MIT Concrete Sustainability Hub Whitepaper

Reducing carbon emissions in the built environment: A case study in 3D printed homes

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Overview

This white paper presents a comparative analysis of the life cycle environmental performance of 3D-printed (3DP) and stick frame (STF) homes in various US climate conditions. The results of this analysis demonstrate that:

- The 3DP home possesses lower operational carbon emissions compared to STF in all cases. The annual savings in operational carbon range from 2% in the mixed-humid climates up to 9% in the dry hot climates.
- The embodied carbon emissions of the model 3DP Single Family home is similar to that of the model STF home (approximately 0.5% lower than STF).
- 3DP homes achieve lower life cycle carbon emissions ranging from 2% to 6% (depending on the climate zone) compared to STF.

The lower emissions in the 3DP homes come from:

- Use of low-carbon 3DP mix design in the real case study.
- Efficient design of the 3DP wall system having simpler assemblage of materials.
- Operational advantages of concrete construction.

Despite lower life cycle carbon emissions, the sustainability advantages of 3DP concrete construction will be further enhanced as the industry evolves to adopt scalable mixture designs with ever lower carbon impacts.

The life cycle carbon emissions were determined for a modeled 2,000 square foot residential home with a garage created with 3DP construction versus the conventional Stick-Frame (STF) construction method. The embodied carbon emissions and concrete carbon uptake were modeled based on publicly available data sources. The embodied carbon emissions of the 3DP construction home structure and material was based on a proprietary printable mix, wall system, and 3D printing robot based on a real case study in Austin, Texas (design, material, and construction details provided by ICON). The STF home structure and material is based on a code compliant STF design typical of volume production builders. Finally, the operational energy consumption of the building was simulated using Energy Plus for four different climate zones over a 75 year service life. Also, the operational carbon impact was calculated with regards to the U.S. Energy Information Administration (EIA) grid decarbonization projections.

Introduction

Global projections from the IEA[1] predict that, between 2022 and 2050, the number of households will increase by 34% to exceed 2.96 billion worldwide. This demographic surge will be paralleled by a substantial 56% expansion in residential floor area reaching 310 billion square meters. This growth will be accompanied by challenges, including a rise in labor cost and limited availability to high-quality materials. 3D construction printing (3DCP) stands out as a potentially promising response to both of these challenges, by enhancing labor productivity and minimizing waste generation.

Notably, 3DCP has the potential to excel in efficiency concerning both materials and energy usage[2]. The construction process is localized, minimizing transportation needs, while also reducing labor requirements and significantly accelerating building timelines. A constructible wall system simplifies the construction process by minimizing the array of materials, finishes, and trades typically involved in traditional wall construction. This approach not only promotes cost-effectiveness but also enhances design flexibility, enabling efficient customization and optimization of materials to meet specific structural requirements[3].

Alongside these advantages, the environmental life cycle performance of 3DCP remains a question. In fact, there is a debate on the carbon intensity of 3DP mixtures. Owing to a smaller maximum aggregate size and specific rheological requirements, the binder content of 3DP mixtures is reported to be larger than conventional concrete and consequently, result in substantial carbon footprints[4]. On the other hand, it is reported that the complexity of wall systems in various building applications make the 3DPC a more efficient system in terms of concrete consumption[5]. This study provides a first ever detailed analysis of the carbon intensity of 3D printed homes based on real cases already constructed in the US context.

Methodology

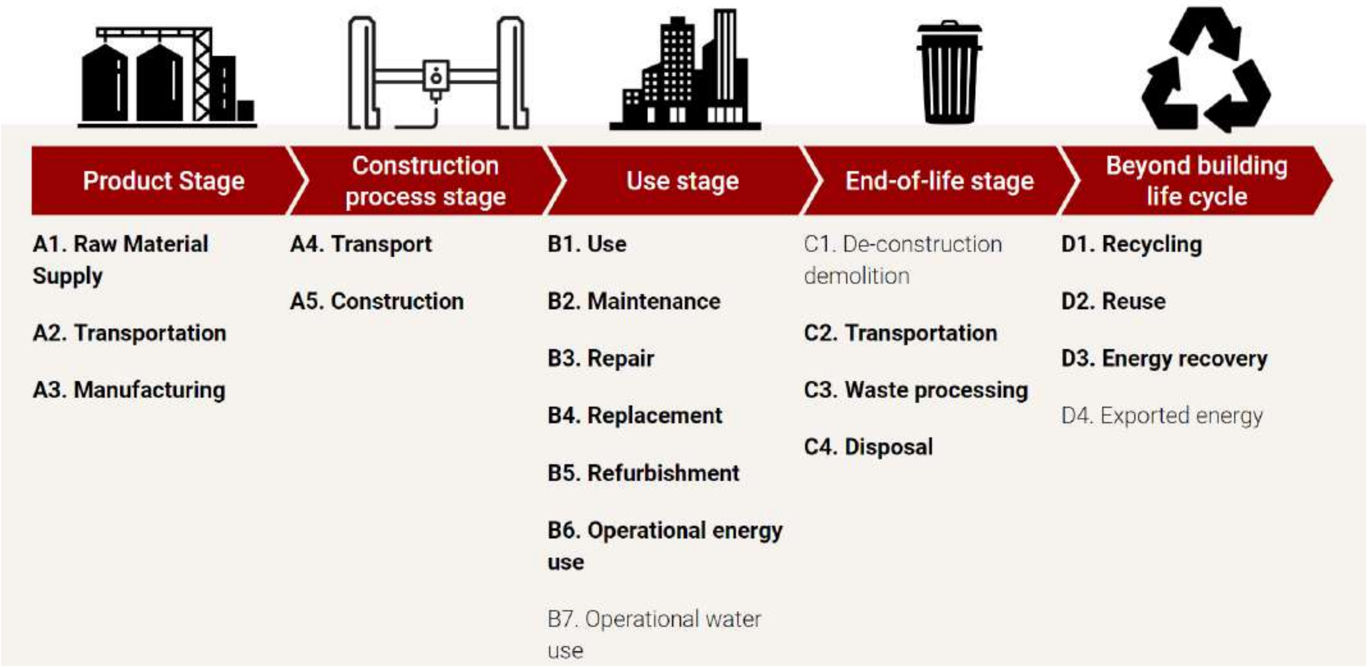
Goal and Scope Definition

The objective of this study is to compare the life cycle carbon performance of two different residential construction methods (3DP and stick frame) for a given home layout (Figure 2). Life Cycle Assessment (LCA) is used to analyze the potential environmental impact associated with the 3DP and STF buildings[6]. STF was selected as a conventional construction method prevalent in the selected regions. The carbon performance of the homes is modeled for four different US climates zones at two different humidity levels. The life cycle carbon impacts are determined in terms of the embodied (associated with the initial construction, maintenance and repair, and during the service life of the homes) and the operational carbon, both associated with a 75 year service life. The two structural wall systems (STF and 3DP concrete wall) are considered to have an equal service life of 75 years. The assumptions on the service life and replacement rate of the building elements are provided in Table A.2. In order to be representative of the context, this study includes home design details that are consistent with generic market finishes both for STF construction as well as 3DP homes. For example, the STF home in the present analysis includes a fiber cement panel exterior finish. The functional unit of the present analysis is a house of a defined habitable floor area of 2000 sq ft maintained and in use over 75 years. The house is simulated as built with two different construction systems: 3DP and STF. The impact category of interest is Global Warming (GWP) measured in kg CO_2 eq.

System boundary (inclusions and exclusions)

LCA is defined by different system boundaries. The European Standard for sustainability of construction works EN 15978:2011[7] divides the system into five stages as shown in Figure 1: Product (A1-A3), Construction (A4-A5), Use (B1-B7), End of Life (C1-C4), and Beyond building life cycle (D1-D4). The analysis presented in this study includes all stages with the exception of B7 Operational Water Use, C1 Demolition, and D4 Exported Energy due to

Figure 1: Boundary conditions.



their negligible contribution to the life cycle emissions of residential buildings.

For the 3DP Product Stage, a dry concrete material is batched and transported to the construction site. The system includes the embodied carbon of each raw material supplied, the transportation of the raw materials from the suppliers to the batch plant location, and the energy required for batching operations. A second stage is considered at the construction site where the dry mix is blended with the water and chemical admixtures during printing operations. For both of these stages, primary data on energy consumption were collected and used. Carbon emissions for operations were calculated considering the carbon intensity of the Austin, TX, energy grid. To complete the assessment at the construction stage (A5), carbon emissions associated with the use of equipment on site were collected and used. Design details, including material quantities, and all operational data for the 3DCP home were collected from ICON construction operations conducted during 2023 in Austin, TX.

The construction installation process (A5) of the STF wall system was modeled using Athena Impact Estimator for Buildings[8] based on the wall construction details in Table 3.

The Use Stage includes use, maintenance, repair, replacement, refurbishment and operational energy over the 75 year service life. Details on Operational Energy follow an analysis described below.

The software used for the bill of materials and embodied emission estimates is Tally®[9], an Autodesk® Revit® application that allows quantifying the environmental impact of building materials for whole building analysis as well as comparative analyses of design options.

Embodied Carbon Assessment: 3D printable mix design

The mixture used for 3DCP differs from other forms of concrete construction. The mixture analyzed in this study was used in 3DCP homes constructed in Austin, TX by ICON. The embodied carbon of a 3DCP mixture was assessed by attributing the materials and amounts in Table 1 below, to a "custom concrete mix" in Tally. To model stage A2, the distances between raw material suppliers and a dry mix batch plant were also used as inputs.

The use of a custom concrete mix in Tally presents some limitations, particularly the number of components

Table 1: Mix design for 3DP concrete. Emission factors are related to the customized calculator. *The emission factor for admixture is a weighted average of each admixture's emission factor.

Material	Amount [lb/CY]	Transportation distance [mi]	Emission factor [kg CO_2 eq /lb]	Emissions factor source
Type 1L cement	517	80	0.384	2021 PCA Portland Limestone Cement EPD
Supplementary cementitious materials	189	105	0.008	Direct data from producers on grinding energy (45KWh/t)
Mineral fillers	328	48	0.012	Direct data from producer
Aggregates	1927	80	0.012	Direct data from producer
Liquid admixtures	28	1500	2.060*	Direct data from producer and EPD from equivalent products
Mineral admixtures	22	250	0.472	EPD of equivalent product
Water	311	-	0.0002	Bath ICE Database[10]

that can be used as inputs. Some simplifications worth noting are:

- Tally does not allow separate embodied carbon calculations for the specific admixtures, so the total mass of admixtures was calculated and attributed to "general admixture" with a calculated specific emissions factor.
- Tally does not allow input of a specific amount of filler, so the total mass of fillers was added to the material with the most similar embodied carbon, in this case fine aggregates (sand).
- Type 1L cement is not included in the cement options; the only option is portland cement.
- The amount of reinforcement for the 3DP home design was assumed to be 36 kg/m^3 based on the provided design data.

For this reason, the Tally analysis was completed but compared to a purpose built embodied carbon calculation that considered the specific embodied carbon of each raw material as per the EPD from the supplier, the data disclosed by the supplier in terms of energy required to produce said material, or an EPD for analogous material available on the market.

Embodied Carbon Assessment: Wall System

To minimize the amount of material used during printing, it is important to consider how the material is used to create the structural system for the wall assembly. There are a wide variety of approaches currently being taken in the 3DP construction industry ranging from using the printed material as formwork for infill material to different configurations of shell structures. Even with an optimized mix, overuse of printed material or the addition of cast infill material to achieve the required structural performance will impact the embodied carbon of the wall system. The 3DP wall system in this study utilizes a shell structure with alternating vertical pilasters or cores on each side of the shells. The cores are grout-filled with the remaining cavity space filled with insulation to provide the walls thermal performance as required. No additional infill material is required to satisfy structural requirements. The two bead wall system in Figure 3 is designed to use 27% less material than previous iterations. Table 3 outlines wall system details and considerations included in this study.

Embodied Carbon Assessment: Home

For this analysis, a 2000 sq ft home (detailed in Figure 2 on the next page) was designed and modeled using Revit. As the model was originally designed for standard construction documentation of the projects, some post-manipulation was necessary for the analysis. In particular, the building was copied into two different Revit worksets to represent two different building framing systems: 3DP and STF. As a result, two models were created.

Table 2 describes details that were included in the model. The elements that were not modeled include: false ceilings; kitchen cabinets and cooktops; miscellaneous framing; finishes; mechanical; electrical and plumbing systems fixtures' air vents and ventilation ducts; chimneys; fireplaces; attic stairs; exterior decking; concrete porch, landing, and steps beyond the footprint of the foundation drawings; concrete paving and driveways; boundary walls, fences, and gates.

Figure 2: Floorplan of the 2000 sq ft home used for the LCA.

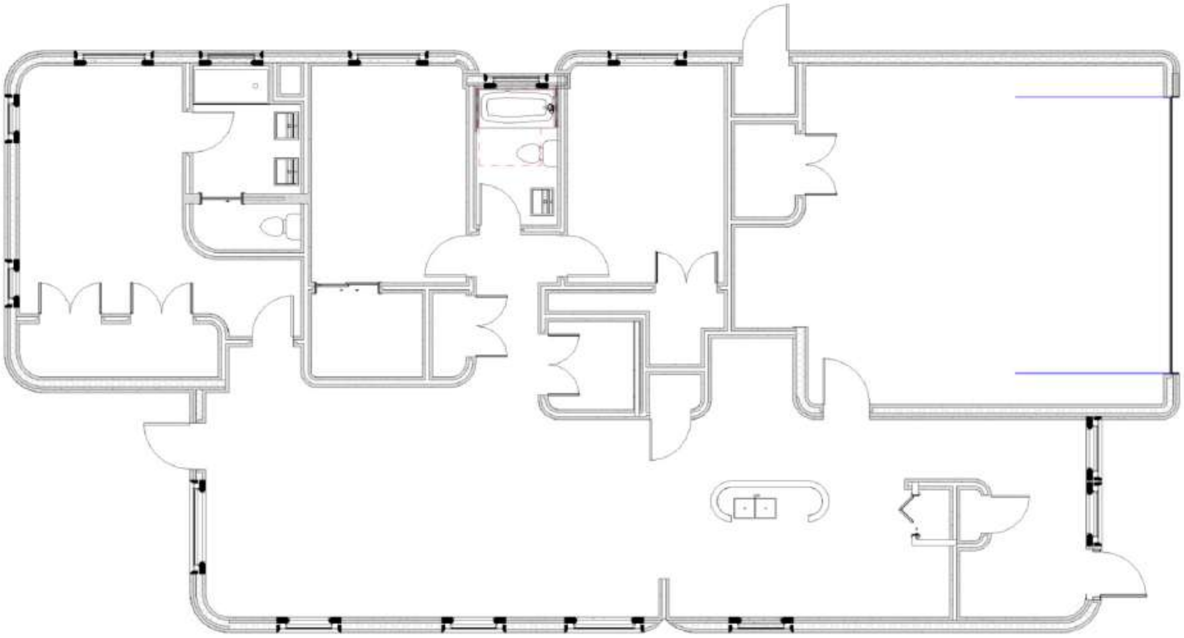


Table 2: Description and unique aspects to the home.

Description	Unique aspects	Roof and Foundations
3 bedroom 2 bath **Height**: 1 story | 9' 0" **Foundation**: Shallow concrete slab on grade with perimeter and interior grade beams. **Roof Framing**: 2x8" Rafters @ 24 inches. Covered with standing seam steel sheet	For all 3DP projects, all of the interior and exterior walls were printed with the exception of two 6' wide stick framed interior walls. Unique elements pertaining to each wall system studied were added to each workset based on available data. For example: bond beams, top plates, and baseboards. All the 3DP unique elements such as rebars, cross-ties, and grouting were accounted for based on the 3DP home design bill of materials.	The roof design indicates 2x8" members @ 24" o.c.. Certain elements such as ridge members, hips and valleys, and ceiling joists were not in the model and excluded from the study for simplicity. The foundations were dimensioned considering the same load for all two building construction systems. As a result, the embodied carbon due to the foundation is the same for the two construction systems. In this model, the foundation is assumed to be realized with a cast in place concrete (3000 psi) with moderate slab reinforcement by volume (87 kg/m^3). The mix design considered is the US South Central average 3000 psi as reported by the NRMCA[11]

Table 3: Wall construction details.

Wall type	3DP wall provided by ICON (See Figure 3)	STF (See Figure 4)
Exterior Walls	3DP concrete	5/8" fiber cement panel
	#3 rebars horizontal rebar & #5 vertical rebar	Weather barrier
	3/16" stainless steel z-ties	1/2" plywood sheathing
	Open cell insulation	2"x6" @ 24" o.c. wood studs (wall frame + wood sill + double top plate) + wool blanket insulation within the studs (mineral wool)
	Wood top plates	R-19 glass-fiber blanket
	Steel lintels at long span openings	5/8" gypsum drywall
Interior Walls	3DP concrete	2"x4" @ 16" o.c. wood stud (wall frame + wood sill + double top plate)
	#3 rebars	5/8" gypsum drywall (on each side)
	3/16" stainless steel z-ties	
	Wood top plates	

Figure 3: Detailed views of 3DP printed wall.

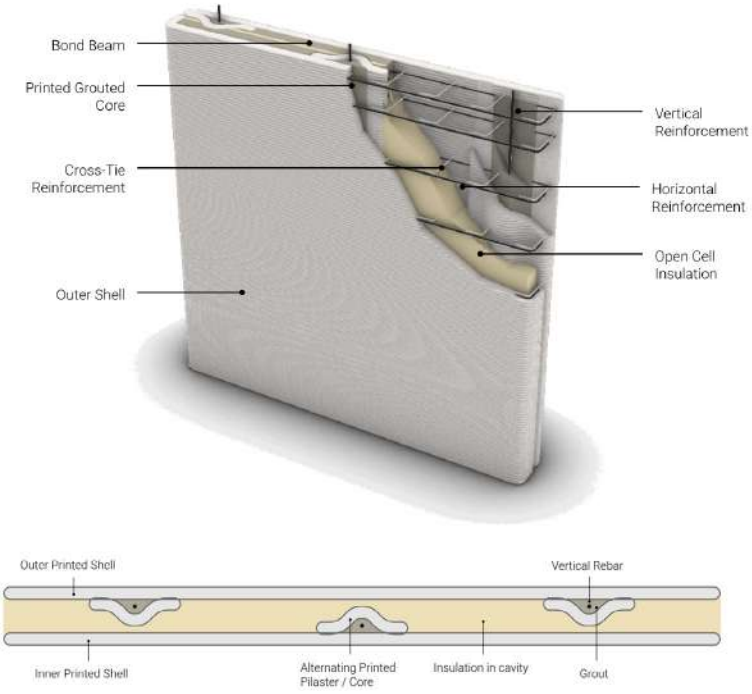
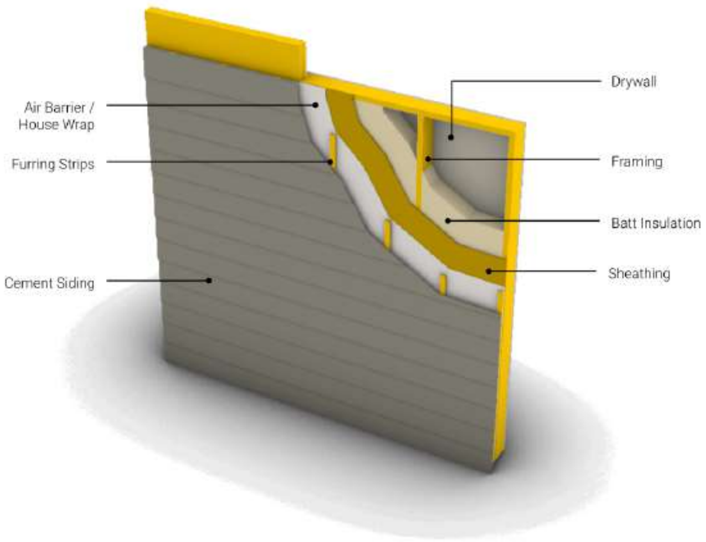


Figure 4: Detailed view of STF wall construction.

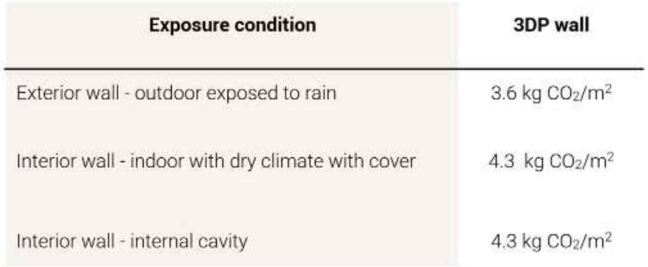


CO_2 Uptake

The CO_2 uptake (carbonation) of concrete is a chemical reaction by which the CO_2 in the atmosphere reacts with the hydration products in the concrete that contain reactive calcium phases. This means that part of the carbon emissions released during cement production are sequestered back into the concrete. This is a natural process that happens during both the service life of the concrete structure as well as during demolition and crushing of the concrete[12].

The CO_2 uptake was estimated by following the guidelines of Annex G of the EN 16757:2022 standard - Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements[12]. For the 3DP Wall, the maximum theoretical CO_2 uptake is related to the amount of reactive calcium oxide in the binder, which depends on the clinker percentage in the portland cement as well as the types and quantity of alternative binders such as supplementary cementitious materials. The CO_2 uptake during the use stage depends on variables such as exposure condition, strength class (16-20 MPa), years of use stage (75 years), and the surface area exposed to the air. The CO_2 uptake during the end of life stage is calculated using the simplified method described in Annex G (5 kg CO_2/m^3 of concrete). It should be noted that the width of a 3DP bead is 2.5", and this represents the upper limit for the depth of carbonation. The CO_2 uptake resulting from applying guidelines of Annex G is summarized in Table 4.

Table 4: CO_2 uptake resulting from applying guidelines of the EN 16757:2022 standard - Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements.



Exposure condition	3DP wall
Exterior wall - outdoor exposed to rain	3.6 kg CO_2/m^2
Interior wall - indoor with dry climate with cover	4.3 kg CO_2/m^2
Interior wall - internal cavity	4.3 kg CO_2/m^2

Operational Carbon Assessment: Homes

Operational carbon emissions, a key component of building life cycle emissions, includes carbon emissions linked to energy consumption during the use phase of a building (e.g., energy consumed for heating, cooling, and lighting). Understanding operational carbon is essential for a comprehensive view of the total carbon footprint of 3D printed walls. The importance of operational carbon lies in its relationship with embodied carbon in determining a building's total carbon impact.

Operational carbon emissions are directly related to the climate zone where a given building is located. The International Energy Conservation Code (IECC) classifies the U.S. into 8 different climate zones[13] shown in Figure 5, based on weather factors like seasonal temperatures along with humidity and rainfall (to define the "Dry" and "Marine" sub-climates). The analysis includes energy consumptions for climate zones 1, 2, 3, and 4 with relative sub-climates.

The methodology for calculating operational carbon in buildings comprises the simulation of energy consumption loads, using Building America (BA) as a starting point[14]. To modernize the BA assumptions, changes were introduced including adoption of ENERGY STAR® appliances and LED lighting. Adjustments to heating and cooling setpoints were also made to reflect higher winter and lower summer temperatures as informed by NREL's Residential Indoor Temperature Study[15]. This revised framework established a comprehensive set of model definitions for the study.

The interior load boundaries, defined at the envelope, excluded elements such as electric vehicle chargers and secondary appliances like wine fridges, second fridges, or freezers.

The envelope definitions, encompassing values for walls, roofs, slabs, and windows for both construction methods across the studied climates, are outlined in Table 5. The International Energy Conservation Code (IECC) 2021

Figure 5: IECC climate zone map.[13] The climate zones considered in the analysis are 1, 2, 3, and 4.

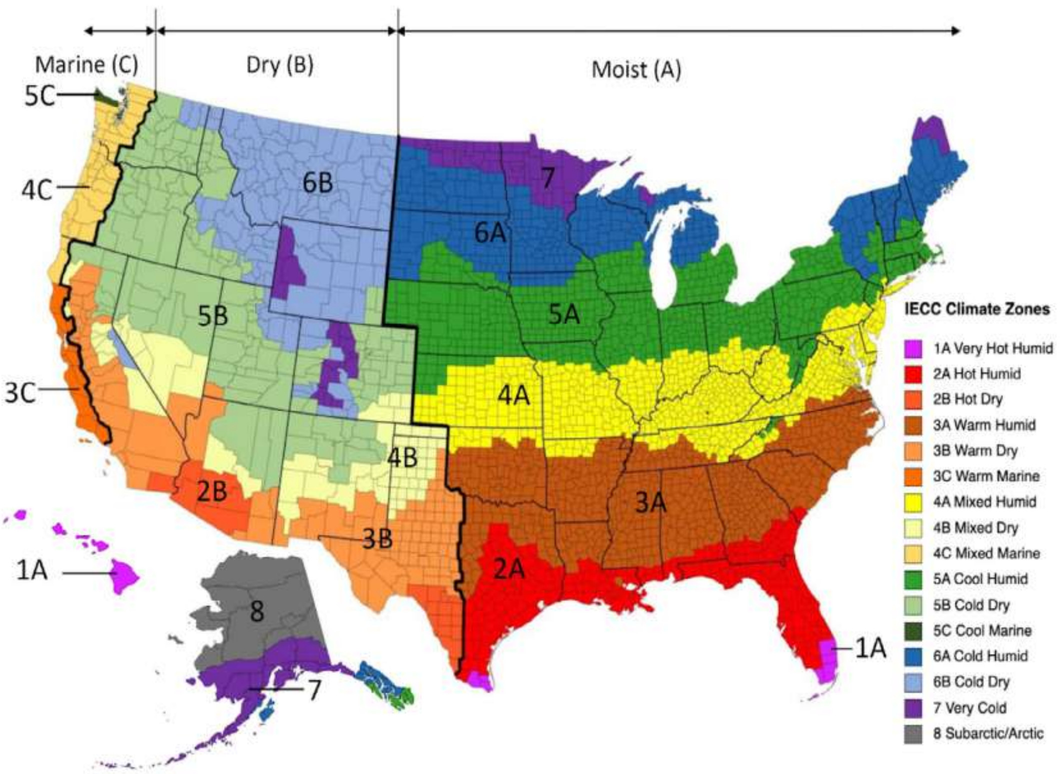


Table R402.1.1 provided the reference points for envelope R-values. To better represent the constructed assembly value, the IECC 2021 R-values for stick framed walls were adjusted according to Appendix JA4.1 from California's energy code known as Title 24. This adjustment ensured that the evaluation of STF envelopes used R-values that closely mirror actual construction, as assessed by the California Energy Commission.

Energy simulations were performed using the Department of Energy (DOE) Energy Plus[16] engine running in the Ladybug plugin for Grasshopper. The EnergyPlus simulation engine[17] has the capability to calculate the heat capacitance of a construction assembly to assess how the thermal mass of an assembly impacts the annual energy consumption. This means the operational carbon assessment takes into account the mass of printed wall construction assemblies.

Results

Embodied Carbon Assessment: 3DP material

The embodied carbon for the 3DP concrete mixture is equal to 291 kg CO_{2e}/CY, 68% of which is due to the emission associated with the cementitious material production (Figure 6). Considering the process, 3% of the total global warming impact is due to the transportation of the raw materials from the producers to the batch plant located in Austin TX (9 kg CO_{2e}/CY).

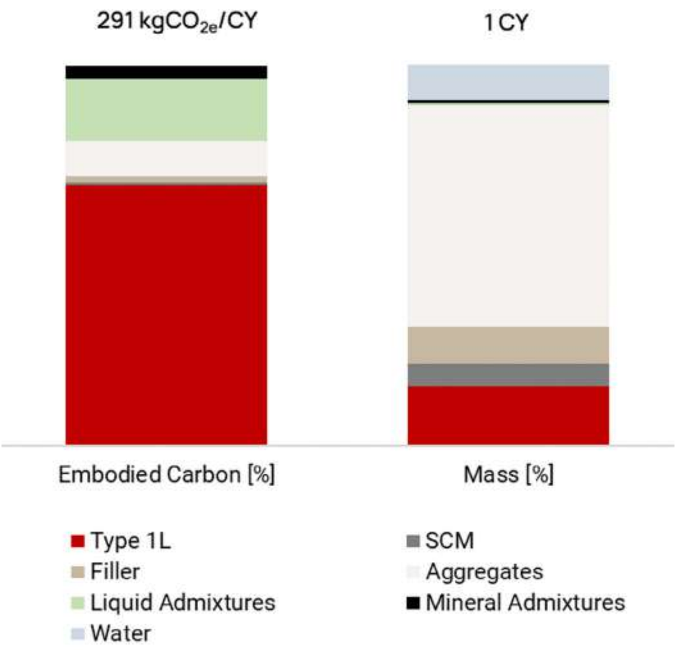
The low-carbon mixture was enabled by implementing multiple solutions. First, the binder intensity was improved while satisfying the minimum mechanical performance requirement. Second, the aggregate grading was optimized to lower the cement and powder content. Finally, the bulk of the raw material was sourced within 80 miles from the batch plant to reduce the embodied carbon related to transportation.

Table 5: Building envelope parameters.

Wall Type	Climate Zone 1	Climate Zone 2	Climate Zone 3	Climate Zone 4
3DP wall	2 Bead wall (R-19)	2 Bead wall (R-19)	2 Bead wall (R-19)	2 Bead wall (R-19)
STF Wall U Factor [Btu/h-ft-F]	0.102 (R-10)	0.102 (R-10)	0.064 (R-16)	0.047 (R-21)
Roof U Factor (Btu/h-ft-F)	0.032 (R-31)	0.020 (R-50)	0.020 (R-50)	0.016 (R-63)
Slab F Factor [W/m-K]	0.73 (R-0)	0.73 (R-0)	0.54 (R-10)	0.48 (R-10)
Window U Factor [Btu/h-ft-F]	0.50 SHGC: 0.25	0.40 SHGC: 0.25	0.30 SHGC: 0.25	0.30 SHGC: 0.40
Infiltration	ACH5	ACH5	ACH3	ACH3
Interior Mass	Per home plans	Per home plans	Per home plans	Per home plans

The embodied carbon for each CY of 3DP concrete from Tally is overestimated by 20% compared to the embodied carbon calculated from the customized calculator. This discrepancy is due to the assumptions embedded into Tally in particular regarding the custom mix definition as mentioned in the Methodology section.

Figure 6: Relative contribution of raw materials to the embodied carbon and mass.



Embodied Carbon Assessment: Home

The embodied carbon of the home as built in two different ways is summarized in Figure 7. The 3DP home is associated with 93.8 t CO_{2e} while the STF home is associated with 94.4 t $CO_{2e.}$ There are common elements within each home that do not change between the builds (foundation/floor finish, roof, opening and glazing). Any differences are realized in the wall systems and how they are built. The wall construction phase (A5) was estimated using direct field data. Dry mix batching operations account for 2.7 kg CO_{2e} /CY of dry mix, which corresponds to a total of 102 kg CO_{2e} /home. The printer consumes between 1500 and 2000 kWh to print a 2000 sq ft home, which corresponds to 500 - 665 kg CO_{2e} considering the carbon intensity of the Austin, TX energy grid (732 lb CO_2/MWh[18]). This energy is used for on-site batching and printing. Finally, the equipment on site (excluding the printer) consumed an average 50 gal of diesel per home. Considering the emission factor for diesel reported by US EIA (22.45 lb CO_2/ gal[19]), this results in 520 kg CO_{2e}. As a result, the A5 stage for the 3DP wall system accounts for ~1.2 t CO_{2e}. Direct data were not available for the STF wall, therefore the values for the wall construction phase were obtained by modeling the wall system (Table 3) in the Athena Impact Estimator. Results

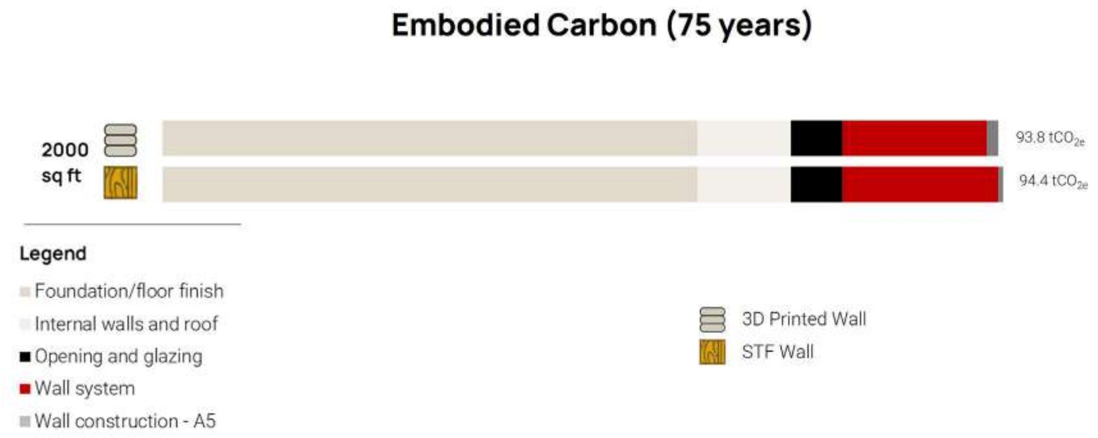


Figure 7: Embodied carbon of the two modeled structures. Results from Tally.

show that the STF wall construction phase accounts for 0.52 t CO_{2e}, 57% lower than the 3DP wall.

CO_2 uptake by carbonation

The CO_2 uptake by carbonation for the 3DP wall is equal to 4.2 t CO_2, resulting from the contribution of three major components:

$$CO_2\ uptake\ Exterior\ wall + CO_2\ uptake\ Interior\ wall +\ End\ of\ Life$$

The results obtained from the LCA of the fiber cement panels have been compared to a commercially available EPD showing similar values over the A1-D stages (see Figure 1 for reference). As a note, carbonation is included in use phase (B1) of the analysis.The embodied carbon of the wall systems are summarized in Figure 8.

Embodied Carbon Assessment: Wall System

The overall embodied carbon of the 3DP wall is the lowest at 16.2 t CO_{2e} with the wood frame wall being 3% higher. It is shown that the structural components, respectively the 3DP concrete (96% of the embodied carbon for the wall) and wood frame (64%), are the aspects with the largest contribution to embodied carbon. Thermal and moisture protection together with finishes are a major contributor for the wood framed wall (36%) while for 3DP wall those categories account for 4% of the embodied carbon.

Operational Carbon Assessment: Home

Figure 9 summarizes the results of the annual operational carbon analysis for the two construction systems across Climate Zones 1 through 4; the analysis uses the 2022 EIA electric grid carbon intensity data. The cities

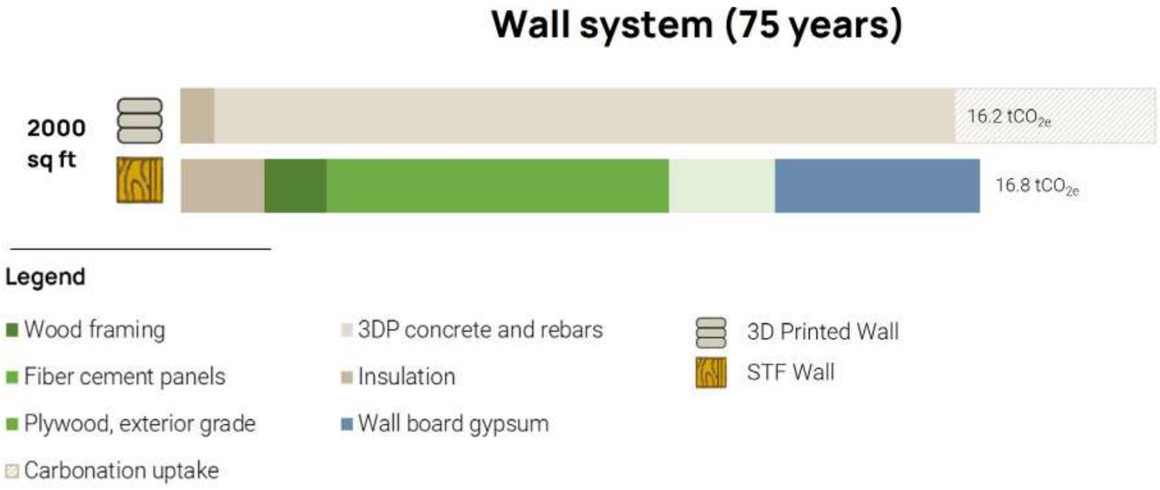


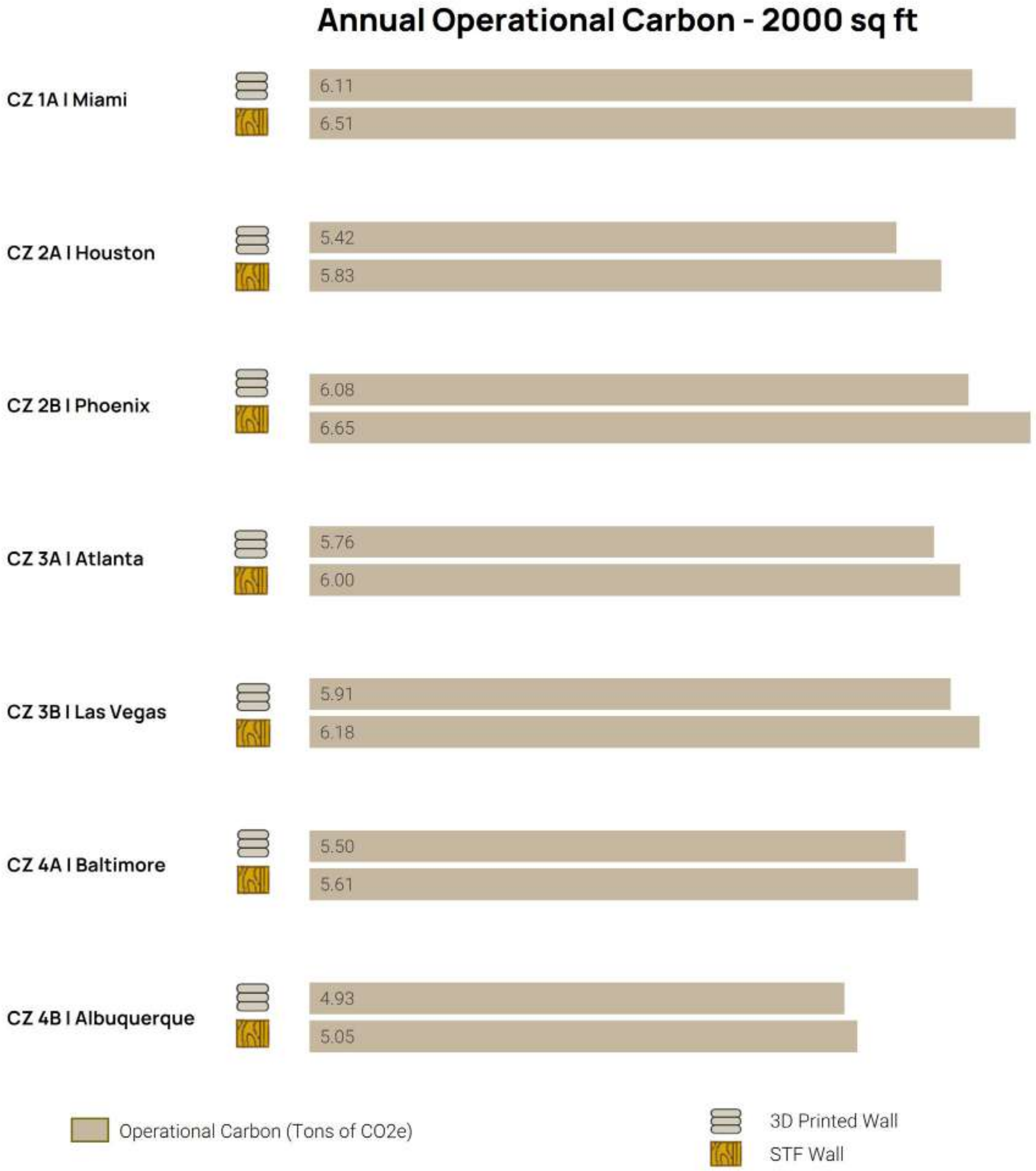
Figure 8: Relative contribution to the embodied carbon of the materials composing 3DP wall, STF wall for the 2000 sq ft floor plan.

for each climate zone were selected based on a similar list available from the Department of Energy reference buildings[20].The results show that 3DP concrete homes consistently achieve annual performance better than the STF homes. The annual savings in operational carbon range from 2% in the mixed-humid climates up to 9% in the dry hot climates. This result aligns with the increased benefits of concrete construction where the thermal mass has a beneficial effect on annual heating and cooling energy consumption.

Total Carbon Assessment: Home

The total carbon footprint of the homes over a 75 year period is shown in the results below (Figure 10). The dark gray bars represent the embodied carbon of the home and the lighter shade bars represent the operational carbon over a 75 year period. The operational carbon shown in the charts is based on the mean electric grid carbon intensity between the high zero carbon tech cost (HZ) and low zero carbon tech cost (LZ) EIA projections through 2050[21] . The

Figure 9: Annual operational carbon data in the four climate zones. Electric Grid Carbon Intensity based on 2022 EIA electric grid carbon intensity data.[22]

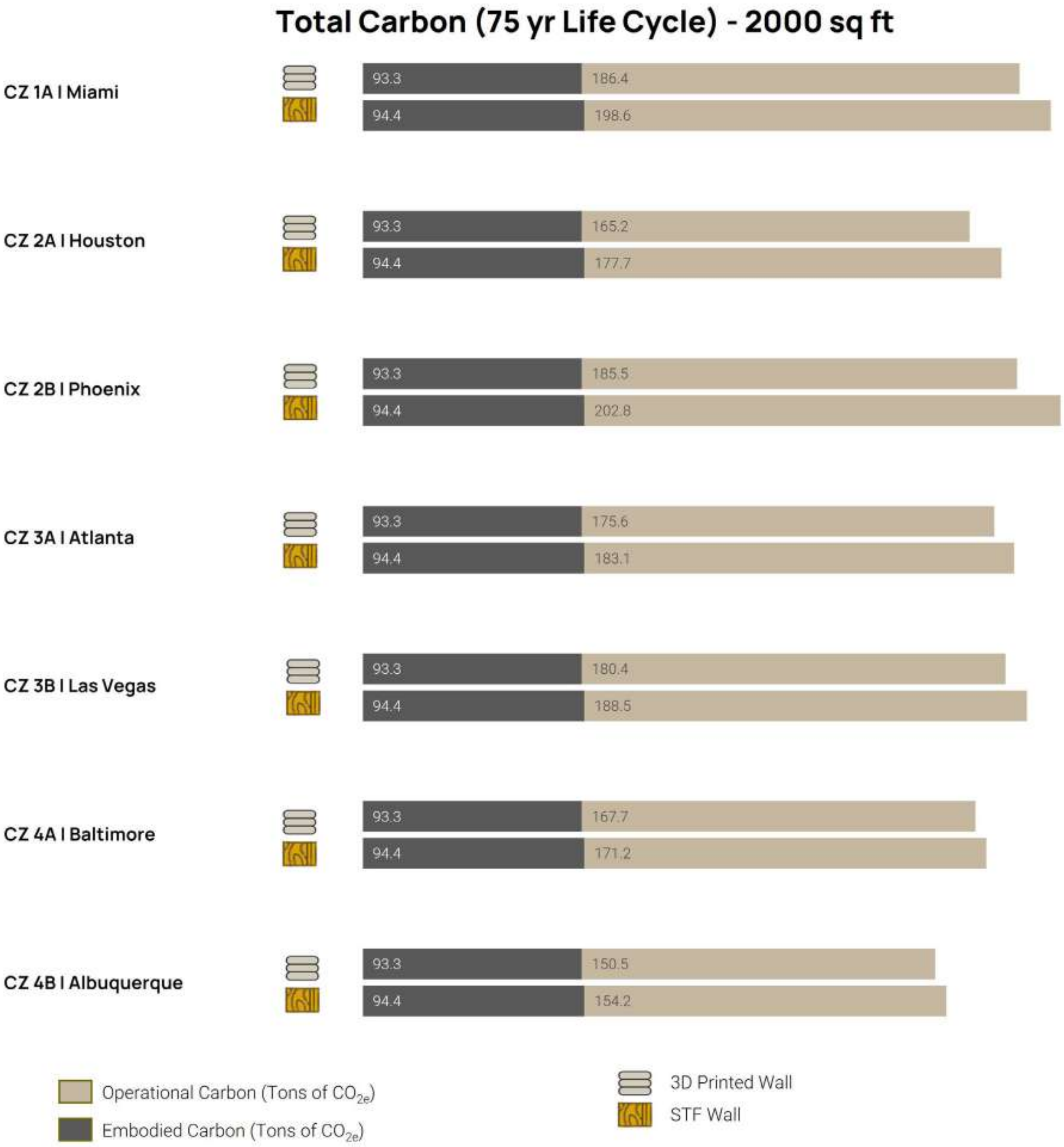


grid carbon intensity after 2050 is held constant at the 2050 levels. At 2050 the mean deviation is approximately 23% and by the end of the 75 year period the deviation increases to 42%.The printed wall construction compared to the stick framed wall is comparable in the mixed-humid and mixed-dry climates of Baltimore and Albuquerque with marginal savings around 2%. Savings up to 6% are achieved in the hot-dry climate zone of Phoenix.

Resilience

In addition, concrete homes may often be associated with lower expected damages than wood homes in case of extreme weather events, resulting in lower carbon emissions due to repairs. The frequency and economic magnitude of major natural disasters have grown over the last several decades[22]. As structural engineers know, natural hazards cause widely different levels of damage to buildings, especially homes, depending on their type of construction. This difference has real carbon emissions consequences

Figure 10: Total carbon for the modeled home produced with two different construction methods and in 8 different climate variants.



that are widely overlooked but can be easily inferred. In the event of a natural disaster, stronger construction can lead to less building damage, and thus a decreased need for repair. Stronger construction may provide life cycle carbon savings if fewer materials are required for repair, meaning there were less carbon emissions from their production.

Unfortunately, the environmental implications of hazard-related repair remain a key oversight in existing building LCA studies. Pomponi and Moncaster[23] found that about one-third of building LCA studies included some consideration of repair. A review by the same authors found that the only type of repair considered by these studies was routine maintenance; none considered the carbon consequences of hazard-related repair. Quantification of those carbon consequences will be left for future study, but their directional magnitude is known from the study of existing structures. The Federal Emergency Management Agency (FEMA) publishes estimates of expected damages by structure type in its HAZUS database. Using wind events as an example, engineered concrete structures are associated with lower expected damages than wood structures in all cases up to wind speeds of 250 MPH. In areas prone to wind-related storms, concrete structures will have lower expected carbon emissions associated with hazard-related repair.

Conclusions and Future State

The analysis presented in this report compares two different residential construction methods: 3DP and STF, and one home layout of 2000 sq ft. The performance of each home is assessed both in terms of embodied and operational carbon, considering the design details are in line with marketed residential single family home construction. The operational energy is assessed for four different climates zones at two different humidity levels, over a service life of 75 years.

The results demonstrate that:

- The embodied carbon of this 3DP Single Family home is approximately 0.5% lower than STF.
- 3DP homes achieve annual performance better than STF. The annual savings in operational carbon range from 2% in the mixed-humid climates up to 9% in the dry hot climates.
- 3DP homes achieve total carbon savings ranging from 2% in Baltimore to 6% in Phoenix compared to STF.

The carbon savings achieved are the result of 3DP construction methods combined with the use of low carbon 3D printable materials.

The materials selected for the initial development of 3DP concrete construction have typically been with mortar systems with high paste content. The mix design used as a reference in this study is designed to reduce its carbon footprint, by minimizing the binder content, by optimizing aggregate grading and by sourcing the bulk of the raw material locally.

It is anticipated that with advancements in 3DP technology, the future will show 3DP with an even lower embodied carbon. Materials with a lower paste content, optimized aggregate size, recycled materials, and a lower cement loading will further drive down total embodied carbon.

Further carbon savings are achieved through the design of the wall system. The amount of material is optimized without compromising the mechanical and durability performance, leading to comparable embodied carbon emissions to the STF alternative. In addition, the wall system is designed to optimize operational energy performance resulting in reduced operational carbon and costs.

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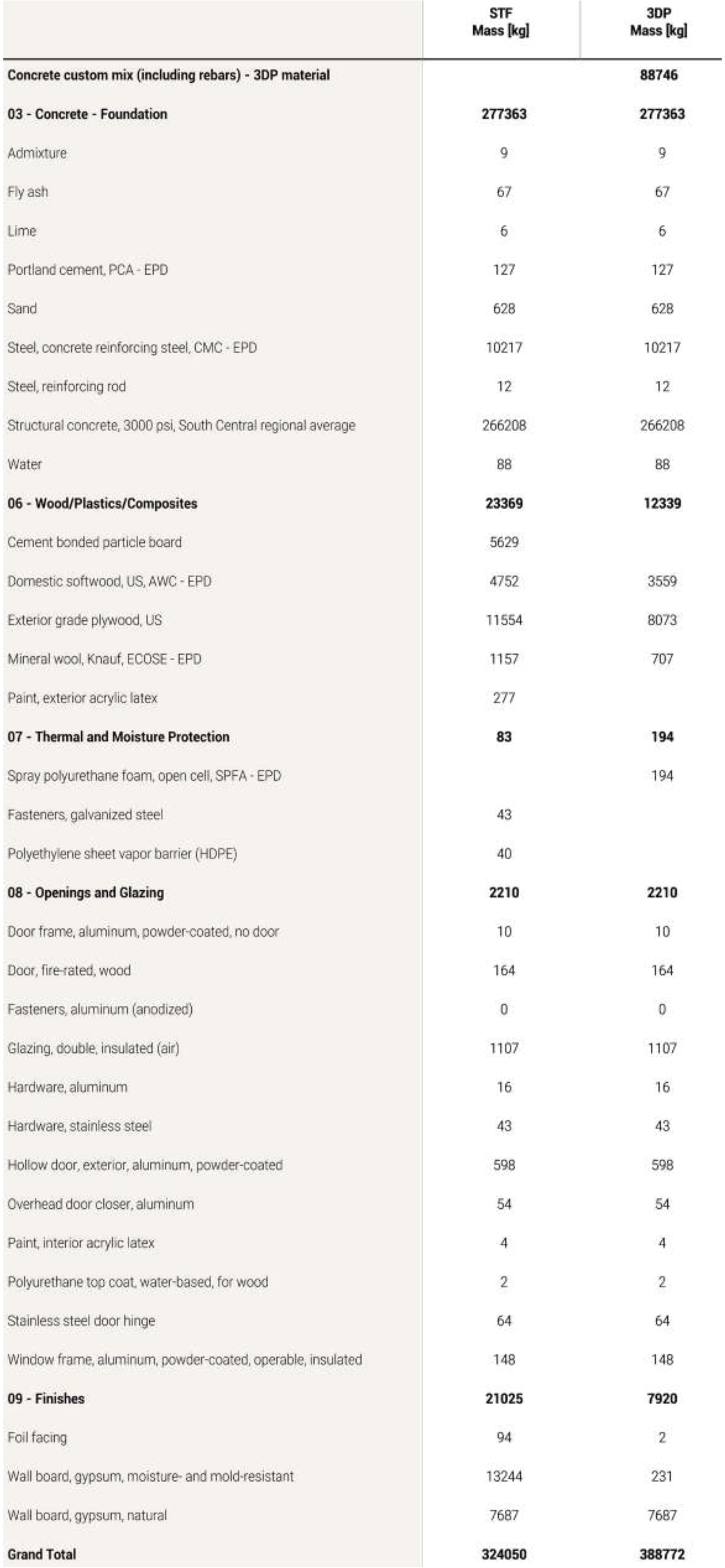
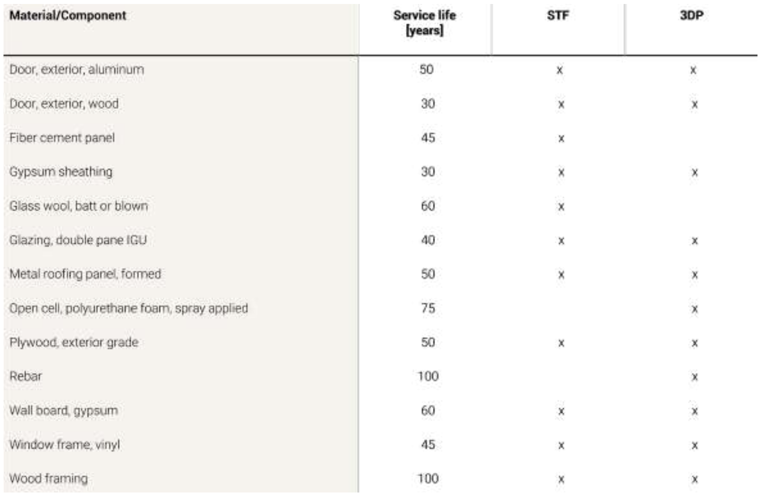
Appendix

Table A.1: Bill of Materials.



	STF Mass [kg]	3DP Mass [kg]
Concrete custom mix (including rebars) - 3DP material		**88746**
03 - Concrete - Foundation	**277363**	**277363**
Admixture	9	9
Fly ash	67	67
Lime	6	6
Portland cement, PCA - EPD	127	127
Sand	628	628
Steel, concrete reinforcing steel, CMC - EPD	10217	10217
Steel, reinforcing rod	12	12
Structural concrete, 3000 psi, South Central regional average	266208	266208
Water	88	88
06 - Wood/Plastics/Composites	**23369**	**12339**
Cement bonded particle board	5629	
Domestic softwood, US, AWC - EPD	4752	3559
Exterior grade plywood, US	11554	8073
Mineral wool, Knauf, ECOSE - EPD	1157	707
Paint, exterior acrylic latex	277	
07 - Thermal and Moisture Protection	**83**	**194**
Spray polyurethane foam, open cell, SPFA - EPD		194
Fasteners, galvanized steel	43	
Polyethylene sheet vapor barrier (HDPE)	40	
08 - Openings and Glazing	**2210**	**2210**
Door frame, aluminum, powder-coated, no door	10	10
Door, fire-rated, wood	164	164
Fasteners, aluminum (anodized)	0	0
Glazing, double, insulated (air)	1107	1107
Hardware, aluminum	16	16
Hardware, stainless steel	43	43
Hollow door, exterior, aluminum, powder-coated	598	598
Overhead door closer, aluminum	54	54
Paint, interior acrylic latex	4	4
Polyurethane top coat, water-based, for wood	2	2
Stainless steel door hinge	64	64
Window frame, aluminum, powder-coated, operable, insulated	148	148
09 - Finishes	**21025**	**7920**
Foil facing	94	2
Wall board, gypsum, moisture- and mold-resistant	13244	231
Wall board, gypsum, natural	7687	7687
Grand Total	**324050**	**388772**

Table A.2: Assumed Service Life.



Material/Component	Service life [years]	STF	3DP
Door, exterior, aluminum	50	x	x
Door, exterior, wood	30	x	x
Fiber cement panel	45	x	
Gypsum sheathing	30	x	x
Glass wool, batt or blown	60	x	
Glazing, double pane IGU	40	x	x
Metal roofing panel, formed	50	x	x
Open cell, polyurethane foam, spray applied	75		x
Plywood, exterior grade	50	x	x
Rebar	100		x
Wall board, gypsum	60	x	x
Window frame, vinyl	45	x	x
Wood framing	100	x	x