15th Canadian Masonry Symposium
Ottawa, Canada
June 2-5, 2025

Cradle to Gate Embodied Carbon LCA Comparison

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ABSTRACT

The primary goal of this investigation is to provide a comparative embodied carbon cradle-to-gate (A1-A3) LCA (Life Cycle Analysis). Three different prototype buildings are compared: a CMU (Concrete Masonry Unit) structure with architectural CMU veneer, a wood and steel light frame podium-style building with metal panel rainscreen, and an insulated precast panel concrete building with a thin brick veneer. This study incorporates recent carbon sequestration research for the CMU.

Due to the unique structure of dry-cast concrete products, a relatively large amount of carbon dioxide is sequestered at significantly faster rates within the first 28 days of manufacture when compared with other types of wet-cast concretes. This timeframe is considered to be within A1-A3 for concrete masonry unit manufacturing. Building elements included in this LCA are the foundation, beams and columns, exterior walls, and stairwells/shafts.

The secondary goal of this study is to serve as a frame of reference to use when evaluating the embodied carbon of CMU structures and making comparisons. It can also serve as a roadmap for LCA practitioners, providing guidance for how to evaluate the embodied carbon of masonry components such as mortar, grout, and how to calculate the volume of units used.

The tertiary goal of this study is to serve as a starting point for future embodied carbon Whole Building LCA studies incorporating use stage scenarios. Examples of this are demonstrating how masonry structures can lower use phase embodied carbon with low maintenance requirements, less replacement due to durability and inherent resiliency, and incorporating carbon sequestration that occurs during the building's use stage and beyond. Such analysis can also be used in conjunction with energy modeling to demonstrate how operational carbon can be lowered by accounting for concrete masonry's inherent thermal mass.

The findings of this study show that conventional concrete masonry construction has only 6% more embodied carbon compared to the wood and steel light frame prototype, whereas the precast prototype contained 51% more embodied carbon than the wood and light frame building. These comparative values do not take into consideration the additional carbon sequestration that would be realized during the use phase of the concrete structures.

KEYWORDS

Concrete masonry, embodied carbon, dry-cast concrete, sequestration, LCA, Life Cycle Analysis, A1-A3, Global Warming Potential

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Introduction

CMU construction has much lower embodied carbon than other types of concrete construction and offers all of the same benefits, such as thermal mass for energy efficiency, durability, low maintenance, and inherent resiliency. CMU construction can be closer to and even lower than envelope systems typically considered to be low carbon, such as wood when the entire envelope system is evaluated, and efficient structural design is implemented. CMU construction has low embodied carbon due to three main factors: less cement, more sequestration, and less volume of concrete in a wall due to the cores of the units. CMU are made using a dry-cast manufacturing method, which requires less water and cement compared to wet-cast concrete (inclusive of cast-in-place, precast, and other slump concrete materials). The structure of the dry-cast concrete itself has a unique void structure enabling more carbon dioxide to be sequestered and at a faster rate than wet-cast concrete [1]. Finally, CMU have open cores, which means less concrete is needed in the wall. To capture all three of these factors, it is necessary to look at the building envelope including all the main wall components and not just comparisons of individual materials.

This LCA study considers A1-A3 only, where concrete structures in general have relatively high embodied carbon. It is beyond the scope of this study to incorporate the use phase, where the impressive performance of concrete structures is well established in the areas of durability, inherent resiliency, low maintenance, and energy efficiency due to thermal mass. This study serves as a baseline for future LCA studies, which can include strategies to lower (GWP) global warming potential of CMU assemblies through the use of SCM (Supplementary Cementitious Materials), efficient structural design strategies, carbon sequestration inclusion during the use phase, use phase scenarios that incorporate durability by investigating the RSL (Relative Service Life) of materials used, and (EOL) End Of Life scenarios. It also serves as a baseline model for incorporating energy modeling, demonstrating lowered operational carbon due to thermal mass.

Building Identification

Three conceptual buildings used in this study are in the Northeastern part of the United States. Each comply with the prescriptive continuous insulation R-value tables in the International Energy Conservation Code (IECC) 2021 for climate zone 5 [2]. Each building is four stories above grade, has a parking garage below grade, and a stairwell/elevator shaft at each end. They are mixed use, providing retail on the first floor and residential apartments on floors 2-4.

Each building has a concrete column and beam structure to support the first and second floor. For floors 2-4 only the envelope is included as it is assumed that interior partitions and floors are the same across all three building scenarios. The stairwells are considered to be part of the thermal envelope. The below grade level of all three buildings consists of cast-in-place concrete walls and footings that support the floors above. Fig.1 shows the general configuration for all three buildings.

Figure 1: General configuration of all 3 conceptually designed buildings

- **Building 1:** CMU cavity wall with rigid board insulation and ground face/burnished CMU anchored veneer. The stairwell/elevator shaft has the same construction.
- **Building 2:** Podium-style structure where the first floor is steel stud with metal panel and floors 2-4 are wood stud with metal panel. Board insulation and insulation between the studs is used. The stairwells/elevator shafts are fully grouted CMU with metal panels as it is assumed they will provide structural support to the surrounding frame.
- **Building 3:** Insulated precast panel structure with adhered clay brick veneer. The stairwell/elevator shaft has the same construction.

GENERAL INFORMATION

Functional Equivalent

Functional equivalent is a description that includes the building's design characteristics, functions, required service life, and in-use conditions. It is an important factor when determining the comparability of different LCA and WBLCA (Whole Building Life Cycle Analysis) studies. This conceptual building is a 4 story 8387 square meter (90,280 square foot) mixed use structure above grade with a below grade 2097 square meter (22,570 square foot) parking garage. It is home to retail on the ground floor and multi-family residential on floors 2-4. It complies with climate zone 5 prescriptive tables of the 2021 IECC (International Energy Conservation Code).

System Boundary

The system boundary defines which life cycle activities are included in the analysis. The life cycle names and labeling used to describe the assessment system boundary are defined by ISO 21930 [3] and EN 15978 [4], and are grouped into modules. This designation format is used for WBLCA and environmental product declarations (EPD).

The system boundary of this assessment is cradle-to-gate, (A1-A3), which includes 28-day carbon sequestration for the CMU per the industry average EPD, as 28 days is within the gate of CMU production [5]. After manufacturing, CMU undergoes additional processing and often remains at the manufacturing site after the hydration process continues before being delivered to the project site and being installed. Wet-cast concrete does not include 28-day sequestration for several reasons: the installation of materials is within module A5 [6] and sequestration does not occur until hydration begins; wet-cast sequesters CO_2 much slower and the amount of CO_2 that is sequestered in the first 28 days after hydration begins is relatively small [7]; the wet-cast foundations and footings are buried below grade, impeding sequestration; and lastly, below grade sequestration would be the same for all three scenarios. Precast-panel sequestration is also not included, for the same reasons.

BUILDING MODEL SCOPE

Inclusions

This assessment includes the wet-cast concrete foundation and reinforcement, the reinforced concrete columns and beams, the building envelope including structure, insulation, exterior veneer, the concrete floors for the below grade garage, the wet-cast reinforced floors for levels 1 and 2, and the envelope of the stairwell/elevator shafts.

Building components that are consistent for all three buildings are omitted, such as interior partition walls, interior finishes, doors, windows, stairs, floors for the third and fourth floor, and the roof. All fasteners and anchors are also omitted for simplicity. Table 1 shows a complete list of inclusions and exclusions in the model scope.

Table 1: Building Model Scope

BUILDING COMPONENT	INCLUDED	
	Yes	No
Footings	X	
Footing Reinforcement	X	
Cast-In-Place Below Grade Walls	X	
Cast-In-Place Below Grade Wall Reinforcement	X	
Concrete Floor Slabs - Garage	X	
Concrete & Metal Deck Floor 1 & 2 - Concrete	X	
Concrete & Metal Deck Floor 1 & 2 - Metal Deck		X
Concrete Floors - Reinforcement	X	
Generic Floor - Floor 3 & 4		X
Stairs		X
Roof		X
Interior Walls		X
Exterior Wall Structure	X	
Exterior Wall Insulation	X	
Exterior Wall Vapor Barrier		X
Exterior Wall Veneer	X	
Fasteners (Anchors, Ties, Nails)		X
Windows		X
Doors		X
Stairs		X
Interior Finishes		X

Envelope Assemblies

Typical wall details for all 3 building types are shown in Fig.2.

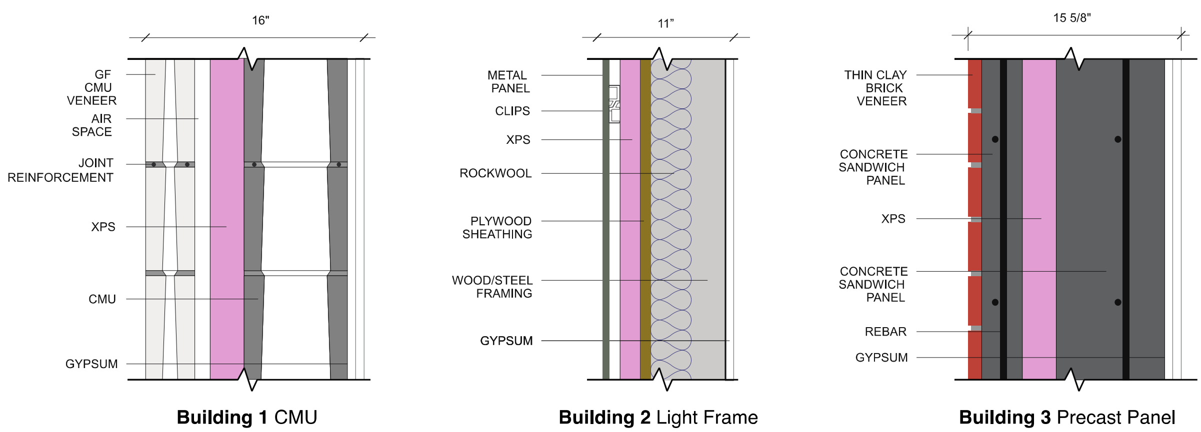


Figure 2: Typical wall details

MAJOR ASSUMPTIONS

To provide a simple baseline for embodied carbon, SCM (Supplementary Cementitious Materials) were not used for any of the concretes. All concrete is normal weight. Waste is not included in this assessment for any building material.

Energy Performance

Using the prescriptive R-value tables of the 2021 IECC climate for zone 5, R-values of only the insulation are considered and credit is not given for the thermal performance of the other building materials.

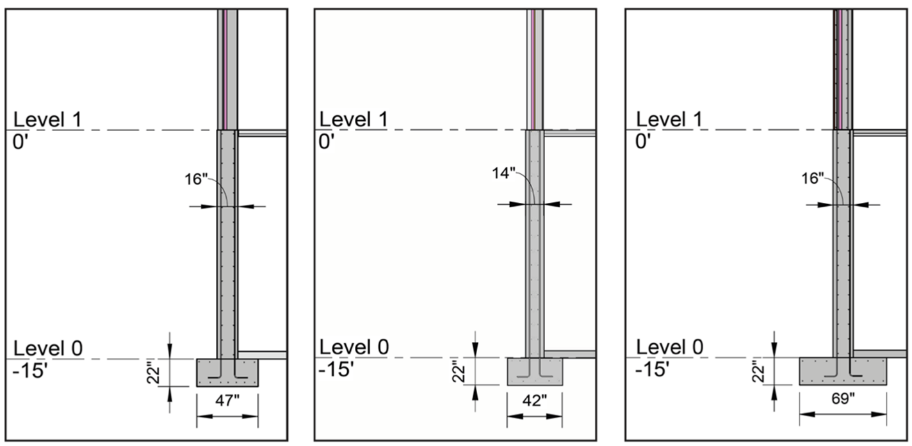
- **Building 1** (CMU) complies with prescriptive mass wall R-value requirement, R-11.4 CI.
- **Building 2** (steel frame portion) complies with prescriptive R-value requirement, R-13+R-10 CI.
- **Building 2** (wood frame portion) complies with prescriptive R-value requirement, R-13+R-7.5 CI.
- **Building 3** (Precast Panel) complies with prescriptive mass wall R-value requirement, R-11.4 CI

Foundations

The width of the foundation wall below the CMU structure is 406 mm (16 in.), the width of the foundation wall below the frame structure is 356 mm (14 in.), and the width of the foundation wall below the precast panel structure is 406 mm (16 in.) as shown in Fig. 3. Foundations walls for all three buildings are reinforced with two layers of M#15 (No. 5) rebar spaced 305 mm (12 in.) on center both horizontally and vertically.

Strip Footings

Foundation footings were adjusted to accommodate the weight of the wall assembly above it assuming a soil bearing capacity of 95 kPa (2500 lb/ft^2). For building 1, CMU cavity wall partially grouted construction, the strip footings are 56 x 120 cm (22 x 47 in.). For building 2, podium style building, the strip footings below the frame structures are 56 x 107 cm (22 x 42 in.) and below the fully grouted CMU shafts the strip footings are 56 x 147 cm (22 x 58 in.). For building 3, precast panel construction, the strip footings supporting these walls are 56 x 175 cm (22 x 69 in.). See Fig. 3 for section details of the walls, including foundation and strip footing sizes with rebar placement.



Building 1 CMU partially grouted strip footing & cast-in-place concrete below grade wall

Building 2 Frame strip footing & cast-in-place concrete below grade wall

Building 3 Precast panel strip footing & cast-in-place concrete below grade wall

Figure 3: Footing and foundation walls

Columns And Beams

Cast-in-place column and beam systems located in the lower floors were used for all three building types. Interior square columns for each building are 60 x 60 cm (24 x 24 in.), with four vertical M#25 (No. 8) reinforcing bars wrapped with M#13 (No. 4) stirrups every 20 cm (8 in.). The rectangular beams are 40 x 80 cm (16 x 32 in.) with four M#16 (No. 5) longitudinal bars and M#13 (No. 4) stirrups every 20 cm (8 in.). Footings for the columns are 90 x 180 x 180 cm (36 x 72 x 72 in.), with (M#16 (No. 5) rebar cages spaced at 20 cm (8 in.) on center O.C. in both directions as illustrated in Fig. 4.

Column footings for each building type are the same. Fig. 5 shows reinforcement placement in the foundation, footings, columns and beams for building 2, frame structure. It does not show reinforcement placement in the stairwell/elevator shafts.

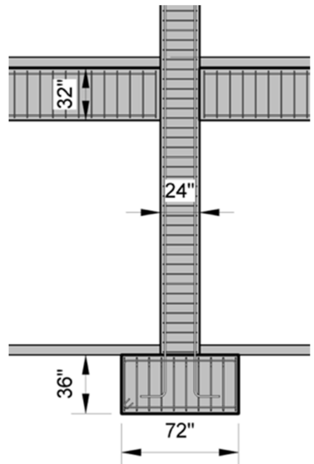


Figure 4: Typical column & beam rebar placement

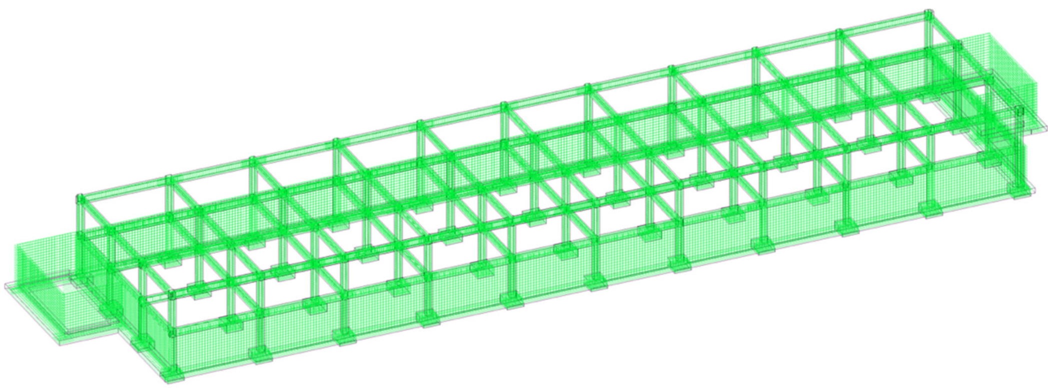


Figure 5: Reinforcement placement for superstructure and below grade structural concrete cast-in-place walls for Building 2

Both the podium style and precast panel buildings have structural columns on the perimeter to hold the beams shown in Fig. 7 & 8. The CMU structure does not use perimeter columns shown in Fig. 6. Instead, where beams meet the exterior walls, 30 x 20 x 40 cm (12 x 8 x 16 in.) reinforced CMU pilasters are used within the wall. The pilasters continue up the entire height of the building.

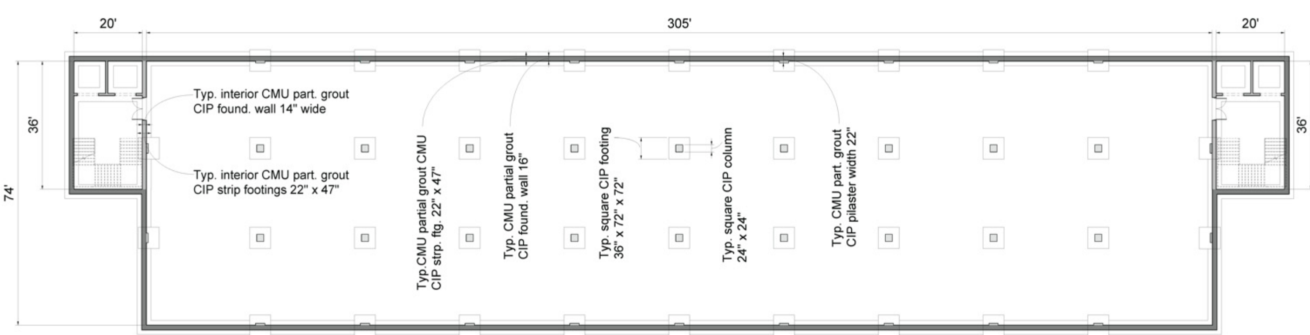


Figure 6: Building 1 (CMU) below grade structural concrete cast-in-place wall plan

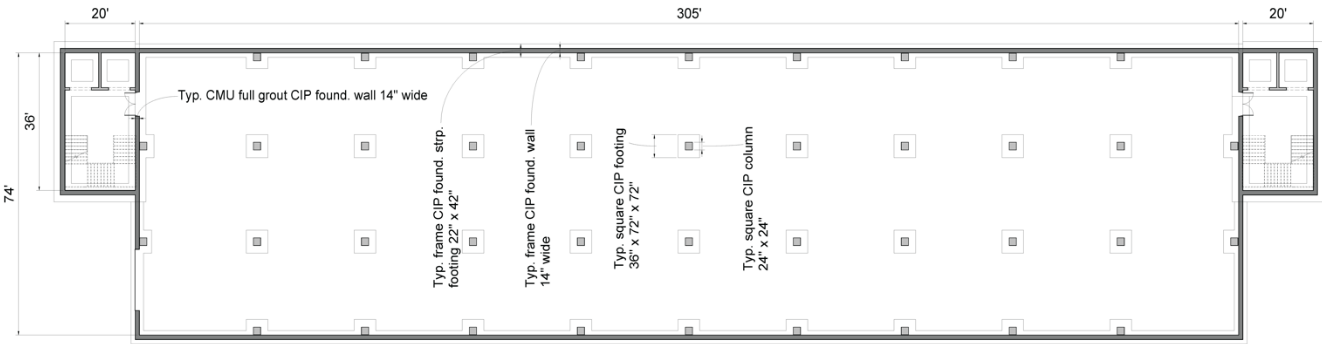


Figure 7: Building 2 (framed) superstructure and below grade structural concrete cast-in-place wall plan

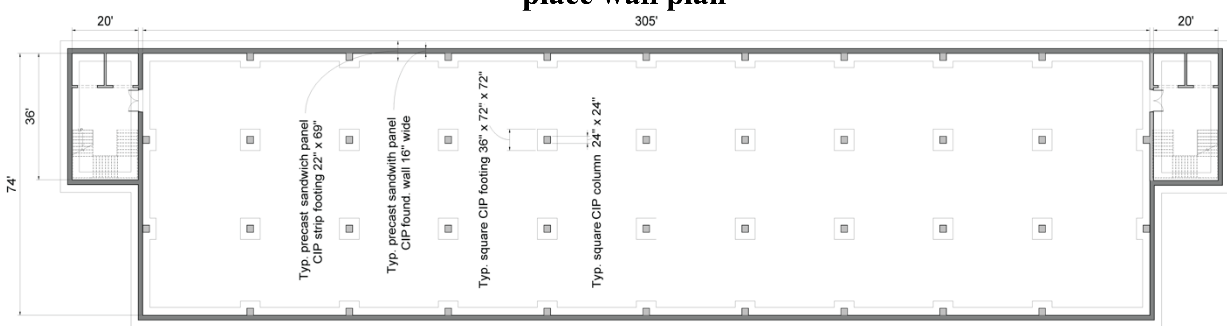


Figure 8: Building 3 (precast panel) superstructure and below grade structural concrete cast-in-place wall plan

Wall Structure

To determine the reinforcement placement for Building 1 (CMU) Direct Design software was used [8]. The design criteria for the masonry included f'_m = 15.5 MPa (2,250 lb/in.^{2}) with Type S portland-lime mortar, risk category II, and windspeed of 116 mph. As a strategy to lower embodied carbon, horizontal joint reinforcement was used along with the vertical reinforcement as primary structural steel to reduce the number of bond beams in the structure. See Fig. 9.

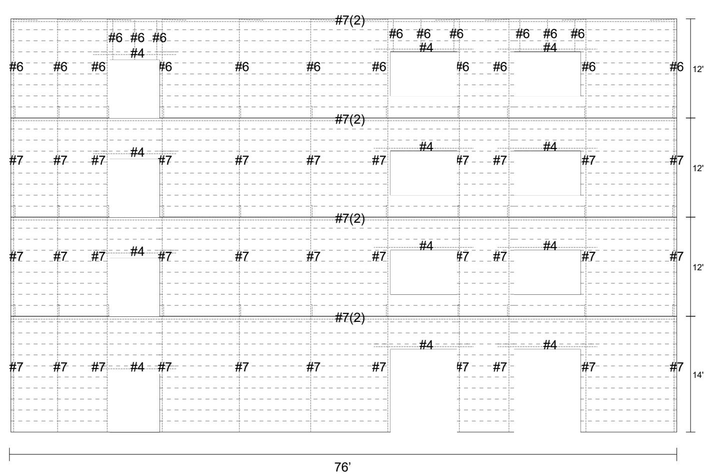


Figure 9: Side elevation of main building with joint reinforcement bond beam placement from Direct Design Software

Building 2, framed podium style, estimates for both steel and wood stud framing was based on the following assumptions; 50 x 150 mm (2 x 6 in.) nominal studs at 400 mm (16 in.) on center, three studs at the corners, two 50 x 150 mm (2 x 6 in.) studs at the side of each opening, one 50 x 150 mm (2 x 6 in.) at the top and bottom of each opening, one 50 x 150 mm (2 x 6 in.) perimeter plate, two 50 x 300 mm (2 x 12 in.) headers over each opening, and two 50 x 300 mm (2 x 12 in.) at the perimeter of each floor. To calculate the size and thickness of the steel studs, a lateral load of 1.68 kPa (35 lb/ft^2) was used in designing the light gauge steel system via online design resources [9]. It is assumed the stairwell/elevator shaft will provide structural support for the adjacent wood structure and therefore is fully grouted with reinforcement every 400 mm (16 in.) on center both vertically and horizontally.

Building 3, precast sandwich panels, a 34.5 MPa (5000 lb/in^2) concrete was used with vertical and horizontal reinforcement at 300 mm (12 in.) on center. The interior concrete layer is 200 mm (8 in.) deep and the exterior concrete layer is 76 mm (3 in.) deep.

ADDITIONAL INFORMATION

Treatment Of Biogenic Carbon For Wood Structures

Biogenic carbon for wood is not included in this LCA for the following reasons; Wood makes up one of the largest markets of bio-based building products. In 2018 the EPA reported that 17% of wood waste is recycled, 16% is incinerated, and the rest is left to de-compose in a landfill [10]. As an organic material, if wood decomposes with access to oxygen, it will release stored carbon. If it decomposes anaerobically without access to oxygen, it produces methane, which has roughly 28 times [11] the potency as a greenhouse gas when compared with carbon dioxide. Second, different trees hold different amounts of carbon in the soil. According to the USDA [12], trees from the boreal forests in Canada hold as little as 5 percent of their carbon in the tree and the rest is held below the surface in the root system and surrounding biomass. When lumber is extracted, and in particularly clear cut, this soil can be disturbed, releasing carbon dioxide. The Sustainable Forestry Initiative in Canada allows for up to 49 hectares (120 acres) or more to be clear cut [13]. Third, tree stumps and root systems are left in the ground to decompose after extraction, which will release carbon dioxide over time. Because of the uncertainty created by these examples, biogenic carbon is not counted as either a negative or a positive in the wood construction scenarios.

QUANTIFICATION OF THE BUILDING

For this assessment, most of the material list was acquired from building models generated in Revit. The wood and steel stud material list was estimated based on the criteria described under the wall structure section. The amount of reinforcement used in the CMU walls was determined using the Direct Design software. Other materials were calculated based on their volumes. See Tables 204 for the Bill Of Materials (BOM) used in this LCA.

Table 2: BOM for Building 1 – CMU

CATEGORY	SOURCE	DESCRIPTION	MATERIAL NAME	QUANTITY	UNITS
Below Grade Structural Walls	BIM model	Wall: 16" wide	Cast-in-place concrete 4000 PSI	524.3	M3
	BIM model	Reinforcement: wall	Rebar #5	29.1	MT
Envelope	calculation	8" & 12" CMU grouted cores	Grout - concrete 3000 PSI (proxy)	71.2	M3
	calculation	Exterior finish material: architectural CMU	CMU ground face 4"	204.8	M3
	BIM model & calculation	Structure & pilaster: CMU	CMU - NW 8" (including KOBB) & 12"	318.7	M3
	calculation	Mortar - 4",8",12" CMU	Mortar C270 portland-lime	60.0	MT
	BIM model	Insulation	XPS rigid Insulation 2 1/2"	3407.1	M2
	calculation	Wall board	Gypsum 5/8"	36674.0	SF
	calculation	Joint reinforcement	Joint reinforcement	6.2	MT
	calculation	Reinforcement: masonry	Rebar #5, #7	14.4	MT
Floors	BIM model	Floor: 6" slab on grade	Cast-in-place concrete 3000 PSI	338.2	M3
	BIM model	Floor: concrete on metal deck	Cast-in-place concrete 3000 PSI	334.1	M3
	calculation	Reinforcement: floors	Rebar #5 (12" x 12" OC)	5.7	MT
Footings	BIM model	Column footings: 72" x 72" x 36	Cast-in-place concrete 4000 PSI	122.5	M3
	BIM model	Strip footings: 47 x 22	Cast-in-place concrete 4000 PSI	168.5	M3
	BIM model	Reinforcement: column & strip footings	Rebar #5	11.1	MT
Superstructure	BIM model	Rectangular beam: 16 x 32	Cast-in-place concrete 4000 PSI	240.9	M3
	BIM model	Pilaster: 32 x 4 bump out of below grade wall	Cast-in-place concrete 4000 PSI	12.8	M3
	BIM model	Square column: 24 x 24	Cast-in-place concrete 4000 PSI	59.6	M3
	BIM model	Reinforcement: columns & beams	Rebar #4, #5, #8	20.8	MT

Table 3: BOM for Building 2 – Podium style framed structure

CATEGORY	SOURCE	DESCRIPTION	MATERIAL NAME	QUANTITY	UNITS
Below Grade Structural Walls	BIM Model	Wall: 14" wide	Cast-in-place concrete 4000 PSI	456.8	M3
	BIM Model	Reinforcement: wall	Rebar #5	29.1	MT
Envelope	estimate	Wood framing 2x12 (1 5/8" x 5.5")	2x12 (1 5/8" x 5.5")	18.1	M3
	estimate	Wood framing 2x6 (1 5/8" x 5.5")	2x6 (1 5/8" x 5.5") 16" OC	38.6	M3
	estimate	Steel framing 2x6 (1 5/8" x 5.5")	550S162-43 mils unpunched stud	4.7	MT
	BIM Model	Stairwell/shaft	CMU NW 8" fully grouted (incl KOBB)	89.7	M3
	calculation	8" CMU grouted cores (8" OC)	Grout - concrete 3000 PSI (proxy)	91.0	M3
	BIM Model	Reinforcement: CMU	Rebar #5 - 16" OC	9.1	MT
	calculation	Mortar	Mortar C270 portland-lime	14.5	MT
	BIM Model	Wall board	Gypsum 5/8"	36624.0	SF
	BIM Model	Exterior finish material: rainscreen	Flush metal panel .063 mm aluminum	3402.2	M2
	BIM Model	Exterior finish material: rainscreen components	Metal panel Z CLIPS 3/4 x 1 1/4 x 3	12.2	MT
	BIM Model	Sheathing	Plywood 3/4"	52.0	M3
	BIM Model	Insulation for wood framed walls	XPS rigid insulation 1 1/2"	2014.0	M2
	calculation	Insulation between wood framing 80% of SF	Rockwool 3"	1611.2	M2
	BIM Model	Insulation for CMU walls	XPS rigid insulation 2 1/2"	672.7	M2
	BIM Model	Insulation for metal framed walls	XPS rigid insulation 2"	715.5	M2
	calculation	Insulation between metal framing	Rockwool 3"	715.5	M2
Floors	BIM Model	Floor: 6" Slab on grade	Cast-in-place concrete 3000 PSI	368.4	M3
	BIM Model	Floor: concrete on metal deck	Cast-in-place concrete 3000 PSI	359.7	M3
	calculation	Reinforcement: floors	Rebar #5 (12" x 12" OC)	5.7	MT
Footings	BIM Model	Column Footings: 72" x 72" x 36	Cast-in-place concrete 4000 PSI	122.4	M3
	BIM Model	Strip footings	Cast-in-place concrete 4000 PSI	178.8	M3
	BIM Model	Reinforcement: column & strip footings	Rebar #5	10.0	MT
Superstructure	BIM Model	Rectangular beams: 16 x 32	Cast-in-place concrete 4000 PSI	233.7	M3
	BIM Model	Square columns: 24 x 24	Cast-in-place concrete 4000 PSI	132.4	M3
	BIM Model	Reinforcement: columns & beams	Rebar #4, #5, #8	27.0	MT

Table 4: BOM for Building 3 – Insulated pre-cast panel

CATEGORY	SOURCE	DESCRIPTION	MATERIAL NAME	Quantity	Units
Below Grade Structural Walls	BIM Model	Wall: 16" wide	Cast-in-place concrete 4000 PSI	523.0	M3
	BIM Model	Reinforcement: wall	Rebar #5	29.1	MT
Envelope	BIM Model	Precast insulated sandwich panel concrete	Concrete 5000 PSI	1013.8	M3
	BIM Model	Precast insulated sandwich panel finish	Clay thin brick 1"	86.7	M3
	BIM Model	Precast insulated sandwich panel insulation	XPS rigid insulation 2 1/2"	3411.9	M2
	BIM Model	Precast insulated sandwich panel wall board	Gypsum 5/8"	36726	SF
	BIM Model	Precast panel wall board	Gypsum Wall Board 5/8"	3206.0	SF
	BIM Model	Reinforcement: panel walls	Rebar #5 (12" x 12" OC)	76.7	MT
Floors	BIM Model	Floor: 6" slab on grade	Cast-in-place concrete 3000 PSI	338.3	M3
	BIM Model	Floor: concrete on metal deck	Cast-in-place concrete 3000 PSI	333.7	M3
	calculation	Reinforcement: floors	Rebar #5 (12" x 12" OC)	5.7	MT
Footings	BIM Model	Column footings: 72" x 72" x 36	Cast-in-place concrete 4000 PSI	122.4	M3
	BIM Model	Strip footings: 69 x 22 - under precast panels	Cast-in-place concrete 4000 PSI	242.9	M3
	BIM Model	Reinforcement: column & strip footings	Rebar #5	12.9	MT
Superstructure	BIM Model	Rectangular beams: 16 x 32	Cast-in-place concrete 4000 PSI	233.2	M3
	BIM Model	Square column: 24 x 24	Cast-in-place concrete 4000 PSI	130.4	M3
	BIM Model	Reinforcement: columns & beams	Rebar #4, #5, #8	27.0	MT

Environmental Data Sources

Third party verified North American EPDs were used for this analysis. Where EPD were not available, suitable proxies were used.

Results

Embodied Carbon, or GWP results were calculated manually and are summarized in Fig. 10. These results include 28-day sequestration as this is considered to be within the gate or A3 of CMU manufacturing. At the gate, the embodied carbon of the CMU building is within 5% of the light frame structure. If 2 year sequestration (as reported in the concrete products industry average EPD) is included, the CMU structure's embodied carbon is lowered to 1,042,124.7 kg CO_2e, which is within 3.8% of the light frame structure. For reference, if sequestration is not included, the GWP of the CMU building is 1,064,633.7 kgCO_2e.

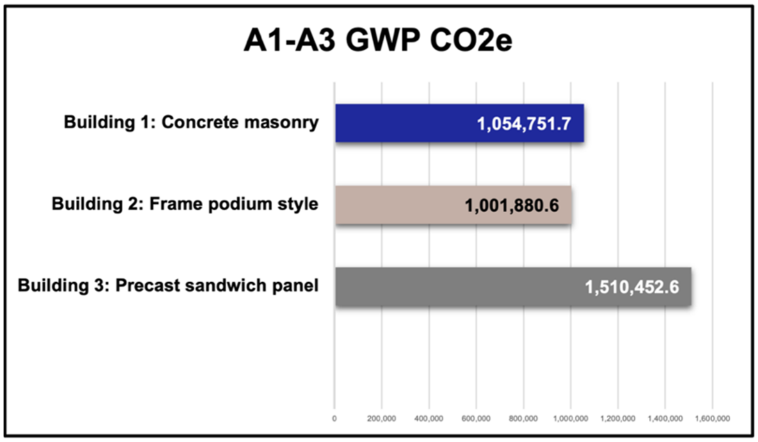


Figure 10: Results of embodied carbon building comparison

Conclusion

Results show that when a CMU structure is efficiently designed, it can have similar embodied carbon to a framed structure in the Cradle to Gate Stage, without extra measures to lower embodied carbon. This study serves as a baseline, and subsequent studies can expand the analysis in several key areas, bringing the embodied carbon of the CMU structure down even lower. These are:

- Inclusion of later use phase sequestration as data becomes available.
- Using lower embodied carbon structural CMU and CMU architectural veneer units.
- Include how operational carbon can be affected by incorporating thermal mass with whole building energy modeling.
- Incorporate additional efficient structural design strategies, lowering carbon and cost simultaneously.
- In the use phase, create scenarios incorporating inherent durability and resilience of CMU construction by analyzing the embodied carbon associated with the replacement of less durable materials.
- The inclusion of supplementary cementitious materials (SCM) such as slag, fly-ash, and other pozzolans in the concrete and CMU mix designs.

Future studies will focus on evaluating these strategies in the A1-A3 stage, and by creating a WBLCA (Whole Building Life Cycle Analysis) which will highlight the inherent durability, low-maintenance, resilience, and the thermal mass benefits associated with concrete masonry construction.

Acknowledgements

This study was made possible with a grant from the NCMA Education and Research Foundation. Technical support was provided by Jason Thompson, and this wouldn't have been possible without him. Sequestration research data was provided by Craig Walloch and Nick Lang of CMHA.

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