposure (i.e. not too coastal or too inland, as exposure is highest on the coast, decreasing moving inland). **Figure 3** shows hazard repair results for two additional Census Tracts, one on the coast (labeled as 'higher' exposure) and one furthest inland (labeled as 'lower' exposure).

We found the largest differences in the product (A1-A3) and construction (A4-A5) stages (117 versus 85 Mt CO2e for concrete and wood homes, respectively, as depicted in red in Figure 2) and the hazard repair (B3) stage (34 versus 120 Mt CO2e for concrete and wood homes, respectively, as depicted

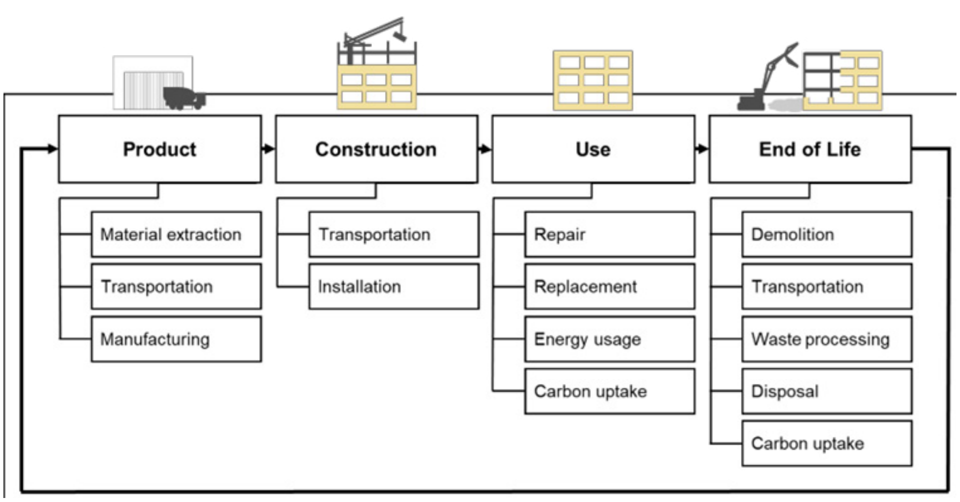


Figure 1. Building life cycle stages considered in this study.

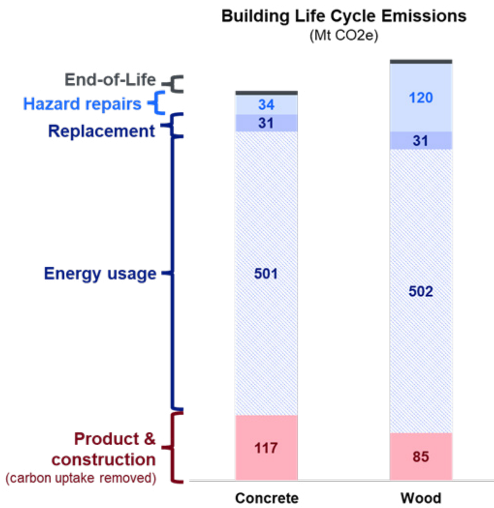


Figure 2. Building life cycle emissions for an example Census Tract in Miami-Dade, FL; mean of 5,000 actualizations, median scenario of 100 wind loading scenarios.

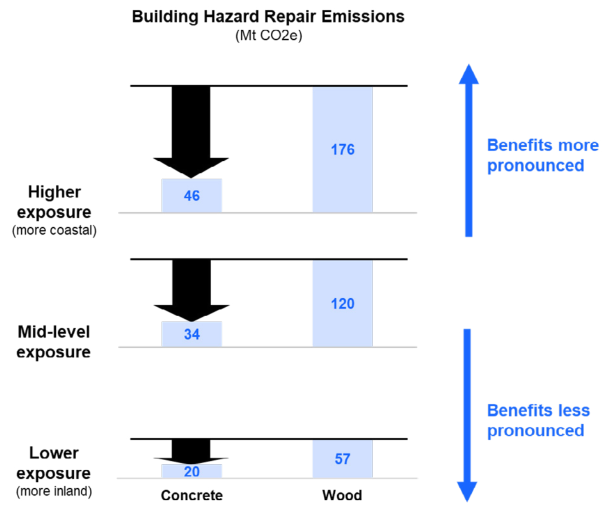


Figure 3. Building hazard repair emissions of the studied Census Tracts in Miami-Dade, FL; mean of 5,000 actualizations, median scenario of 100 wind loading scenarios.

in light blue in Figure 2). Based on these results, accounting for latter stage emissions and capturing a more complete picture of building life cycle emissions highlights concrete as the lowest emissions exterior wall core material, especially in a climatological context that favors more durable and hazard resilient construction materials.

Particularly, differences in the hazard repair (B3) stage are more pronounced in areas with higher hurricane wind exposure (top row of plots in Figure 3) and less pronounced in areas with lower hurricane wind exposure (bottom row of plots in Figure 3). This suggests a strong context dependency in evaluating the influence of hazard vulnerability on the entire building life cycle.

In these figures, carbon uptake (a negative emission) is removed from A-stage emissions. The total carbon uptake is roughly 1.7, 1.6, and 1.3 Mt carbon-dioxide-equivalent (CO_2e) for concrete and wood homes, respectively. Thus, carbon uptake sequesters a portion of building life cycle emissions.

Mapping recommendations for construction material choice

We expanded on building life cycle emissions from the previous section to derive exterior wall core material recommendations. **Figure 4** shows results of the comparative study for Miami-Dade, FL. **Figure 5** shows the same for the entire state of Florida. These maps are based on the 95th-percentile scenario of wind loading for each iteration.

As discussed in the previous section, most studies of buildings embodied emissions only account for product (A1-3) and construction (A4-5) emissions. Hence, such studies would lead to recommendations as depicted in orange on the left side of Figure 4, as wood homes yield the lowest A-stage emissions.

In addition to product (A1-3) and construction (A4-5) emissions, this study accounts for repair (B3), replacement (B4), operational energy usage (B6), and end-of-life (C) emissions, as well as carbon uptake, capturing a more complete picture of building life cycle emissions. Our approach leads to recommendations as depicted in blue on the right side of Figure 4 and in Figure 5.

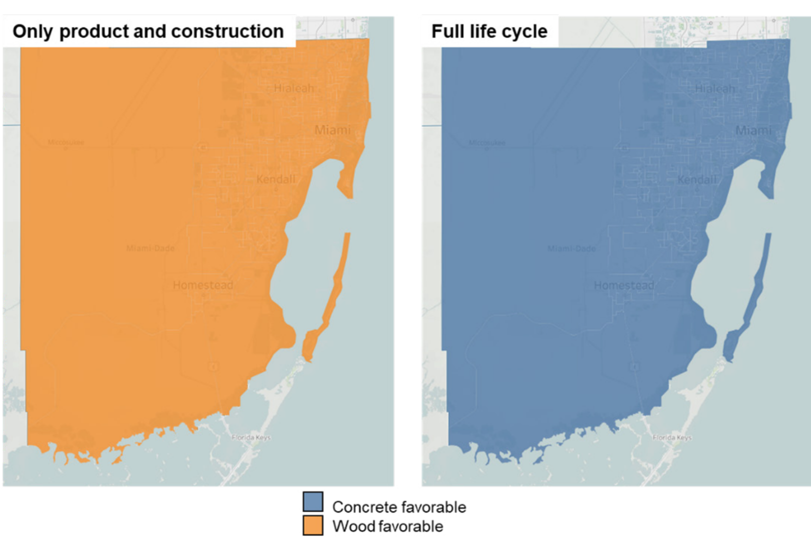


Figure 4. Exterior wall core material comparisons based on building life cycle emissions in Miami-Dade, FL; $p < .05$ across 5,000 actualizations, 95th-percentile scenario of 100 wind loading scenarios.

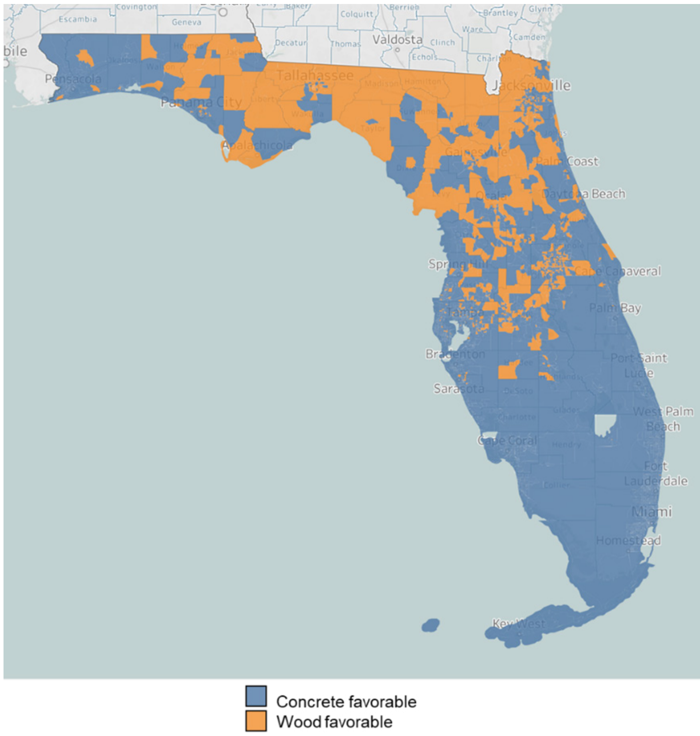


Figure 5. Exterior wall core material comparisons based on building life cycle emissions in Florida; p < .05 across 5,000 actualizations, 95th-percentile scenario of 100 wind loading scenarios.

A broader look at these maps suggests that there is no one-size-fits-all solution, as concrete homes are favorable in 3,497 Census Tracts which are more coastal and southern, where hurricane wind exposure is relatively higher, while wood homes are favorable in 709 Census Tracts which are more inland and northern Census Tracts, where hurricane wind exposure is relatively lower. Therefore, assessing the outcomes of the choice of exterior wall core material is highly dependent on the climatological context.

Redefining what makes buildings 'green'

Most recent studies of building environmental impacts are limited to only material production emissions associated with initial construction and, in a few cases, the emissions over the life cycle under a steady set of climate conditions (i.e., the hazard impacts excluded). However, this leads to a misleading assessment of which construction materials constitute 'green' buildings. Typically, this assessment is boiled down to an absolute preference between one construction material over the other (e.g., wood over concrete). We demonstrated that a comprehensive assessment results in a 'mix of fixes' highly dependent on the climatological context.

We created a more comprehensive assessment of building embodied emissions by incorporating the emission implications of hazard vulnerability and carbon uptake. We then combined embodied emissions with operational energy usage emissions to capture the full life cycle of emissions associated with construction material choice. Our results show that durable, hazard-resilient materials may increase emissions associated with initial construction while reducing life cycle emissions by avoiding emissions from repair and replacement.

Particularly in hurricane-prone communities, hazard repair emissions can comprise a similar order of magnitude as initial construction emissions. Regarding the choice of materials for the exterior wall core, we found that concrete is favorable in more coastal and southern communities, where hurricane wind exposure is relatively higher. The hazard repair stage is the dominating factor. At the same time, wood is favorable in more inland and northern communities, where hurricane wind exposure is relatively lower, and the initial construction stage is the dominating factor.

Based on this research, we developed the CSHub Hazard-informed Building LCA Dashboard which can be accessed online in the "related links" section. This dashboard can be used to compute life cycle costs and emissions as well as exterior wall core material recommendations by state, county, or ZIP code for the states of Florida, Georgia, Alabama, Mississippi, Louisiana, and Texas.

Related Links

MIT Concrete Sustainability Hub Hazard-informed Building LCA Dashboard (prepared by Dr. Ipek Bensu Manav): https://cshub.mit.edu/hazard-lca-dashboard/

References

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(2) Pomponi, F., and A. M. Moncaster. Embodied Carbon Mitigation and Reduction in the Built Environment – What Does the Evidence Say? Journal of Environmental Management, Vol. 181, 2016, pp. 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036.

(3) Baek, C. H., S. H. Park, M. Suzuki, and S. H. Lee. Life Cycle Carbon Dioxide Assessment Tool for Buildings in the Schematic Design Phase. Energy and Buildings, Vol. 61, 2013, pp. 275–287. https://doi.org/10.1016/J.ENBUILD.2013.01.025.

(4) Azarijafari, H., I. B. Manav, M. Rahimi, E. Moore, B. Huet, C. Levy, C. Hazaree, and R. Kirchain. Estimating Carbon Uptake at Building Level: Insights from a Bottom-up Approach. 2023.

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Appendix A

Table 1. List of HAZUS wind building characteristics (WBCs).

Code	Description
rship	Roof shape hip
rsgab	Roof shape gable
rcshg	Roof cover asphalt shingles
rccnt	Roof cover concrete tiles
rcmet	Roof cover metal cladding
walow	Window area low
wamed	Window area medium
wahig	Window area high
swrys	Secondary water resistance present
swrno	No secondary water resistance
rda6d	Roof decking 6d @ 6”/12”
rda8d	Roof decking 8d @ 6”/12”
rda6s	Roof decking 6d @ 6”/6”
rda8s	Roof decking 8d @ 6”/6”
tnail	Roof-to-wall connections toenails
strap	Roof-to-wall connections straps
shtys	Shutters present
shtno	No shutters
gdnod	No garage door (homes w/o shutters)
gdkwd	Garage door weak (homes w/o shutters)
gdstd	Garage door standard (homes w/o shutters)
gdno2	No garage door (homes w/ shutters)
gdsup	Garage door superior (homes w/ shutters)
rmfys	Masonry reinforcement present
rmfno	No masonry reinforcement

Table 2. List of BAIA Attribute-to-Activity Model for Energy (AAME) inputs.

Code	Description
LivingArea	Living area (sqft)
Bedrooms	Bedrooms
Stories	Stories
AspectRatio	Aspect ratio
DegreesFromS	Degrees from south (deg)
RoofType	0 = gable, 1 = hip
RoofPitch	Roof pitch
FrontWWR	Front window-to-wall ratio
BackWWR	Back window-to-wall ratio
SideWWR	Side window-to-wall ratio
WallU	U-value of exterior walls (W/m2K)
SlabU	U-value of slab foundation (W/m2K)
RoofU	U-value of roof (W/m2K)
WinU	U-value of windows (W/m2K)
WinSHGC	Solar heat gain coefficient of windows
HeatingShadeFactor	Heating shade factor
CoolingShadeFactor	Cooling shade factor
OverhangLength	Overhang length (ft)
ACH50	Air leakage rating
VentHeatRecoveryRate	Ventilation heat recovery rate
PctOpenWin	Percentage of openable windows
PctLED	Percentage of LED lightbulbs
WaterHeaterEff	Water heater efficiency
HeatingEff	Heating efficiency
CoolingEff	Cooling efficiency
HeatingSetPoint	Heating set point (F)
CoolingSetPoint	Cooling set point (F)

Note: several of these inputs depend on the building geometry and material definitions, such as window-to-wall ratios (depend on window and exterior wall areas) and U-values (depend on wall, roof, slab foundation, and window materials).