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A Pragmatic Approach to Lowering Embodied Carbon | 2023

Introduction

The built environment generates 40% of annual global CO_2 emissions. Of those total emissions, building operations are responsible for 27% annually, while embodied carbon is responsible for 13% annually.

Embodied Carbon is evaluated based on the Global Warming Potential ($kgCO_2e/m^2$) of a material and accounts for CO_2 equivalent emissions from the manufacturing, transportation, installation, maintenance, and disposal of building materials.

Concrete is typically the largest contributor to a building's Embodied Carbon. Cement is the primary contributor to the Global Warming Potential (GWP) of concrete and can account for as much as 90% of the overall embodied carbon impact while only accounting for approximately 10% of its weight. Concrete accounts for 8% of global GWP, and is estimated to account for over 50% of the total GWP in a typical commercial core and shell.

Until recently, the building industry has focused on Operational Carbon reduction. However, to effectively reduce carbon emissions associated with buildings it is necessary to reduce *both* Embodied Carbon and Operational Carbon. Designed as an interactive document, this guide offers pragmatic options at key project decision points to support stakeholders and consultants in the development of low-embodied carbon concrete solutions.

The technical guidance contained herein has been developed through the experience gained in the Lower Mainland of British Columbia, Canada by co-authors ZGF Architects, Fast+Epp, EllisDon, and Lafarge. This guide serves as a snapshot in time and will be updated by the authors as knowledge, products, and opportunities for low-embodied carbon concrete opportunities continually advance.

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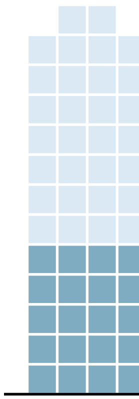
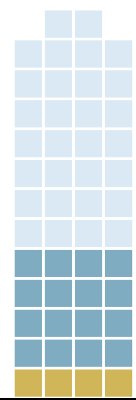


The built environment generates 40% of annual global CO_2 emissions.



At 8% of of global GWP, Concrete accounts for 20% of those emissions.

Concrete is one of the biggest opportunities to reduce carbon in the built environment.

Interactive Guide

Efficient and cost-effective low-embodied carbon concrete solutions are optimized when decision-makers and key consultants are onboarded earlier in the project design process. The graphical table below is an interactive tool designed to support identification of low-embodied carbon concrete through building project phases based on a typical concrete building project delivery in the Lower Mainland of British Columbia.
Click on the "blue text" in the graphical table below to navigate to each section of the Interactive Guide.

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Client | Architect | Structural Engineer | Contractor | Concrete Supplier

Pre-Design	Schematic Design	Design Development	Construction Documents	Bidding	Construction Admin.

Baselines and Targets →
Set carbon reduction goals and targets with client. Review embodied carbon reduction goals and targets with structural engineer.
Team Members involved: Client, Architect, Structural Engineer, Contractor

Efficient Structure →
Invest in detailed geotechnical investigations and structural analysis; minimize cement content; maximize utilization; embrace efficient lay-out; optimize foundations; evaluate prefabrication and novel solutions.
Team Members involved: Structural Engineer, Architect

Optimize Mix Design →
Work with structural engineer and contractor to understand maximum cure time, and with concrete supplier to gain best mix designs for specs and cure time requirements.
Team Members involved: Architect, Contractor, Concrete Supplier, Structural Engineer

Specifications and Procurement →
Ensure Global Warming Potential (GWP) targets for low carbon concrete are included in specs. Consider concrete GWP performance targets and Environmental Product Declaration (EPD) availability during concrete supplier bidding.
Team Members involved: Architect, Structural Engineer, Contractor

Early Embodied Carbon Calculations →
Perform preliminary baseline and embodied carbon calculations for concrete mixes and structural schemes during Schematic Design and early Design Development.
Team Members involved: Architect, Contractor, Concrete Supplier, Structural Engineer

Whole Building Life-Cycle Analysis (LCA) →
Perform whole building LCA through late Design Development through Construction Administration to understand relative impact.
Team Members involved: Architect, Contractor, Concrete Supplier, Structural Engineer

Baselines & Targets

Pre-Design | Schematic Design | Design Development | Construction Documents | Bidding | Construction Admin.

Checklist

- ☑ Set carbon reduction goals and targets with the team no later than Schematic Design.
- ☑ Review opportunities to reduce concrete GWP and associated impact.

Whole building embodied carbon reduction targets are typically set by codes (City of Vancouver) and building certification bodies (LEED, CaGBC Zero Carbon Building design standard, and ILFI Zero Carbon). Typically, targets are set as a 5-20% reduction over a preset baseline or as an absolute Global Warming Potential ($kgCO_2e/m^2$) target.

Low-embodied carbon concrete solutions can play a significant role and can provide no-cost / low-cost solutions in achieving a project's whole building embodied carbon reduction target. Recent projects have achieved 10-20% whole building embodied carbon reduction through low-embodied carbon concrete solutions (section Optimize Mix Design Case Studies).

Setting the baseline and target early allows for an evaluation of a greater number of opportunities that can reduce the carbon impact of a project. This includes concrete volume reduction and optimizing the concrete mix design.

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Baselines

For each concrete mix design, develop a realistic baseline specific to the concrete strength, exposure class, and cure time requirements as defined by the structural engineer.

Use industry recognized guidelines in setting a baseline, such as:

- NRCan LCA2 initiative
- Upcoming City of Vancouver LCA guidelines for the Vancouver Building By-law

Common Global Warming Potential (GWP) baselines can be set using the following:

- CLF: Generic Pan-North America baseline, note that these are conservative
- Concrete BC association: regionally specific concrete GWP numbers for BC

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Quick Links:

[National guidelines for whole-building life cycle assessment - NRC Publications Archive - Canada.ca]

[CLF Material Baselines for North America]

[Concrete BC Industry-wide EPD]

Setting Targets

Specific targets for concrete GWP reductions should be set in collaboration with the project team and be in alignment with the Owner's project requirements, sustainability goals and budget.

Low-embodied carbon concrete solutions can play a significant role in a cost-effective achievement of a project's whole building reduction target. It is recommended to establish concrete targets based on the GWP of mix designs and analyze these as percentage reductions on the baseline. The Procurement section of this guide includes an example bid form that can be used to document the GWP baseline, targets and percentage reduction of concrete.

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Opportunities & Scale of Impact

Setting the baseline and target early allows for the evaluation of a greater number of opportunities to reduce the embodied carbon of concrete.

There are a few examples of the opportunities and the associated scale:

- Reduction in parking levels through implementation of Traffic Demand Management (TDM) measures can significantly reduce the volume of concrete and contribute to a projects overall carbon reduction strategy
- Evaluation of alternate structural systems that have the potential to reduce the carbon impact of a project such as mass timber and structural steel systems
- Optimizing architectural and structural design to reduce transfer slabs
- High performing mix designs utilizing Supplementary Cementitious Materials (SCM's), reducing the amount of cement, and the associated GWP of the mix design

The list is not exhaustive but acts as a primer for discussion with the team to determine project relevant opportunities.

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Efficient Structural Use

Pre-Design | Schematic Design | Design Development | Construction Documents | Bidding | Construction Admin.

Less concrete volume per floor area, leading to lower overall embodied carbon, can be accomplished through developing a more efficient structural system. To achieve this, it is critical for the design team to optimize the architectural concept with the help of the structural engineer early in the design process.

In the design of concrete structures, simple adjustments to the conventional approach can lead to significant embodied carbon reductions. Some of the most effective ways to reduce concrete volumes are:

- ☑ Invest in geotechnical investigations and structural analysis.
- ☑ Optimize foundation system.
- ☑ Embrace efficient vertical grid and shear wall lay-out.
- ☑ Maximize element resistance utilization.
- ☑ Minimize cement content.

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General Strategies

Less is more — in concrete buildings, most of the embodied carbon is located within the structure. Commitment to early concept optimization and lean detailed design is critical. In addition, a few fundamental yet simple strategies can lead to significant embodied carbon reductions.

Consider concrete with high compressive strength

- 40 MPa concrete is 60% stronger than 25 MPa concrete
- GWP increase is only 35%

Consider steel with high tensile strength

- 500 MPa steel is 25% stronger than 400 MPa steel
- Both have similar GWP

Minimize concrete volume by maximizing reinforcement ratio for flexural members

- Nearly 100% of steel used for producing reinforcing bars comes from recycled scrap, and more than 65% of all reinforcing bars are recycled
- Slab reinforced with 0.4% vs slab reinforced with 0.2% may be 40% thinner
- 32% GWP reduction

Maximize resistance utilization by maximizing number of element sizes

- Maximizing structural utilization (i.e. resistance/demand) of each element will minimize total material volumes
- GWP values are linearly dependent on material volumes

Round up sizing to nearest 25 mm vs higher increments

- Adapting 225mm thick slab vs 250mm thick slab
- 11% GWP reduction

Deeper beams are more efficient than wider beams

- 400 wide x 800 deep beam is as strong as 750 wide x 600 deep
- 40% GWP reduction

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Gravity System

Most of the structural embodied carbon is utilized in the gravity load resisting system. Well-organized column grid and elimination of vertical transfers are the essential carbon reduction strategies. Use of more efficient slab systems and prefabricated elements will lead to additional reductions.

Embrace Regular Column Grid

- Columns account for 5-10% of structural carbon and slabs account for 40-50%
- Tighter column spacing will result in thinner slabs and lower overall material volume
- Equal column spacing in both directions is the most efficient solution
- Corner and end bays are the worst conditions increasing slab thickness - reduce spans by insetting columns from slab edges

Eliminate Vertical Transfers

- Continuity of vertical elements is the most efficient way to transfer loads down to foundations
- Avoid transfer beams, as they include large masses of concrete and are heavily reinforced

Use Efficient Slab Systems

- Post-tensioned slabs: Provides longer spans, thinner slabs and reduces building height which can result in a smaller envelope area
- Ribbed slabs: Lighter and stiffer system and effective for vibration-sensitive occupancies
- Voided slabs: Eliminates unnecessary concrete volume and reduces loads on foundations

Precast Concrete

Current EPDs for precast concrete are suggesting higher GWP than cast-in-place concrete. However, with factory setting and associated efficiencies precast concrete has the potential to improve the GWP performance of concrete and has other attributes to consider:

- Variety of efficient structural shapes such as double tee and hollow core are readily available, with the opportunity to prestress elements that can result in reduced concrete volume
- Factory formwork can be repurposed and reused
- High-quality concrete finishes can eliminate the need for additional finishing materials
- Precast concrete often leads to lower waste compared to cast-in-place

Slabs can account for 40-50% of the embodied carbon in a building structure

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Lateral System

Effective layout of the lateral load resisting system results in leaner superstructure and foundations. It should be thoughtfully organized and locked-in early in the design. For high seismic regions, high ductility systems and base isolation systems will result in significant material savings and should be utilized more commonly.

Embrace Structurally Efficient Lay-out

- Embrace symmetry
- Distribute shear walls uniformly throughout the floor plan
- Avoid layouts with only a central core or a core located on one side
- Eliminate structural irregularities (vertical off-sets, out-of-plane off-sets, non-orthogonal systems, etc.)

Favour Shear Walls over Moment Frames

- Concrete moment frames are significantly less efficient in resisting lateral loads than concrete shear walls
- Moment frames are inherently more flexible and require a larger volume of concrete and rebars to satisfy strength and drift demands

Avoid Short Shear Walls

- Short shear walls are not efficient in resisting an overturning
- Results in thicker walls and high volumes of rebar steel
- Bigger foundations are required for shorter shear walls

Use High Ductility Systems

- Ductile seismic force resisting systems dissipate energy more efficiently and reduce design forces
- This results in noticeable member size and material volume reductions

Use Base Isolation

- Superstructure is separated from foundations with an energy dissipating system (elastomeric pads, sliding plates, etc.)
- Amount of energy that is transferred to the structure during an earthquake is significantly reduced, resulting in a lower volume of concrete and rebar steel in the superstructure and foundations

Base isolation significantly reduces the amount of energy transferred to the structure during an earthquake, minimizing concrete and rebar volumes.

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Foundations

Foundations are responsible for a significant portion of embodied carbon for any building. Complexities of soil properties and building load transfer often lead to a conservative design approach. More detailed investigations and analysis will provide more information and will help reduce the size of structural elements.

Invest in Investigations and Analysis

- More sophisticated geotechnical investigations can lead to higher soil bearing resistance, resulting in smaller footings
- Soil-structure interaction analysis evaluates the behaviour of soil and structure as a system and may reduce the predicted magnitude of seismic force resulting in a lighter lateral load resisting system including foundations

Maximize SCM

- Target to maximize cement substitution with SCM's for foundations
- Most of the potential impacts of SCM's—including time strength gain, finishability, and adhesion—are rarely applicable to foundations

Minimize Slab-on-Grade (SOG)

- SOG thickness is often increased to minimize cracking caused by uneven settlements and concrete creep and shrinkage
- Uneven settlements can be mitigated by improving the quality of subgrade preparation
- Concrete creep and shrinkage cracking can be improved by placing rebars at tighter spacing
- It is often feasible to decrease SOG thickness by at least 25 mm (e.g. 125 mm vs 150 mm)

Release Hydrostatic Pressure

- High water table causes hydrostatic pressure, resulting in uplift forces underneath foundations
- 1 m of water table above the bottom of the foundations requires 0.7 m of concrete to balance the uplift
- Avoid using the self-weight of concrete to resist the uplift and eliminate it by releasing the hydrostatic pressure using alternative strategies
- (pumping system, storage tanks, bioswale, etc.)

Foundation systems can account for 20% of the overall structural embodied carbon.

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Specifications & Procurement

Checklist

- [x] Concrete specifications to be developed with Global Warming Potential (GWP) maximum limits.
- [x] Provide bidding form that allows concrete supplier to provide mix designs, associated cost, and additional considerations to the maximum GWP limits set.

Architect works with the Structural Engineer and Contractor to understand the required concrete specifications:

- Specify GWP limits along with strength
- Specification to call for the provision of Environmental Product Declarations (EPD) for the concrete mix design

Concrete supplier collaborates with the Architect and/or Structural Engineer and Contractor to identify strategies to reduce ordinary Portland cement (GU). This can be done by:

- Substituting cement with Portland limestone cement (GUL)
- Adding slag, fly ash, and/or other supplementary cementitious materials (SCMs) to the mixture
- Contractor works with the Owner and Architect to identify concrete products and suppliers that have EPDs available
- Utilize bidding form to attain alternate concrete mix designs with lower GWP

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Specifications

Specifications are a key element in realizing low embodied carbon concrete and should consider:

- Define concrete GWP maximum limits by mix design or element in line with other performance parameters required within the specifications.
  - Concrete bidding form allows for alternate mix designs options, considering cost / GWP / strength and other elements as needed by project team.
- Specify Portland Limestone Cement (GUL) as a direct substitution for GU cement
  - An approximate 10% reduction in GWP of cement with GUL instead of GU cement
  - GUL cement is widely available in the Lower Mainland
- Outline a preference for steel from Electric Arc Furnaces (EAF) instead of Basic Oxygen Furnaces (BOF) and ask for the supporting EPD's
  - Utilize A1 and A2 GWP numbers until manufacturers have relevant EPD's

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Quick Links:

CLF Model LCA Specifications

CLF Guidance on Embodied Carbon Disclosure

Building Transparency Embodied Carbon Specification language template

Guide to Improving Specifications for Ready Mixed Concrete (nrmca.org)

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Procurement

Utilize a concrete procurement form to allow concrete suppliers to propose alternate low carbon concrete mix designs to the maximum GWP concrete elemental mix designs.

Below is an example of the bidding form template that the authors have utilized on some projects to gain bids on concrete mixes. The example can be used as a template, modifying the elements, volume, and project target GWP values.

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Elements	**Exposure Class**	**Mix (MPa)**	**VOL (m^3)**	**Provisional Concrete BC Baseline Mix GWP from astm.org (Link)**	**Total Baseline GWP per mix ($kgCO_2e$)**	Mix GWP Maximum Target ($kgCO_2e/m^3$)	Total GWP per mix ($kgCO_2e$)	Mix GWP for lowest carbon, lowest cost @28 day ($kgCO_2e/m^3$)	Total GWP per mix ($kgCO_2e$)	Mix GWP for lowest carbon, lowest cost @56 day ($kgCO_2e/m^3$)
Foundations and Footings	-	25	6,028.2	231	1,389,630	182.0	1,097,140	182	1,097,140	
Walls	F2	30	2,495.7	270	673,413	215.0	536,574	215	536,574	
Columns	F2	30	139.3	270	37,593	215.0	29,954	215	29,954	
Suspended slabs and beams	-	30	2.4	270	657	248.0	604	248	604	
Suspended slabs and beams (parking)	C1	35	7,102.1	311	2,205,268	248.0	1,761,317	248	1,761,317	
Architectural concrete, exterior	F2	30	1,938.2	270	522,987	215.0	416,715	215	416,715	
Architectural concrete, interior	-	30	3,120.2	270	841,913	198.0	617,792	198	617,792	
Slabs on grade, exterior	C2	32		285	-	319.0	-	319	-	
Slabs on grade, interior	-	32		285	-	277.0	-	277	-	
Topping concrete	-	32		285	-	277.0	-	277	-	
Masonry grout	-	20		194	-	189.0	-	189	-	
				Project GWP ($kgCO_2e$)	5,671,460	**Project GWP**	4,460,094	**Project GWP**	4,460,094	**Project GWP**
				% Reduction	NA	**% Reduction (30% min)**	21%	**% Reduction**	21%	**% Reduction (40% min)**

Optimize Mix Design

Checklist:

- ☑ Engage in early conversations with concrete suppliers to explore cement reduction opportunities.
- ☑ Engage contractor to understand construction schedule and potential to increase cure time.

Strategies to optimize mix design:

- **Aggregates**
  - Optimize combined aggregate gradations
  - Use water-reducing admixtures
  - Use recycled aggregates where possible
- **Air content**
  - Higher air content results in higher GWP. Air content depends on exposure class, but should minimize where possible
  - Specify different mixes for different exposure classes
  - Avoid exterior design mixes for interior elements
- **Chemical admixtures:**
  - Use water-reducing and mix optimization admixtures
- **Supplementary Cementitious Materials (SCM)**
  - Increase SCM dosage with SCMs such as fly ash, slag, silica-fume to reduce cement content wherever possible

New generation SCM's are being introduced including pozzalon and white mud.

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Quick Links:

[Steps to Develop a Buy Clean Policy - Carbon Leadership Forum]

[EPD Requirements in Procurement Policies - Carbon Leadership Forum]

[Bid Document Examples from Building Transparency]

Case Study 1

As previously established, cement has the highest CO_2 emissions relative to mass among all concrete ingredients. ZGF worked with the concrete supplier during the early stages to optimize mix designs for all concrete mixes at no or negligible added cost for an institutional project in British Columbia. Below is an example of the findings.

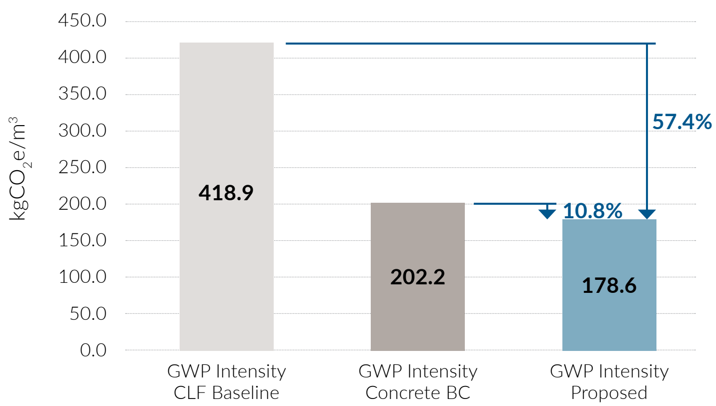
Project: 55,000 m² institutional project in British Columbia

Properties of Selected Concrete Elements*

	% Air Content	% SCM Dosage	% Cement Reduction	GWP
25 MPa Foundations	2.0	40.4	-67%	230
30 MPa Beams and Slabs	2.0	15	-54%	281
25 MPa Slab-on-grade	2.0	40.4	-61%	235
45 MPa Columns	0.37	30.0	-43%	365

*The table represents examples of concrete elements with their GWP. All concrete elements achieved reductions over the baseline GWP values.

Concrete GWP - Baseline vs Proposed



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Case Study 2

In this commercial project in British Columbia, the structural engineer worked with the team during early design stages to provide selection constraints to the mix designs such as exposure class and aggregate properties, along with overall quantities to evaluate reduction. The supplier recommended products that reduced GWP at no added cost.

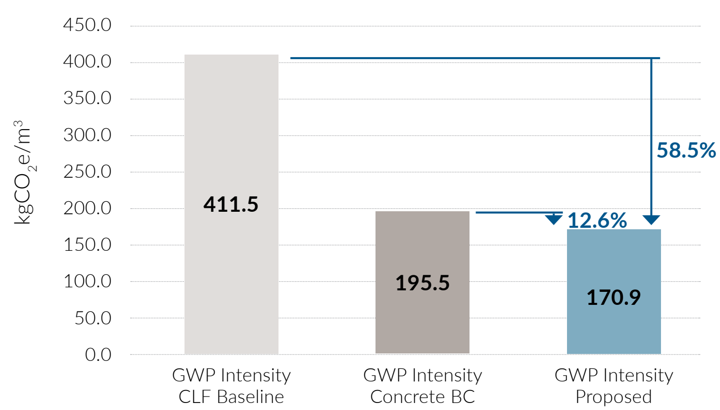
Project: 22,000 m^2 commercial project in British Columbia

Properties of Selected Concrete Elements*

	Exposure Class	Max Aggregate	GWP
35 MPa Foundations	N	0.75"	252
35 MPa Slabs and Beams	C-1	0.75"	297
30 MPa Slab-on-grade	C4	0.75"	230
50 MPa Columns	L3	0.75"	275

*The table represents examples of concrete elements with their GWP.
All concrete elements achieved reductions over the baseline GWP values.

Concrete GWP - Baseline vs Proposed



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Calculating Embodied Carbon & LCA

Pre-Design | Schematic Design | Design Development | Construction Documents | Bidding | Construction Admin.

Checklist:

Early Design Embodied Carbon Calculations:

- ☑ Gain approximate concrete quantities from structural during early design (schematic design and design development phases).
- ☑ Run baseline calculations using Environmental Product Declarations (EPD's) released by Concrete BC.
- ☑ Establish project embodied carbon reduction target from baseline.

Detailed Life-Cycle Analysis:

- ☑ Gain updated concrete quantities from final structural quantities and/or procurement data.
- ☑ Update baseline GWP and targeted values using concrete supplier information, which includes Environmental Product Declarations.
- ☑ Calculate Whole Building Life-Cycle Analysis for proposed building based on updated concrete information.

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Early Embodied Carbon Calculations

During the early stages of the project (SD or early DD), calculating projected embodied carbon of concrete is essential to establish a realistic baseline as well as the reduction targets. Requiring the following:

1. Gain approximate concrete quantities from structural during early design (schematic design and design development phases).
2. Run baseline calculations using Environmental Product Declarations (EPD's) released by Concrete BC
3. Establish project embodied carbon reduction target from baseline.

Embodied Carbon Calculations based on material quantities and related EPD's include impacts associated only with Transport and Manufacture (A1-A3) stages, which accounts for most of the total embodied carbon.

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Quick Links:

National guidelines for whole-building life cycle assessment - NRC Publications Archive - Canada.ca

CaGBC Zero-Carbon Design Standard, v3: Zero Carbon Building

Concrete BC Industry-wide EPD

Life Cycle Assessment for Buildings – Why it matters and how to use it, Ebook by OneClick

Tally LCA Resources

Athena Impact Estimator for Buildings

Baselines & Targets

Efficient Structural Use

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Early Embodied Carbon Calculations

Whole Building Life-Cycle Analysis

Whole Building Life-Cycle Analysis

Whole Building Life-Cycle Analysis (LCA) evaluates the environmental impact of a product through its life cycle and typically covers Transport and Manufacture (A1-A3), Construction (A4-A5), Use (B2-B4), and End of Life (C1-C4). Beyond Life (D) is optional depending on the boundary scope of the project.

In relation to concrete, a detailed LCA primarily helps with 2 things:

1. Comparing the relative impact of concrete against overall building GWP.
2. Verifying and validating reductions for the purpose of achieving project targets.

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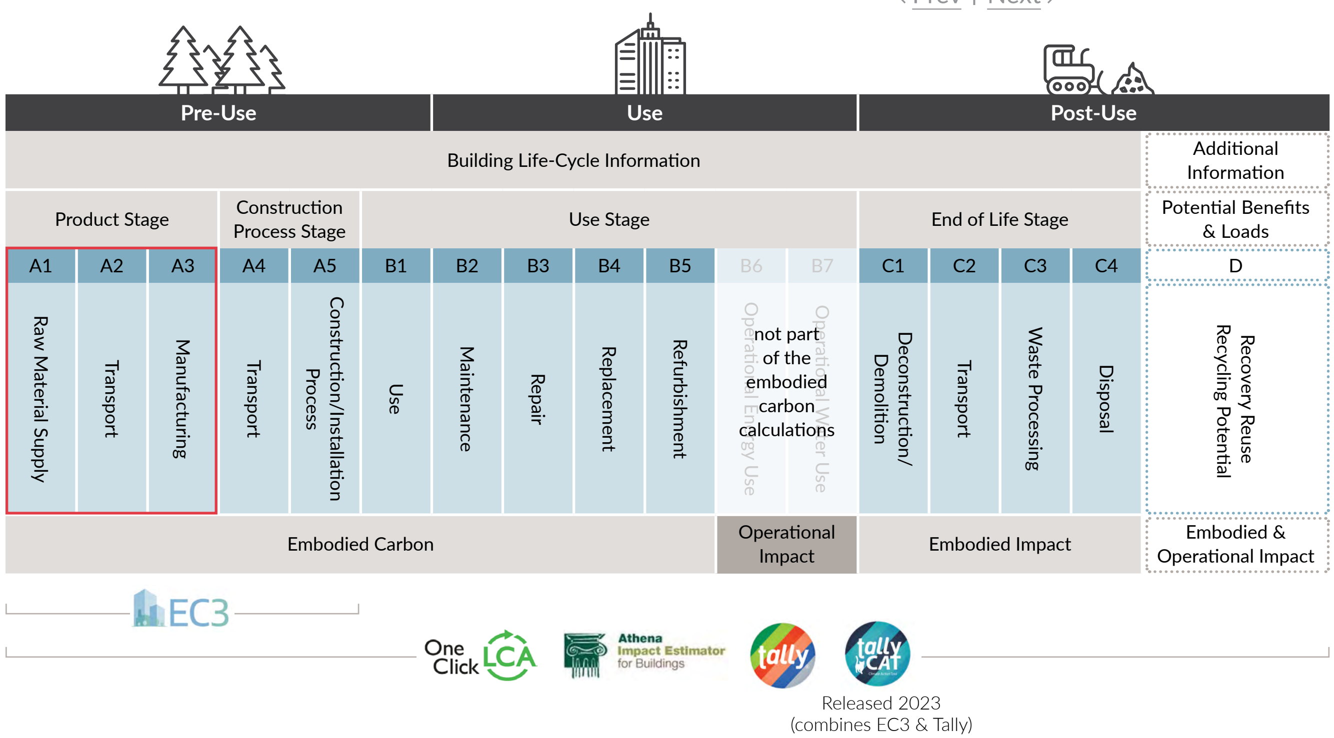

Key Terminology

Embodied Carbon: All the CO_2 emitted in the production of the building and is a result of distinct, rather than ongoing, processes that produce carbon. This includes the extraction and production of materials used during construction, and their transportation in addition to the carbon released by plants and machinery throughout the building process itself. In the case of rebuilds, demolition adds to the embodied carbon of a site.

Embodied Carbon Calculation: Method of quantifying the carbon environmental impact of a material or an element associated with its supply and manufacturing.

Environmental Product Declaration (EPD): According to the International EPD system, an EPD transparently reports objective, comparable, and third-party verified data about products and services' environmental performance from a life-cycle perspective. This includes estimated embodied carbon emissions data over a presumed life-cycle of the product through various life-cycle stages.

Global Warming Potential (GWP): According to the Government of Canada, the Global Warming Potential (GWP) metric examines each greenhouse gas's ability to trap heat in the atmosphere compared to carbon dioxide (CO_2). We measure this over a specified time horizon.

Life-Cycle Analysis or Assessment (LCA): Method of quantifying the environmental impacts associated with a material. Whole building LCA accounts for the sum of environmental impacts associated with all major contributing materials in a building.

Operational Carbon: The carbon released from the ongoing operation of a building. Sources will include lighting, power, heating, ventilation, air conditioning, and other infrastructure such as lifts and automatic doors.

Ordinary Portland Cement (GU or OPC): A finely powdered hydraulic binding material, which, when mixed with water, holds aggregates, sand, and other supplementary cementitious materials to form concrete.

Portland Limestone Cement (PLC or GUL): A blended cement with a higher limestone content (GU has 5%, while GUL has up to 15%). GUL performs similarly to Ordinary Portland Cement (GU) but can have up to 10% less GWP compared to GU.

Supplementary Cementitious Materials (SCM): Materials such as fly ash, slag, silica fume, pozzalon and white mud that work in conjunction with cement to form concrete and contribute to the properties of the concrete such as strength, durability, permeability, finish, and carbon impact.

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Resources

Baselines & Targets

Concrete BC Industry-wide EPD
CLF Material Baselines for North America
National guidelines for whole-building life cycle assessment - NRC Publications Archive - Canada.ca

Specs & Procurement

CLF Model LCA Specifications
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