CPCI TECHNICAL RESEARCH BULLETIN

Life Cycle Assessment of Precast Concrete Commercial Buildings

Precast Concrete...
Sustainable Structures for Tomorrow!

Canadian Precast/Prestressed Concrete Institute

CPCI-TRB#12-01

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1. Introduction

Life cycle assessment (LCA) is defined as an analytical tool used to comprehensively quantify and interpret the energy and material flows to and from the environment over the entire life cycle of a product, process, or service (ISO 2006). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product and a more accurate picture of the true environmental trade-offs in product selection. This technical research bulletin is a summary report of "cradle-to-grave" life cycle assessment research conducted on precast concrete commercial buildings (CPCI 2012). The bulletin also discusses how owners, architects and engineers can use this information in the context of true sustainability. By integrating the features and benefits of precast concrete products with the understanding of environmental impacts, designs can go beyond cradle-to-grave solutions, and ultimately provide "cradle-to-cradle" solutions.

2. Background and Goal

The LCA study *Life Cycle Assessment of Precast Concrete Commercial Buildings* (CPCI 2012) is a "cradle-to-grave" LCA of precast concrete commercial applications in two Canadian locations, Toronto and Vancouver. The study was conducted with a goal of gaining a better understanding of precast concrete's environmental life cycle performance in Canadian mid-rise precast concrete buildings. The study includes five variations of building envelope and follows LCA standards, ISO 14040 and 14044 (ISO 2006). It considers the impacts at each stage of a product's life-cycle, from the time natural resources are extracted and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal.

Environmental flows include emissions to air, land, and water, as well as the consumption of energy and material resources. Figure 1 shows the four iterative phases of the LCA: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation.

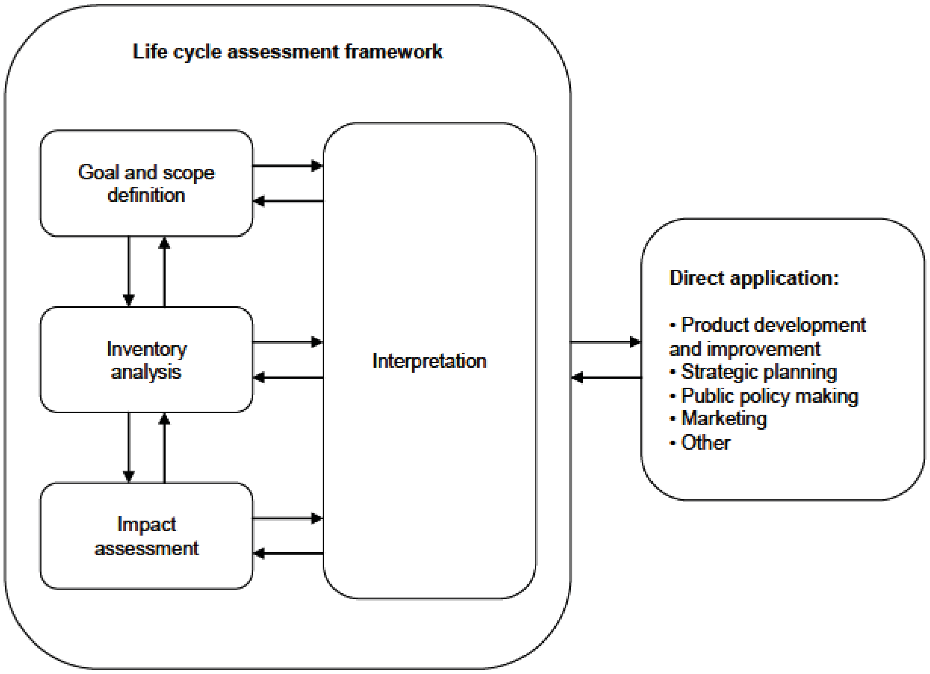


Figure 1. The four phases of life cycle assessment are an iterative process: the results of each phase can influence the phases that come before and after.

3. Precast Product Inventory Analysis

Inventory analysis, or life cycle inventory (LCI), is the first step towards environmental impact assessment. The inventory analysis for this project involved collecting data for precast concrete products within a plant process boundary as shown in Figure 2. Precast concrete product LCI data were obtained from surveys of three Canadian precast concrete plants in three provinces; British Columbia, Ontario and Quebec. Other material and construction LCI process data for upstream materials were taken from Athena Institute™ proprietary LCI building material and construction database, and third-party validated sources (CPCI 2012). These were used, ultimately, to model selected building components and other ancillary materials.

Precast operations offer economies of scale and a high level of quality control. Precast concrete components for walls, columns, floors, roofs, and facades are made by placing concrete and steel reinforcement into forms at the plant and then subsequently curing the product. Production procedures vary between the different categories of precast concrete products. Architectural precast concrete is usually made with conventional reinforcement in custom-made individual forms. These forms can be made of wood, fibreglass, concrete, or steel. Wood or fibreglass forms can generally be used 20 to 100 times depending on need without major maintenance while concrete and steel forms have practically unlimited service lives. Form-release agents are applied to forms prior to placing the concrete to prevent the product from adhering to the forms when they are removed. The steps in the precast production process typically include: (1) concrete mixing; (2) conveying to the form in trucks or specially designed transporters or concrete buckets carried by overhead cranes; (3) placing the concrete in the form; (4) consolidation by vibration, levelling, and surface finishing; (5) curing; and (6) form stripping.

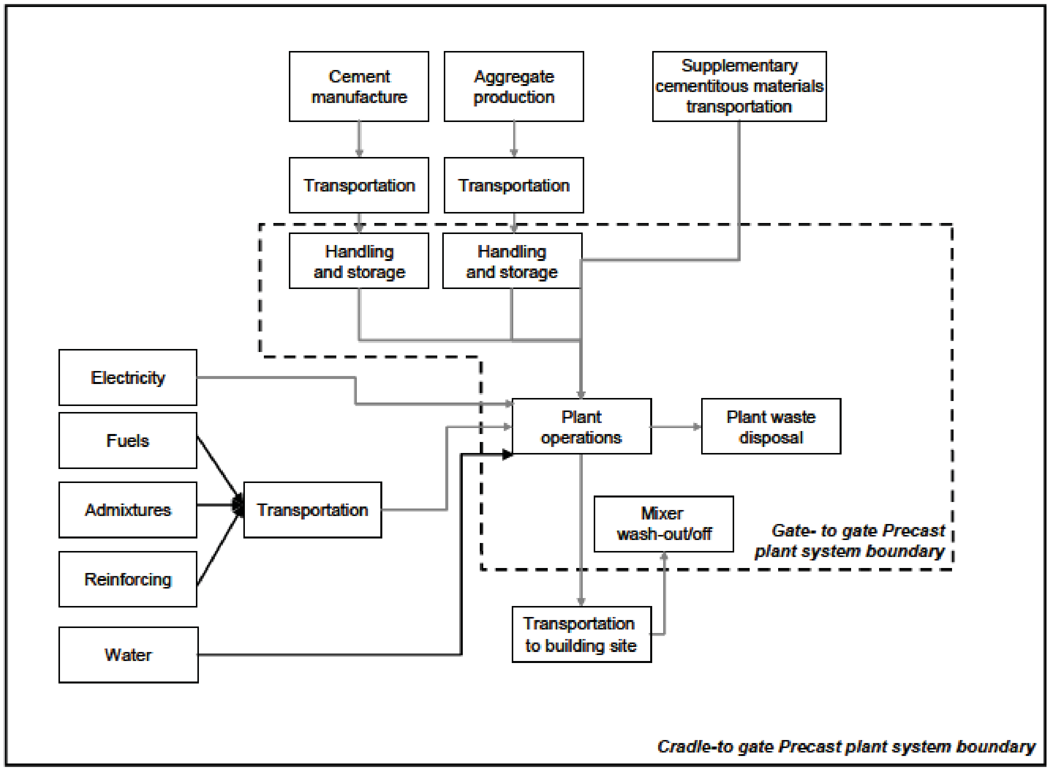


Figure 2. The system boundary of precast concrete production defines the unit processes included in the product system (this system boundary is a subset of the building system boundary and is included as the upstream profile of precast concrete products).

4. Building and Location

The definition of the functional unit, which is the basis for comparison, is defined in ISO 14040:2006 as the quantified performance of a product system for use as a reference unit. The modelled building chosen for the CPCI LCA study is based on prototype commercial buildings used by other building industry groups to model the effects of materials and energy use. These include technical committees of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) and the U.S. Department of Energy (US DOE 2011).

The building is a five-storey commercial structure with plan dimensions 27.4 m by 36.6 m, a height of 19.2 m, a gross floor area 5017 m^2 and a column grid spacing of 9.1 m by 12.2 m. Storey heights are 4.6 m for the first storey and 3.7 m for the remaining four stories, with storey height measured from finished floor to finished floor.

For this study, the "precast concrete building with precast concrete framing" (P-P) is designated as the baseline building. It consists of conventional architectural precast concrete exterior walls, a precast concrete structural frame, and precast concrete hollow-core floors. Other precast buildings evaluated in the study include precast concrete structural frame interchanged with varying envelopes; curtain wall, brick and steel stud, architectural precast, insulated precast, and insulated precast with a thin brick veneer. Table 1 provides a summary of the five structural precast buildings that were modelled. In this study the term curtain wall refers to a building envelope system that consists of extruded aluminum tubes (horizontal rails and vertical mullions); insulated vision glass; opaque spandrel glass (glass that spans between floors); insulated steel back pans (inboard of spandrel glass); and various anchors, fasteners, and sealants. Thin-brick veneer consists of bricks that are 13 mm to 16 mm thick, embedded into the precast concrete panels.

Table 1: The Five Precast Concrete Structural Assemblies

Envelope and Abbreviation	Building Abbreviation
Curtain Wall (CW)	CW-P
Brick and Steel Stud (S)	S-P
Precast Concrete (P)	P-P
Insulated Precast Concrete (Pi)	Pi-P
Insulated Precast Concrete and Thin Brick Veneer (Pib)	Pib-P

Note: All assemblies are precast structures. For example, CW-P is Curtain Wall on Precast Structure.

The facade of each storey has a band of windows each measuring approximately 1.5 m by 1.5 m as shown in Figure 3, for an overall window-to-wall ratio of 0.40. For energy modelling purposes the windows are considered as non-recessed, equally spaced, and non-operable with no blinds or shading devices. Windows are an inherent part of the curtain wall system. In the brick and steel stud envelope and the precast concrete envelopes, windows are aluminum framed.

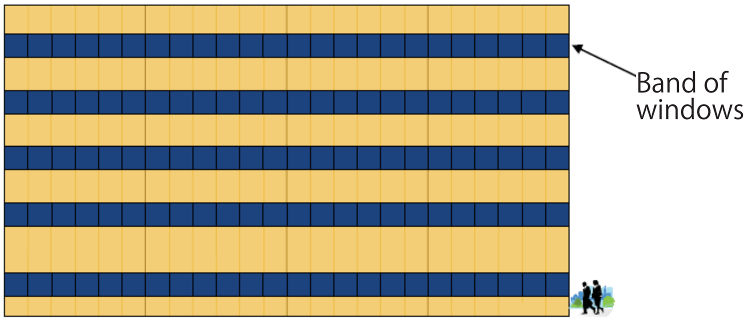


Figure 3. Each façade consists of bands of windows (shown dark blue).

Since energy use and thermal mass effects vary with climate, the buildings were modelled in two cities representing two distinct Canadian climates: Vancouver, British Columbia, a cool climate (Climate Zone 5C) and Toronto, Ontario, a cold climate (Climate Zone 6A). These cities were intentionally chosen to be consistent with cities used in other North American LCA studies. They have similar climates to those used by energy modellers to estimate national energy use in buildings; Vancouver is similar to Seattle but slightly colder, and Toronto is similar to Minneapolis.

5. Thermal Performance Design Criteria

The criteria for thermal performance of the exterior envelope assemblies is based on the requirements in ASHRAE Standard 90.1-2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* The Canadian Model Energy Code was derived from ASHRAE 90.1 and both the Ontario and British Columbia energy codes reference ASHRAE 90.1. This energy standard was chosen as a common baseline to ensure consistent comparisons to buildings within a particular location.

The requirements for fenestration (meaning windows) and insulation are shown in Table 2. Overall heat transfer coefficient (U-factor) and solar heat gain coefficients (SHGC) requirements are maximums, whereas R_{SI}-values are minimums. U-factor is a measure of thermal conductance and generally represents the overall rate of heat loss of a given assembly (such as in a window), whereas R_{SI}-value is a measure of thermal resistance and generally represents the thermal resistance of a given thickness of material. U-factor is expressed in SI units as W/(m^2•K), and R_{SI}-value is the inverse and is also expressed in SI units of (m^2•K)/W. The wall assemblies for the study are shown in Tables 3 to 6.

The modelled rate of infiltration is based on the typical Canadian maximum rate of 0.5 L/s •m^2 of envelope area when measured at a pressure difference of 75 Pa and, solely for comparison purposes, each building envelope is assumed to be designed and constructed as equally airtight.

Table 2. ASHRAE 90.1-2007 Energy Code Requirements for the Modelled Buildings in Vancouver and Toronto

Climate zone	City	Fenestration		CW fenestration	Roof R_{SI}-value	CW wall R_{SI}-value	Mass wall R_{SI}-value	Slab R_{SI}-value & depth
		U-factor	SHGC	U-factor				
5C	Vancouver	3.12	0.40	2.56	3.5	2.3 + 1.3	2.0 ci	NR
6A	Toronto	3.12	0.40	2.56	3.5	2.3 + 1.3	2.3 ci	1.8 for 600 mm

* Adapted from *ASHRAE 90.1-2007*, Table 5.5. U-factor in W/(m^2 • K) and R_{SI}-value in (m^2 • K)/W.
Note: CW = curtain wall; NR = no insulation requirement; ci = continuous insulation across structural members without thermal bridges other than fasteners and service openings; and "2.3 + 1.3" = R_{SI}-2.3 cavity insulation plus R_{SI}-1.3. continuous insulation.

Table 3. Insulated Precast Walls (Pib) Used to Meet Building Energy Code Requirements (Includes Option with Thin-Brick Veneer)

		R_{SI}-value	
Layer (outside to inside)	**Material**	**Vancouver**	**Toronto**
Exterior air film	Air, 24 km/h wind	0.03	0.03
Precast concrete exterior wythe	Concrete, 50 mm (75 mm for thin-brick)	0.03	0.03
Drainage plane	Air space	minimal	minimal
Rigid insulation, continuous	Extruded polystyrene, thickness, mm	60	70
	Extruded polystyrene, R_{SI}-value	2.03	2.38
Precast concrete interior wythe	Concrete, 75 mm.	0.03	0.03
Thermal break air space	Air space	minimal	minimal
Framing	Steel stud and air space, 65 mm	0.14	0.14
Interior finish	Gypsum wallboard, 16 mm	0.10	0.10
Interior air film	Air, horizontal heat flow	0.12	0.12
Total R_{SI}-value, $m^2 \cdot K/W$		**2.47**	**2.83**
U-factor, $W/m^2 \cdot K$		**0.40**	**0.35**

* R_{SI}-value except where noted; R_{SI}-value in $(m^2 \cdot K)/W$; U-factor in $W/(m^2 \cdot K)$; and R_{SI}-value of layers containing framing includes the effect of thermal bridging which reduced thermal performance.

Table 4. Conventional Precast Walls (P) Used to Meet Building Energy Code Requirements

		R_{SI}-value*	
Layer (outside to inside)	**Material**	**Vancouver**	**Toronto**
Exterior air film	Air, 24 km/h wind	0.03	0.03
Precast single wythe	Concrete, 150 mm	0.07	0.07
Rigid insulation, continuous	Extruded polystyrene, thickness, mm	60	70
	Extruded polystyrene, R_{SI}-value	2.03	2.38
Thermal break air space	Air space	minimal	minimal
Framing	65 mm	0.14	0.14
Interior finish	Gypsum wallboard, 16 mm	0.10	0.10
Interior air film	Air, horizontal heat flow	0.12	0.12
Total R_{SI}-value, $m^2 \cdot K/W$		**2.48**	**2.83**
U-factor, $W/m^2 \cdot K$		**0.4**	**0.35**

* R_{SI}-value except where noted; R_{SI}-value in $(m^2 \cdot K)/W$; U-factor in $W/(m^2 \cdot K)$; and R_{SI}-value of layers containing framing includes the effect of thermal bridging which reduced thermal performance.

Table 5. Brick on Steel Stud Backup Walls (S) Used to Meet Building Energy Code Requirements

		R_{SI}-value*	
Layer (outside to inside)	**Material**	**Vancouver**	**Toronto**
Exterior air film	Air, 24 km/h wind	0.03	0.03
Face brick	Brick, 90 mm	0.10	0.10
Drainage plane	25 mm air space, vented	0.08	0.08
Semi-rigid insulation, continuous	Rock wool, thickness varies, mm	70	80
	Rock wool, R_{SI}-value	2.00	2.37
Weather resistant barrier	Self-adhered membrane	minimal	minimal
Exterior sheathing	16 mm DensGlass Gold	0.10	0.10
Framing	Steel stud and air space, 90 mm	0.14	0.14
Vapour barrier	Polyethylene	minimal	minimal
Interior finish	Gypsum wallboard, 16 mm	0.10	0.10
Interior air film	Air, horizontal heat flow	0.12	0.12
Total R_{SI}-value, $m^2 \cdot K/W$		**2.66**	**3.03**
U-factor, $W/m^2 \cdot K$		**0.38**	**0.33**

* R_{SI}-value except where noted; R_{SI}-value in $(m^2 \cdot K)/W$; U-factor in $W/(m^2 \cdot K)$; and R_{SI}-value of layers containing framing includes the effect of thermal bridging which reduced thermal performance.

Table 6. Curtain Walls - Spandrel Areas Only (CW) Used to Meet Building Energy Code Requirements

		R_{SI}-value*	
Layer (outside to inside)	**Material**	**Vancouver**	**Toronto**
Exterior air film	Air, 24 km/h wind	0.03	0.03
Spandrel panel	Opaque glass	minimal	minimal
Air space	Air space	0.18	0.18
Semi-rigid insulation in spandrel backpan	Rock wool, thickness, mm	80	80
	Rock wool, R_{SI}-value	2.29	2.29
Semi-rigid insulation, continuous	Rock wool, thickness, mm	50	50
	Rock wool, R_{SI}-value	1.33	1.33
Framing	Steel stud and air space, 65 mm	0.14	0.14
Vapour barrier	Foil facing	none	none
Interior finish	Gypsum wallboard, 16 mm	0.10	0.10
Interior air film	Air, horizontal heat flow	0.12	0.12
Total R_{SI}-value, $m^2 \cdot K/W$		**4.19**	**4.19**
U-factor, $W/m^2 \cdot K$		**0.24**	**0.24**

* R_{SI}-value except where noted; R_{SI}-value in $(m^2 \cdot K)/W$; U-factor in $W/(m^2 \cdot K)$; and R_{SI}-value of layers containing framing includes the effect of thermal bridging which reduced thermal performance.

6. Annual Energy Use

Annual energy use was calculated using “whole-building energy simulation”. In whole-building energy simulation, a thermodynamic model of a building is created, and software simulates the operation and response of the building. Whole-building energy software perform these steps: (1) calculation of the heating and cooling loads of each space in a building over a defined period such as a typical year, (2) simulation of operation and response of the equipment and systems that control temperature and humidity and distribute heating, cooling and ventilation to the building, and (3) modelling the energy conversion equipment that uses fuel and electricity to provide the required heating, cooling and electricity.

The buildings were modelled with EnergyPlus™ whole-building energy simulation software developed by the U.S. Department of Energy. It simulates the complex interactions between climate; internal gains from lights, people, and equipment; building form and fabric; HVAC systems; and renewable energy systems.

The modelled thermal performance of the opaque portions of the building envelope takes into account thermal bridging where steel framing, fasteners, connectors, and anchors penetrate insulation layers (and aluminum in the case of curtain wall), and where insulation is discontinuous at the edge of floor slabs. **Consequently for final modelling purposes the *effective* R_{SI}-value is reduced from those presented earlier.** The percentage reduction is based on a combination of sources; calculations provided by the Canadian Precast/Prestressed Concrete Institute (CPCI) for the precast concrete walls, calculations from curtain wall manufacturer published information (for the curtain wall), ASHRAE *90.1-2007* (for all walls), and building envelope consultant Morrison Hershfield project experience (CPCI 2012) for all walls. The as-modelled U-factors and overall R_{SI}-values (1/U) are shown in Table 7.

In the curtain wall, insulation effectiveness in the spandrel areas is reduced by 50% due to thermal bridging through horizontal and vertical mullions exposed to the exterior. The insulation effectiveness of continuous interior insulation for curtain wall is reduced by 50% due to a combination of thermal bridging through horizontal mullions exposed to the interior and the discontinuity in insulation at the edge of floor slabs. In the brick walls, brick ties reduce the insulation effectiveness by 23% and the steel brick angle (offset on struts) at the slab edge further reduces insulation effectiveness by 10%. In the conventional precast concrete wall, steel connectors that penetrate the mostly continuous insulations reduce the insulation effectiveness by 6%. In the wall panels, steel connectors that penetrate the mostly continuous insulation reduce the insulation effectiveness by 7%.

Table 7. As-Modelled "Effective" U-factors and R_{SI}/R-values

City	Building Envelope	Wall U-factor	Wall U-factor	Overall wall R_{SI}-value (1/U)	Overall wall R-value (1/U)
		W/m² • K	Btu/hr•ft²•°F	m²•K/W	hr•ft²•°F/Btu
Vancouver	Curtain wall (CW)	0.433	0.0763	2.31	13.1
	Brick and steel stud (S)	0.498	0.0877	2.01	11.4
	Precast concrete (P)	0.424	0.0747	2.36	13.4
	Insulated precast concrete (Pi)	0.430	0.0757	2.33	13.2
	Insulated precast concrete and thin-brick veneer (Pib)	0.428	0.0754	2.34	13.3
Toronto	Curtain wall (CW	0.433	0.0763	2.31	13.1
	Brick and steel stud (S)	0.444	0.0782	2.25	12.8
	Precast concrete (P)	0.372	0.0655	2.69	15.3
	Insulated precast concrete (Pi)	0.376	0.0662	2.66	15.1
	Insulated precast concrete and thin-brick veneer (Pib)	0.374	0.0659	2.67	15.2

Annual energy use (by end-use), as determined by the energy simulation software, is presented in Table 8 (Vancouver) and Table 9 (Toronto). The results for both locations show relatively similar values for annual site energy use regardless of envelope, with the precast envelope options (P-P, Pi-P, and Pib-P) having the lowest overall site energy use by approximately 1% compared to curtain wall (CW-P) or brick and steel stud (S-P). Total Site Energy Use is shown in Figure 4.

Figure 4. Total Annual Site Energy Use Toronto and Vancouver

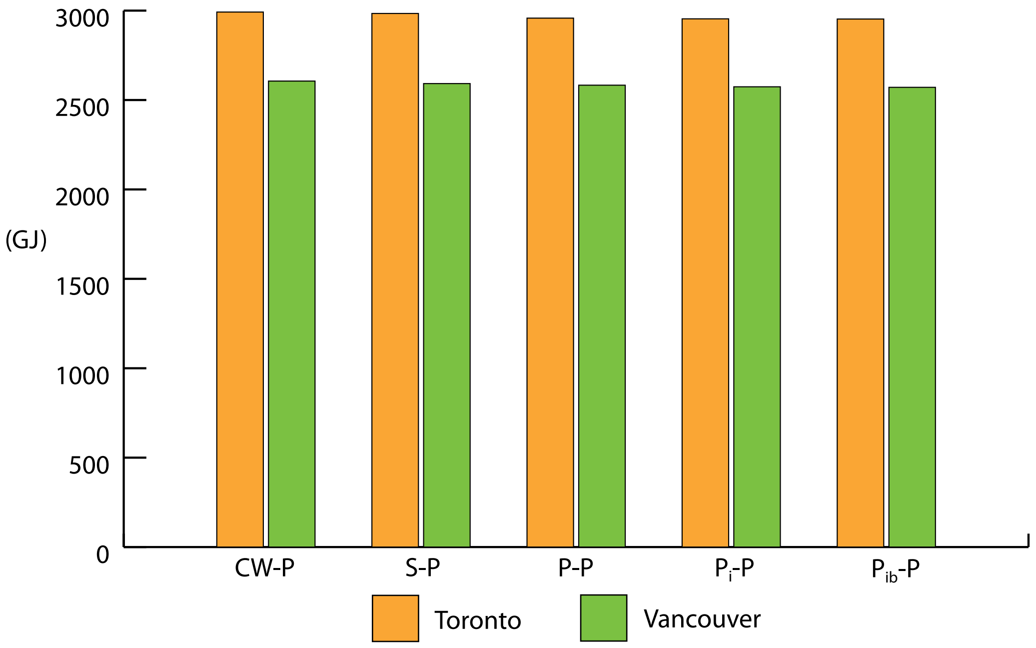


Table 8. Annual Site Energy Use by End-Use, Vancouver

	Annual Site Energy Use (GJ)				
Building	**CW-P**	**S-P**	**P-P**	**Pi-P**	**Pib-P**
Heating	446	436	427	420	417
Cooling	118	115	115	114	114
Interior Lighting	610	610	610	610	610
Exterior Lighting	232	232	232	232	232
Interior Equipment	908	908	908	908	908
Elevators	165	165	165	165	165
Fans	72	71	71	70	70
Pumps	0.4	0.4	0.4	0.4	0.4
Water Systems	54	54	54	54	54
Total	**2606**	**2592**	**2583**	**2574**	**2571**

Table 9. Annual Site Energy Use by End-Use, Toronto

	Annual Site Energy Use (GJ)				
Building	**CW-P**	**S-P**	**P-P**	**Pi-P**	**Pib-P**
Heating	735	730	705	702	701
Cooling	205	203	203	202	202
Interior Lighting	610	610	610	610	610
Exterior Lighting	233	233	233	233	233
Interior Equipment	908	908	908	908	908
Elevators	165	165	165	165	165
Fans	78	77	77	76	76
Pumps	0.4	0.4	0.4	0.4	0.4
Water Systems	58	58	58	58	58
Total	**2992**	**2984**	**2958**	**2954**	**2953**

7. Life Cycle Modelling

The LCI and LCIA modeling software used was *SimaPro* version 7.3.0, 2011. Each building constituent element (material, product, or process) is modelled independently from cradle-to-grave. These elements are then combined to comprise a complete building subassembly. Finally, each of these building subassemblies is then combined to model the complete building structure and envelope as constructed on-site (See Table 10). The buildings are modelled for 60 and 73 year service lives. 73-years is the median life for large commercial buildings supported by literature (US DOE 2008), however when performing an LCA of buildings in Canada, it is common practice to assume a 60-year life. For example, the default life in the *Athena® EcoCalculator* is 60 years. This bulletin presents the 60 year results.

The model also considers the environmental impact associated with maintenance for each material and assembly. The primary source of information used for maintenance was the Athena® report, *Maintenance, Repair and Replacement Effects for Envelope Materials* (Athena 2002), which describes:

- Maintenance stage activities for each assembly
- Material and energy usage, and the rate at which activities occur
- Construction waste factors

Eight assemblies were identified as undergoing maintenance:

1. Interior partitions (all cases)
2. Roof waterproofing system (all cases)
3. Windows (all cases except buildings with curtain wall)
4. Curtain wall
5. Brick and steel stud wall
6. Conventional precast panel wall
7. Insulated precast panel wall
8. Insulated precast with brick veneer panel wall

Table 10. Precast Subassemblies Modelled

Curtain wall/precast concrete (CW-P) 1. Footings and exterior wall foundation (for concrete structures) 2. Curtain wall 3. Precast concrete beams and columns 4. Hollow-core floors 5. Elevator and stairwell walls (all concrete buildings)
Brick and steel stud/precast concrete (S-P) 1. Footings and exterior wall foundation (for concrete structures) 2. Brick and steel stud 3. Windows (not curtain wall) 4. Precast concrete beams and columns 5. Hollow-core floors 6. Elevator and stairwell walls (all concrete buildings)
Precast concrete/precast concrete (P-P) 1. Footings and exterior wall foundation (for concrete structures) 2. Precast concrete (conventional panel) 3. Windows (not curtain wall) 4. Precast concrete beams and columns 5. Hollow-core floors 6. Elevator and stairwell walls (all concrete buildings)
Insulated precast concrete/precast concrete (Pi-P) 1. Footings and exterior wall foundation (for concrete structures) 2. Insulated precast concrete 3. Windows (not curtain wall) 4. Precast concrete beams and columns 5. Hollow-core floors 6. Elevator and stairwell walls (all concrete buildings)
Insulation precast concrete with brick veneer/precast concrete (Pib-P) 1. Footings and exterior wall foundation (for concrete structures) 2. Insulated precast concrete with brick veneer 3. Windows (not curtain wall) 4. Precast concrete beams and columns 5. Hollow-core floors 6. Elevator and stairwell walls (all concrete buildings)

Maintenance of precast concrete panels is based on Morrison Hershfield's standard recommendations in Building Envelope Maintenance Manuals (CPCI 2012). A building envelope maintenance manual provides a schedule of maintenance activities to ensure building envelope components perform as intended throughout their service life. Standard recommendations are based on decades of building envelope experience, manufacturer's installation instructions, material warranties, and industry best-practice.

The primary source for material quantities is the original design and construction take-offs. The take-offs were adjusted according to information from the referenced Athena report. For construction waste factors not included in the report, waste factors used for the construction stage were assumed. Total maintenance stage material and energy inputs over the course of the service life were calculated with the following equation:

$$Q_{m,n}\ \text{tot} = Q_{m,n} * (SL - P_n) / P_n * (100+WF_m)/100$$

Where,
m = material or energy
n = maintenance stage activity
$Q_{m,n}$ = quantity of material or energy m and activity n
SL= building service life (years)
P_n = activity rate for activity n (years)
WF_m = waste factor for material or energy m (%)

Note that the equation allocates only a percentage of the energy and material usage in the final maintenance activity period to the life cycle. For example, if the quantity of material used in a particular maintenance activity is 1 tonne, the service life of the building is 73 years, the activity rate is 20 years, and the waste factor for the material is 5%, then 2.78 tonnes of material is allocated for maintenance over the building's life cycle as follows: $Q_{m,n}$ tot $= 1 * (73 - 20) / 20 * (100 + 5) / 100 = 2.78$ tonnes. That is, the first maintenance activity starts after 20 years, then 1.05 tonnes are allocated for years 20 to 40, 1.05 tonnes for years 40 to 60, and 0.68 tonnes for years 60 to 73.

The end-of-life scenarios for the reuse, recycling and land filling of all materials are defined in Table 11 for both Vancouver and Toronto. These end-of-life scenarios were chosen to be consistent with the City of Toronto *3Rs Regulation* for construction and demolition of buildings over 2000 m^2 tonnes of material is allocated. One exception is drywall, assumed to be 100% recycled in Vancouver since it is prohibited to dispose of gypsum at the Vancouver Landfill (City of Vancouver 2009).

Table 11. Construction and Demolition Waste End-of-Life Scenarios (Vancouver and Toronto)*

Material	Reused	Recycled	Landfilled
Brick and concrete[1]	0%	100%	0%
Drywall[2]	0%	15%	85%
Steel[3]	0%	RR = 98% (S) & 70% (R)	2% (S) & 30% (R)
Aluminum[4]	0%	RR = 95%	5%
Glass & other materials[5]	0%	0%	100%

*Notes:

1. Assume all brick and concrete crushed on-site with 50% remaining on site as fill and the remainder trucked off-site 60 km to bbe used as a substitute for aggregate.
2. Assume gypsum on-site construction off-cuts are recycled (100%), with the remainder sent to landfill. Drywall in Vancouver is 100% recycled.
3. SRI 2011 data and WSA 2008 LCI EOL modeling are applied for structural and reinforcing steel products.
4. IAI 2007 and EAA 2008 data and LCI EOL modeling are applied for aluminum products.
5. Assume all float glass is landfilled (window or curtain wall).

8. Life Cycle Impact Analysis (LCIA)

Table 12 shows the impact categories and the characterization method used in the research study. TRACI is the U.S. EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. The methodologies underlying TRACI reflect state-of-the-art developments and best available practice for life-cycle impact assessment (LCIA) in the United States (Bare et al, 2003).

Table 12. Selected Environmental Impact Categories

Impact category	Unit equivalence basis (indicator result)	Source of the characterization method	Level of site specificity selected
Global warming	kg CO_2 - equivalents	TRACI	Global
Acidification	kg H+	TRACI	North America
Ozone depletion	kg CFC-11	TRACI	Global
Eutrophication	kg N water	TRACI	North America
Respiratory effects	kg PM2.5	TRACI	North America
Photochemical smog	kg ethylene	TRACI	North America
Solid waste	kg	Sum of LCI flows	North America
Water use	kg	Sum of LCI flows	North America
Abiotic resource depletion, excluding energy	kg antimony/yr	CML 2001	Global
Total primary energy*	MJ	CED adapted	Global
Non-renewable, fossil †	MJ		
Non-renewable, nuclear †	MJ		
Renewable (solar, wind, hydro, geothermal) †	MJ		
Renewable (biomass) †	MJ		
Feedstock, fossil †	MJ		
Feedstock, biomass †	MJ		

* Both the site-specific and the upstream waste realted to electricity production; fossil fuels pre-combustion; and oil, grease, and lubricants production are accounted for in the LCA study.

† Sub-set of primary energy.

The assessments of precast products include prestressed hollow-core floor slab, and conventionally reinforced precast wall panel, column and beam products. Table 13 provides a typical comparison of the LCIA results for the precast products at the gate of the precast plant on a volumetric basis.

The data show a small difference in impacts between the two product types. Each cubic meter of precast product embodies between 5,059 MJ and 5,402 MJ of primary energy, almost all of which is derived from non-renewable fossil fuels. In addition, the cradle-to-gate global warming potential of the two products is quite similar, varying between 482 kg and 512 kg (CO_2 equivalent basis) per m^3 of product, or 6% difference. All other environmental impact indicators and reported inventory flows are similar in their order of magnitude. The life cycle environmental impacts of precast concrete products are driven by their cement content. For example, cement content is responsible for 63 to 66% of the total GWP and 42 to 43% of the TPE. Precast plant operations are also important accounting for 14 – 18% of GWP and 28 to 35% of the TPE of precast concrete products, depending on the location.

Table 13. Typical Cradle-to-Gate LCIA Results* for Two Precast Product Groupings [per m^3] ***

Impact category	Unit	Hollow-core	Precast concrete wall panel, columns, beams
Global warming	kg CO_2 eq.	482	512
Acidification	H+ moles eq.	128	136
Respiratory effects	kg PM2.5 eq.	0.85	0.91
Eutrophication	kg N eq.	0.071	0.075
Photochemical smog	kg NOx eq.	0.739	0.749
Solid waste	kg	93.7	93.9
Water use	m^3	0.836	0.914
Abiotic resource depletion	kg Sb eq.	2.79E-04	3.01E-04
Ozone depletion	CFC-11 eq.	4.35E-08	2.08E-07
Total primary energy	MJ	5,059.2	5,402.9
Non-renewable, fossil	MJ	4,455.0	4,772.6
Non-renewable, nuclear	MJ	274.0	289.2
Renewable (SWHG)**	MJ	317.1	327.8
Renewable, biomass	MJ	13.02	13.20
Feedstock, fossil	MJ	0	0

* Includes steel reinforcement.
** SWHG = solar, wind, hydro and geothermal.
*** Appendix A includes the environmental data sheets for the four precast products in Vancouver and Toronto

The whole building "cradle to grave" LCIA results for the baseline building in Toronto (Precast envelope on precast structure, P-P) on absolute and percent basis by life cycle stage (manufacturing, construction, maintenance, operating energy, and end-of-life) are presented in Table 14 and Table 15. The data show:

- Total global warming potential is 15,877,690 kg CO_2 eq. Of this, 89% is from operating energy; from the extraction, manufacture, delivery, and use of energy for heating, cooling, ventilating, lighting, elevators, office equipment, and hot water during operating of the building. Manufacturing the materials and systems that make up the building itself is responsible for only 9% and maintenance is responsible for 2%. Construction and end-of-life are less than 1%.

- Total primary energy is 547,800,690 MJ, which consists mostly of 91% non-renewable energy and 8% renewable energy. Non-renewable energy consists of 41% fossil and 51% nuclear.

- The life cycle stage of operating energy is responsible for more than 80% of the impacts in global warming, acidification, respiratory effect, eutrophication, water use, total primary energy, non-renewable energy, and renewable energy.

- Most of the solid waste generated is associated with operating energy (69%) and the remainder comes from manufacturing (32%).

- Ozone depletion is split as 54% manufacturing and 46% maintenance.

- All end-of-life impacts are 1% or less. Some end-of-life effects contribute to reducing impacts. These impacts (shown with a minus sign) arise out of the beneficial reuse and recycling of some materials. Reuse and recycling offset the need for extracting and processing virgin materials.

Table 14. Whole-Building LCIA Results for P-P Toronto 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Manufacturing	Construction	Maintenance	Operating energy	End of life
Global warming	kg CO_2 eq.	**15,877,690**	1,352,183	23,618	366,724	14,134,754	411
Acidification	H+ moles eq.	7,107,896	394,146	9,946	154,821	6,548,758	225
Respiratory effects	kg PM2.5 eq.	32,937	2,273	36	564	30,230	-165
Eutrophication	kg N eq.	2,000	231	7	122	1,621	18
Photochemical smog	kg NOx eq.	38,573	2,900	143	952	34,212	367
Solid waste	kg	601,304	194,636	274	5,324	415,797	-14,727
Water use	m^3	23,443	2,597	10	1,332	19,713	-209
Abiotic resource depletion	kg Sb eq.	1.69	1.61	0.12	0.08	0.00	-0.12
Ozone depletion	CFC-11 eq.	4.39E+00	2.36E+00	7.42E-05	2.03E+00	1.70E-04	2.93E-04
Total primary energy	MJ	**547,806,690**	16,292,663	463,220	6,672,793	524,402,212	-24,199
Non-renewable, fossil	MJ	226,054,198	14,349,802	351,023	6,040,502	**205,278,863**	34,007
Non-renewable, nuclear	MJ	279,968,285	1,557,841	97,679	335,580	**278,028,590**	-51,406
Renewable (SWHG)	MJ	41,499,744	300,355	14,469	101,956	**41,089,772**	-6,808
Renewable, biomass	MJ	75,449	27,229	48	43,178	4,986	7
Feedstock, fossil	MJ	209,013	57,436	0	151,577	0	0

Table 15. Whole-Building LCIA Results for P-P Toronto 60 yrs (baseline) – Percent Basis

Impact category	Unit	Total	Manufacturing	Construction	Maintenance	Operating energy	End of life
Global warming	kg CO_2 eq.	100%	**9%**	0%	2%	**89%**	0%
Acidification	H+ moles eq.	100%	6%	0%	2%	92%	0%
Respiratory effects	kg PM2.5 eq.	100%	7%	0%	2%	92%	-1%
Eutrophication	kg N eq.	100%	12%	0%	6%	81%	1%
Photochemical smog	kg NOx eq.	100%	8%	0%	2%	89%	1%
Solid waste	kg	100%	**32%**	0%	1%	**69%**	-2%
Water use	m^3	100%	11%	0%	6%	84%	-1%
Abiotic resource depletion	kg Sb eq.	100%	95%	7%	5%	0%	-7%
Ozone depletion	CFC-11 eq.	100%	**54%**	0%	**46%**	0%	0%
Total primary energy	MJ	100%	3%	0%	1%	96%	0%
Non-renewable, fossil	MJ	100%	6%	0%	3%	91%	0%
Non-renewable, nuclear	MJ	100%	1%	0%	0%	99%	0%
Renewable (SWHG)	MJ	100%	1%	0%	0%	99%	0%
Renewable, biomass	MJ	100%	36%	0%	57%	7%	0%
Feedstock, fossil	MJ	100%	27%	0%	73%	0%	0%

The whole building “cradle to grave” LCIA results for the baseline building in Vancouver (Precast envelope on precast structure, P-P) on an absolute and percent basis by life cycle stage (manufacturing, construction, maintenance, operating energy, and end-of-life) are presented in Table 16 and Table 17. The data show:

- Total global warming potential is 3,382,905 kg CO_2 eq. Of this, 50% is from operating energy. Manufacturing the materials and systems that make up the building itself is more significant in Vancouver for global warming impact, responsible for 38%. Maintenance is responsible for 11%. Construction and end-of-life are less than 1% with end-of-life recycling providing a slight net reduction in global warming.

- Total primary energy is 203,845,957 MJ, which consists of 83% renewable energy and 17% non-renewable energy. Feedstock energy is less than 1%. Non-renewable energy consists predominantly of fossil.

- The life cycle stage of operating energy differs in Vancouver than in Toronto in that only water use, total primary energy, and renewable energy are responsible for more than 80% of the impacts.

- Different than Toronto, most of the solid waste generated is associated with manufacturing (105%) of which 8% is returned at the end of life recycling stage. Only 3% comes from maintenance.

- Ozone depletion is split 51% manufacturing and 49% maintenance.

Table 16. Whole-Building LCIA Results for P-P Vancouver 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Manufacturing	Construction	Maintenance, 60 years	Operating energy, 60 years	End of life
Global warming	kg CO_2 eq.	**3,382,905**	1,288,868	12,285	386,593	1,704,7361	-9,202
Acidification	H+ moles eq.	1,278,754	366,604	5,105	164,759	744,479	-2,194
Respiratory effects	kg PM2.5 eq.	5,937	2,156	1	608	3,367	-196
Eutrophication	kg N eq.	491	224	5	127	120	16
Photochemical smog	kg NO_x eq.	6,032	2,734	114	1,013	1,849	322
Solid waste	kg	183,365	192,675	-150	5,487	7	-14,655
Water use	m3	23,545	2,586	-2	1,459	19,713	-211
Abiotic resource depletion	kg Sb eq.	0.85	1.61	-0.08	0.09	0.00	-0.77
Ozone depletion	CFC-11 eq.	4.17E+00	2.14E+00	-8.76E-08	2.03E+00	3.45E-05	1.33E-04
Total primary energy	MJ	**203,845,957**	14,743,890	224,860	6,941,395	**182,051,060**	-115,249
Non-renewable, fossil	MJ	49,946,321	13,349,802	173,016	6,281,615	**30,061,636**	-89,100
Non-renewable, nuclear	MJ	705,052	247,779	1,413	350,248	190,642	-4,031
Renewable (SWHG)	MJ	152,907,093	892,319	50,431	111,667	**151,847,794**	-22,119
Renewable, biomass	MJ	78,478	27,203	0	46,288	4,986	1
Feedstock, fossil	MJ	209,013	57,436	0	151,577	0	0
Feedstock, biomass	MJ	0	0	0	0	0	0

Table 17. Whole-Building LCIA Results for P-P Vancouver 60 yrs (baseline) – Percent Basis

Impact category	Unit	Total	Manufacturing	Construction	Maintenance, 60 years	Operating energy, 60 years	End of life
Global warming	kg CO_2 eq.	100%	**38%**	0%	**11%**	**50%**	0%
Acidification	H+ moles eq.	100%	29%	0%	13%	58%	0%
Respiratory effects	kg PM2.5 eq.	100%	36%	0%	10%	57%	-3%
Eutrophication	kg N eq.	100%	46%	0%	26%	24%	3%
Photochemical smog	kg NO_x eq.	100%	45%	0%	17%	31%	5%
Solid waste	kg	100%	105%	0%	3%	0%	-8%
Water use	m^3	100%	11%	0%	6%	84%	-1%
Abiotic resource depletion	kg Sb eq.	100%	190%	-9%	10%	0%	-94%
Ozone depletion	CFC-11 eq.	100%	51%	0%	49%	0%	0%
Total primary energy	MJ	100%	7%	0%	3%	89%	0%
Non-renewable, fossil	MJ	100%	27%	0%	13%	60%	0%
Non-renewable, nuclear	MJ	100%	35%	0%	50%	16%	1%
Renewable (SWHG)	MJ	100%	1%	0%	0%	99%	0%
Renewable, biomass	MJ	100%	35%	0%	59%	6%	0%
Feedstock, fossil	MJ	100%	27%	0%	73%	0%	0%
Feedstock, biomass	MJ	n/a	n/a	n/a	n/a	n/a	n/a

The operating energy LCIA results on a percent basis are presented (by energy carrier and water use) in Table 18 and in Table 19 for Toronto and Vancouver respectively. The data show:

- For both Toronto and Vancouver, **electricity use is responsible for the majority of impacts for operating energy** in most of the impact categories, including: global warming, acidification, respiratory effects, eutrophication, photochemical smog, solid waste, ozone depletion, and total primary energy (both fossil and non-renewable).

- When considering operating energy and excluding the impact categories dominated by water use, for the precast concrete envelope with precast concrete structure in Toronto:

  - Lighting is responsible for almost 1/3 of impacts.
  - Equipment (meaning office equipment and elevators) is responsible for slightly more than 1/3 of impacts
  - HVAC system (heating, cooling, fans, and pumps) is responsible for almost 1/3 of impacts.

- Water use is the hot water used in the building for purposes other than space heating. It does not include water for irrigating landscapes or water for washing the exterior of the building. Water use is responsible for all the impacts associated with abiotic resource depletion, water use, and renewable biomass energy.

Table 18. Operating Energy Use LCIA Results for P-P Toronto 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Electricity	Natural gas	Water use
Global warming	kg CO_2 eq.	14,134,754	13,404,744	726,757	3,253
Acidification	H+ moles eq.	6,548,758	6,226,525	321,056	1,177
Respiratory effects	kg PM2.5 eq.	30,230	28,767	1,456	6
Eutrophication	kg N eq.	1,621	1,570	51	10
Photochemical smog	kg NOx eq.	34,212	33,406	799	7
Solid waste	kg	415,797	415,730	0	68
Water use	m3	19,713	0	0	19,713
Abiotic resource depletion	kg Sb eq.	0.00	0.00	0.00	0.00
Ozone depletion	CFC-11 eq.	1.70E-04	1.37E-04	4.04E-07	3.28E-05
Total primary energy	MJ	524,402,212	511,359,286	12,943,411	99,514
Non-renewable, fossil	MJ	205,278,863	192,333,541	12,907,336	37,987
Non-renewable, nuclear	MJ	278,028,590	277,943,200	36,075	49,315
Renewable (SWHG)	MJ	41,089,772	41,082,546	0	7,226
Renewable, biomass	MJ	4,986	0	0	4,986

Table 19. Operating Energy Use LCIA Results for P-P Vancouver 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Electricity	Natural gas	Water use
Global warming	kg CO_2 eq.	1,704,361	1,436,007	267,022	1,331
Acidification	H+ moles eq.	744,479	626,241	117,961	277
Respiratory effects	kg PM2.5 eq.	3,367	2,830	535	2
Eutrophication	kg N eq.	120	101	19	0
Photochemical smog	kg NOx eq.	1,849	1,553	293	2
Solid waste	kg	7	7	0	0
Water use	m3	19,713	0	0	19,713
Abiotic resource depletion	kg Sb eq.	0.00	0.00	0.00	0.00
Ozone depletion	CFC-11 eq.	3.45E-05	1.61E-06	3.27E-07	3.27E-05
Total primary energy	MJ	182,051,060	177,247,342	4,755,620	48,098
Non-renewable, fossil	MJ	30,061,636	25,308,021	4,742,365	11,251
Non-renewable, nuclear	MJ	109,642	92,234	13,255	4,154
Renewable (SWHG)	MJ	151,874,794	151,847,087	0	27,707
Renewable, biomass	MJ	4,986	0	0	4,986
Feedstock, fossil	MJ	0	0	0	0
Feedstock, biomass	MJ	0	0	0	0

8.1 Global Warming Potential (GWP) LCIA results

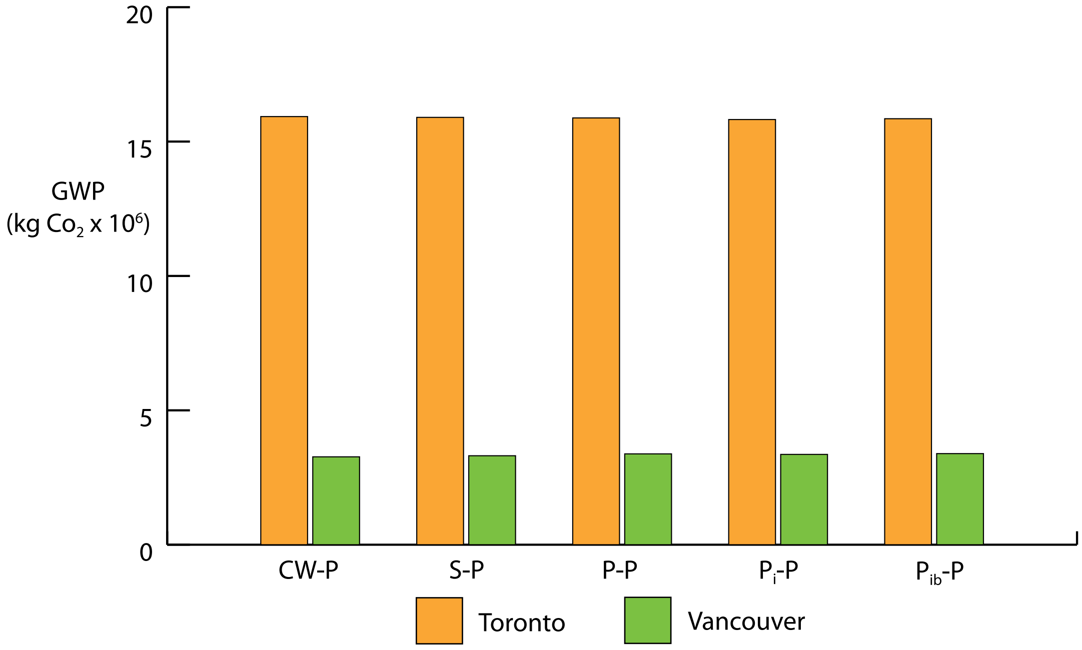
Table 20 shows the global warming potential (GWP) of the precast buildings, for 60 and 73 year service lives. It shows that GWP of the buildings in Toronto varies from 15.82 to 15.93 million kg CO_2 eq. over a 60-year life and 18.98 to 19.10 million kg CO_2 eq. over a 73-year life. Increasing the service life in Toronto increases the GWP by an average of 3.18 million kg CO_2 eq. Therefore, increasing the service life by 22% increases the GWP by 20%. The buildings with the lowest GWP are buildings with precast concrete envelopes (P-P, PiP, and Pib-P) and the buildings with the highest GWP are the buildings with curtain wall envelope (CW-P) and the building with brick envelope (S-P).

The GWP of the buildings in Vancouver varies from 3.27 to 3.39 million kg CO_2 eq. over a 60-year life and 3.72 to 3.87 million kg CO_2 eq. over a 73-year life. The GWP of operating energy is much lower in Vancouver and the GWP of the other stages (manufacturing, construction, maintenance, and end-of-life) have are proportionately larger impact. Increasing the service life increases the GWP by an average of 0.47 million kg CO_2 eq. That is, increasing the service life by 22% increases the GWP by 15%.

Table 20. Precast scenarios LCIA Results: global warming potential (GWP)

	Global Warming Potential (GWP) - kg CO$_2$	
Assembly	**Toronto - 60 years**	**Toronto - 73 years**
CW-P	15,926,743	19,104,461
S-P	15,897,894	19,092,395
P-P	15,877,690	19,048,444
Pi-P	15,817,229	18,982,276
Pib-P	15,846,474	19,010,436
Assembly	**Vancouver - 60 years**	**Vancouver - 73 years**
CW-P	3,274,561	3,723,954
S-P	3,312,647	3,793,663
P-P	3,382,905	3,864,569
Pi-P	3,358,278	3,839,953
Pib-P	3,388,527	3,869,601

Figure 5. Global Warming Potential Toronto and Vancouver (60 years)



8.2 Total Primary Energy (TPE) LCIA results

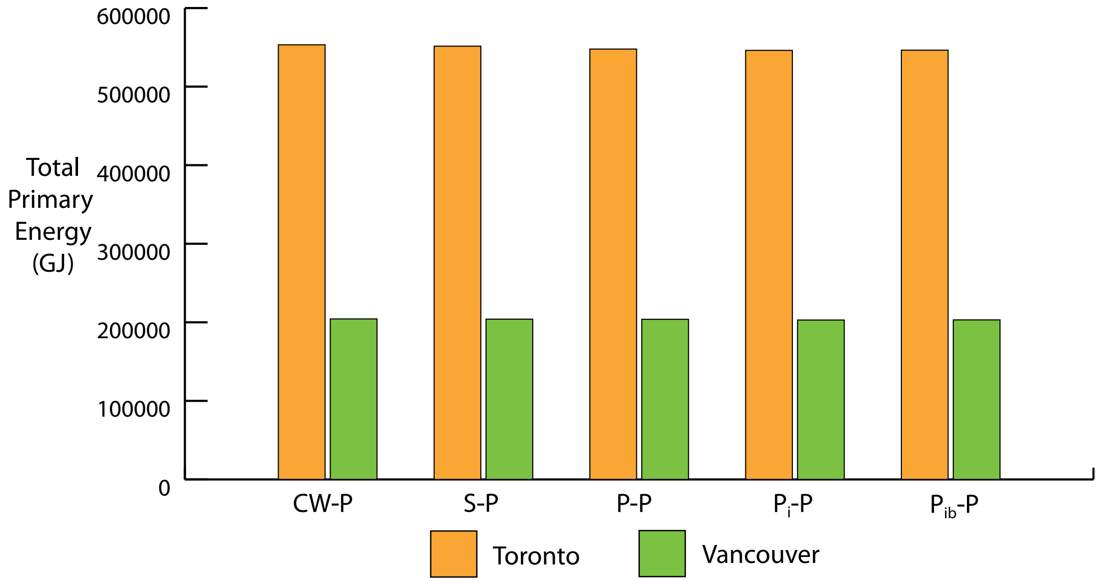
The total primary energy (TPE) for the precast building in both cities and for both service lives are shown in Table 21. The primary energy of the buildings in Toronto varies from 546 to 553 million MJ over a 60-year life and 661 to 668 million MJ over a 73-year life. Increasing the service life increases the primary energy by an average of 55.6 million MJ. That is, increasing the service life by 22% increased the primary energy by 21%. The buildings with the lowest primary energy are buildings with precast concrete envelopes (P-P, PiP, and Pib-P). The buildings with the highest primary energy are the buildings with curtain wall envelope (CW-P) and the building with brick envelope (S-P).

The primary energy of the buildings in Vancouver varies from 203 to 204 million MJ over a 60-year life and 244 to 246 million MJ over a 73-year life. Increasing the service life increases the primary energy by an average of 41.5 million MJ. That is, increasing the service life by 22% increases the primary energy by 20%. The buildings with the lowest primary energy are buildings with precast concrete envelope (P-P, PiP, and Pib-P) and the buildings with the highest primary energy are the buildings with curtain wall envelope (CW-P) and the building with brick envelope (S-P) although there is very little difference.

Table 21. Precast scenarios LCIA Results: Total Primary Energy (TPE)

	Total Primary Energy (TPE) - MJ	
Assembly	**Toronto - 60 years**	**Toronto - 73 years**
CW-P	553,239,357	669,839,881
S-P	551,490,606	667,967,684
P-P	547,806,690	663,384,853
Pi-P	546,137,905	661,451,351
Pib-P	546,377,583	661,650,993
Assembly	**Vancouver - 60 years**	**Vancouver - 73 years**
CW-P	204,307,086	245,619,666
S-P	204,041,508	245,556,290
P-P	203,845,957	245,304,379
Pi-P	202,930,289	244,248,010
Pib-P	203,097,541	244,366,596

Figure 6. Total Primary Energy (GJ) Toronto and Vancouver (60 years)



8.3 Other Significant Comparative Observations

Comparing Steel Structures

The LCA model also included modelling the same envelopes on a steel structure. The World Steel Association (WSA) and Canadian steel industry associations are the primary sources for steel LCI data. Both international organizations subscribe to a "system expansion" method for handling primary (virgin) and secondary (recycled) content production based on closed-loop recycling methodology. This system expansion methodology is ISO-compliant. The methodology essentially starts with primary production and accounts for net recycled content and end-of-life recovered metal to provide an overall primary and secondary mixed product profile for each product.

For the steel framing, the RAM Steel structural engineering software (version 13.0) was used. The curtain wall/structural steel assembly is defined as follows:

Curtain wall/steel (CW-S)

1. Footings and exterior wall foundation (for concrete structures)
2. Curtain wall
3. Structural steel
4. Steel floors
5. Roof (structure for steel building)
6. Elevator and stairwell walls (steel framed buildings only)

Comparing a steel structure demonstrated the efficiency of the precast structure during occupancy. The occupancy stage—that is, the use of energy for operating the buildings—is the most important life-cycle stage in most impact categories. More than half of the impacts in the following categories are due to operating energy: global warming, acidification, respiratory inorganics, water use, ozone depletion, total primary energy, non-renewable fossil fuel, and renewable energy from solar, wind, hydroelectric, and geothermal (SWHG).

For any given envelope type, buildings with precast structures were shown to have lower GWP than buildings with steel structures during the occupancy stage, demonstrating that the effect of more thermal mass in the structure reduces the GWP.

For example, going from a curtain wall building with steel structure (CW-S) to a curtain wall building with precast concrete structure (CW-P), would reduce the GWP by a range of 181 to 220 tonnes of CO_2 eq. in Toronto and a range of 15 to 18 tonnes CO_2 eq. in Vancouver (the range is due to the different service life assumptions, 60 and 73 years).

The effect of increasing the thermal performance of the walls from curtain wall to insulated precast concrete *and* increasing the amount of thermal mass in the structure is to further reduce the GWP. For example, going from a curtain wall building with steel structure (CW-S) to an insulated precast concrete building with precast concrete structure (Pi-P), would reduce the GWP by a range of 373 to 454 tonnes CO_2 eq. in Toronto and a range of 22 to 26 tonnes CO_2 eq. in Vancouver (the range again is due to the different service life assumptions, 60 and 73 years).

During occupancy and operating stages, for a given envelope type, buildings with precast structures were shown to have lower total primary energy than buildings with steel structures.

The effect of more thermal mass in the structure is to reduce the total primary energy. For example, going from a curtain wall building with steel structure (CW-S) to a curtain wall building with precast concrete structure (CW-P), would reduce the total primary energy by a range of 8.3 to 10.1 million MJ in Toronto and a range of 3.8 to 4.6 million MJ in Vancouver (the range, again, is due to the different service life assumptions, 60 and 73 years).

The effect of increasing the thermal performance of the walls from curtain wall to insulated precast concrete *and* increasing the amount of thermal mass in the structure is to further reduce the total primary energy. For example, going from a curtain wall building with steel structure (CW-S) to an insulated precast concrete building with precast concrete structure (Pi-P), would reduce the total primary energy by a range of 16.2 to 19.8 million MJ in Toronto and a range of 6.1 to 7.4 million MJ in Vancouver (the range, again, is due to the different service life assumptions, 60 and 73 years).

Precast Subassembly Contribution Analysis

A contribution analysis of each of the subassemblies for the baseline building (P-P Toronto) was also conducted. The results demonstrate that precast hollow-core floor slab subassembly contributes 25% to the "cradle-to-construction" stage primary energy but just 0.8% of the building's cradle-to-grave primary energy. The precast hollow-core floor subassembly contributes 27% of the cradle-to-construction stage GWP, but just 2.3% of the building's cradle-to-grave GWP. The contribution results for the precast beams and columns show that their contribution towards GWP and primary energy are even less than hollowcore by approximately 8%. Similarly, precast panels are significantly less than hollowcore by 40%.

Precast Thermal Performance Sensitivity Analysis

A sensitivity analysis on the thermal performance of walls was conducted. Although the study modelled thermal performance of insulated precast wall panels according to minimum ASHRAE requirements, R_{SI} values of R_{SI}-3.5 (R-20) insulation can be validated as typical construction for Toronto. Therefore, three additional energy model scenarios were created to determine the sensitivity of annual operating energy consumption on wall insulation level. The scenarios consist of adding 50 mm of XPS insulation, R_{SI}-1.8 (R-10), to the existing Pi walls on the precast building in Toronto, bringing the total overall effective R_{SI} value of the opaque portion of walls to 4.29 m^2•K/W (24.4 hr•ft^2•° F/Btu). This represents an increase in overall effective wall R_{SI}-value of 61%, that is (4.29-2.66)/2.66 = 61%.

A 61% increase in overall effective wall R_{SI}-value for these scenarios results in 7% decrease in annual heating energy, 1% decrease in fan use, 2% decrease in annual energy use, 2% decrease in electricity use, and 1-2% decrease in natural gas use. Conversely, a 61% increase in overall wall R_{SI}-value does not affect cooling energy use, and nor does it affect interior loads (lights and equipment). **In absolute values this represents approximately 50 GJ/year decrease in annual heating energy, 50 GJ/year decrease in annual energy use, 46 GJ/year decrease in electricity use, 3 GJ/year decrease in natural gas use, and no change in cooling energy use.**

9. LCA Assessment Tools for Practitioners

The information from the CPCI LCA study *Life Cycle Assessment of Precast Concrete Commercial Buildings* is included in ATHENA® *Impact Estimator for Buildings*. This software is the only software tool that is designed to evaluate whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology. Using the *Impact Estimator*, architects, engineers and others can easily assess and compare the environmental implications of industrial, institutional, commercial and residential designs, both for new buildings and major renovations. Where relevant, the software also distinguishes between owner-occupied and rental facilities.

The *Impact Estimator* puts the environment on equal footing with other more traditional design criteria at the conceptual stage of a project. It is capable of modeling 95% of the building stock in North America, using the best available data, including precast. The Estimator takes into account the environmental impacts of:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction
- Regional variation in energy use, transportation and other factors
- Building type and assumed lifespan
- Maintenance and replacement effects
- Demolition and disposal

Although the Impact Estimator doesn't include an operating energy simulation capability, it does allow users to enter the results of a simulation in order to compute the fuel cycle burdens, including pre-combustion effects, and factors them into the overall results.

The ATHENA® EcoCalculator for Assemblies is "freeware" software that provides instant LCA results for commonly used building structure and envelope assemblies. Although it does not provide the range of analysis at the Impact Estimator, the results presented in the EcoCalculator are based on detailed assessments conducted using the ATHENA® Impact Estimator. Assemblies are complete systems, such as a wall or roof system, composed of individual products and/or pre-assembled building components. The EcoCalculator can be used for new construction projects, retrofits and major renovations, and for industrial, institutional, office or residential designs, either to compare specific assemblies or to assess all of the assemblies in a structure.

10. Cradle-to-Cradle Precast Concrete Considerations

Precast concrete offers designers a choice to go beyond "cradle-to-grave" comparisons. By involving the precast manufacturer early in the design process, design professionals can offer truly sustainable solutions to owners, such as "cradle-to-cradle" solutions. Precast concrete, because of its segmental nature allows for the design for disassembly and adaptability and the design for deconstruction and reuse. When considering the hierarchy of the 3R's, (reduce, reuse and recycle) precast products inherently reduce the amount of construction waste on-site and can also be designed for substantially greater reuse percentages beyond the intended design life of the building.

A sensitivity analysis was conducted on the precast baseline building (P-P) to determine how sensitive the results are to the assumption about recycling rate. The results show that recycling does reduce the environmental impact in every category, both from an end-of-life perspective and from a cradle-to-grave perspective. For example, transporting and land filling the concrete at the end the building's life produces greenhouse gas emissions equivalent to a GWP of 220,155 kg CO_2 equivalent whereas recycling the concrete by crushing it and reusing it to replace virgin natural aggregate produces only a net 411 kg CO_2 equivalent.

Therefore, by crushing concrete and recycling as aggregate versus demolishing and transporting to landfill, the GWP is reduced by 219,744 kg CO_2 equivalent. From the cradle-to-grave perspective, this represents a 1.4% reduction in GWP.

Although recycling does create environmental impacts in global warming, acidification, eutrophication, ozone depletion, and depletion of non-renewable fossil fuels, the net effect when compared to the alternative (land filling) is a positive benefit. This leads to the analysis on the potential for further reduction of these impacts, by reusing precast concrete elements instead of recycling them.

Reuse Sensitivity Analysis

Although not part of the critical review process, the study included a sensitivity analysis performed on the baseline building (P-P) to determine how the environmental impacts could be reduced by reusing precast concrete elements. For the P-P scenario in Toronto with 60-year service life (the baseline) the following elements are considered as reused; hollow core slab, precast panel, precast beams, and precast columns.

The effects of reuse for various precast assembly service lives, for example 80, 100, 120 years, were then analyzed. The range of service life for precast panels is assumed to be lower than for structural components since the panels are exposed to weather and hence changes in appearance and reusability is more influenced by appearance (See Table 22).

Table 22. Reuse Sensitivity Analysis Scenarios

Scenario #	Subassemblies Considered for Reuse, P-P Toronto, 60 years	Subassembly lifespan (years)	Reuse Coefficient
1	Precast concrete (conventional panel) (precast panel concrete only)	80	0.75
2		100	0.6
3		120	0.5
4	Precast concrete beams and columns (precast beams and columns concrete only)	100	0.6
5		120	0.5
6		140	0.43
7	Hollow-core floors (hollow-core slab concrete only)	100	0.6
8		120	0.5
9		140	0.43
10	All precast subassemblies (precast panel, hollow-core slab, precast beams and columns concrete only)	100	0.6

The sensitivity analysis showed that reusing precast concrete subassemblies reduced the life-cycle environmental impacts considerably (See Table 23). Examples are:

- **Reusing 50% of hollow-core slabs for another 60 years on another building (scenario #5), reduces GWP by 169 tonnes CO_2 eq., primary energy by 2.0 million MJ, and solid waste by 26 tonnes.**
- **Reusing 60% of all precast elements for another 40 years on another building (scenario #10), reduces GWP by 315 tonnes CO_2 eq., primary energy by 3.7 million MJ, and solid waste by 50 tonnes.**

Table 23. Sensitivity Analysis on Reuse: Cradle-to-Grave **Reduction in Environmental Impact**

Impact Category	Unit	Scenario #									
		1	2	3	4	5	6	7	8	9	10
Global warming	kg CO_2 eq.	34,104	54,567	68,208	135,402	169,253	193,432	124,951	156,189	178,501	314,920
Acidification	H+moles eq.	9,393	15,029	18,787	37,294	46,618	53,277	34,397	42,996	49,139	86,721
Respiratory effects	kg PM2.5 eq.	53	84	105	209	261	298	188	235	269	481
Eutrophication	kg N eq.	6	9	12	23	29	33	22	27	31	54
Photochemical smog	kg NO_X eq.	76	121	151	301	376	429	295	368	421	716
Solid waste	kg	5,306	8,489	10,612	21,065	26,332	30,093	20,210	25,263	28,871	49,765
Water use	m^3	52	83	103	205	257	293	181	226	258	469
Abiotic resource depletion	kg Sb eq.	0	0	0	0	0	0	0	0	0	0
Ozone depletion	CFC-11 eq.	0	0	0	0	0	0	0	0	0	0
Total primary energy	MJ	395,987	633,580	791,975	1,572,175	1,965,219	2,245,964	1,450,011	1,812,514	2,071,444	3,655,765
Non-renewable, fossil	MJ	340,625	545,000	681,250	1,352,371	1,690,464	1,931,959	1,247,198	1,558,997	1,781,711	3,144,569
Non-renewable, nuclear	MJ	46,653	74,644	93,305	185,223	231,529	264,605	170,676	213,345	243,823	430,544
Renewable (SWHG)	MJ	7,964	12,742	15,928	31,619	39,523	45,169	29,329	36,661	41,898	73,689
Feedstock, fossil	MJ	746	1,193	1,492	2,962	3,702	4,231	2,808	3,510	4,011	6,963

Two related Canadian standards offer important resources for design professionals. CSA Z782-06 *Guideline for design for disassembly and adaptability in buildings* provides a framework for reducing building construction waste at the design phase, through specific principles. CSA Standard Z783, *Deconstruction of Buildings and their Related Parts* is anticipated to be published in 2012. It provides minimum requirements for processes and procedures connected with the deconstruction of buildings. It is intended for use by contractors, consultants, designers, building owners, regulators, and material chain organizations undertaking deconstruction of a building that is at the end of its life or when it is undergoing renovations or alterations.

11. Summary

Key factors when reviewing an LCA for any product or assembly include; an understanding of the goal and scope, third party confirmation of the validation for the input data, interpretation of the results, and use of a standardized procedure. It is important to distinguish cradle-to-gate life cycle inventories (LCI) from cradle-to-grave life cycle assessments (LCA). To offer valid comparisons, products and assemblies should only be compared if they are full cradle-to-grave life cycle impact assessments.

The CPCI LCA study *Life Cycle Assessment of Precast Concrete Commercial Buildings* was conducted with a goal to better understand precast concrete's environmental life cycle performance in mid-rise concrete buildings relative to alternative structural and envelope systems by applying the ISO 14040:2006 and 14044:2006. A comparative cradle-to-grave LCA has been completed. It considered environmental impacts from key life cycle stages: manufacturing, construction, occupancy, maintenance, and end-of-life (including, demolition, recycling, reuse, and land filling). Data were obtained from a range of sources; from firsthand surveys of precast concrete plants to LCA databases of industry data. In all cases, the selected data, after appropriate modification, were deemed to represent a recent average level of technology in Canada. A critical review was conducted by an independent external panel of LCA and technical experts as per Clause 7.3.3, ISO 14044:2006.

12. References

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Appendix A: Cradle-to-Gate Environmental Data Sheets for the Four Precast Products in Toronto and Vancouver

This appendix includes the environmental data sheet summaries and the environmental impact indicators for four precast products in the two locations (Vancouver and Toronto). These are hollowcore, structural precast columns and beams, architectural panels, and insulated wall panels.

The cradle-to-gate system boundary considers the environmental impacts starting with the extraction of raw materials from the earth (the "cradle") and ending at the precast plant exit (the "gate") where the product is ready to be shipped to the user. In-bound delivery of input fuels and raw materials (e.g., cement, reinforcing steel, aggregates, etc.) to the plant, and plant operations, are included. Out-bound transportation of the product to the user is not included. The use phase, maintenance and disposal phase of the product are also not included. Disposal of upstream and plant operations waste and transportation within the plant are included.

Note: Direct cradle-to-gate system boundary comparison of precast products with cast-in-place concrete alone is dissuaded. For example, the precast profiles listed below include all steel reinforcing required to use the products on-site whereas this is not typically included in cast-in-place concrete profiles. On-site reinforcing steel and concrete forming normally required for cast-in-place concrete, needs to be considered in any comparison. In addition, the precast insulated wall assemblies include the environmental impacts associated with material and labour when adding the required insulation at the plant. Cast-in-place concrete profiles do not include wall insulation that is added at the construction site as part of its profile.

Product: 1 m^3 - Hollow Core - Cradle-to-Gate - Environmental Data Summary

Impact category	**Unit**	**1 m^3 - Hollow Core - Toronto**	**1 m^3 - Hollow Core - Vancouver**
Global warming	kg CO_2 eq.	485	452
Acidification	H+ moles eq.	130	115
Respiratory effects	kg PM2.5 eq.	0.866	0.795
Eutrophication	kg N eq.	0.071	0.067
Photochemical smog	kg NOx eq.	0.745	0.657
Solid waste	kg	94	93
Water use	m3	0.836	0.836
Abiotic resource depletion (non-energy)	kg Sb eq	2.8E-04	2.8E-04
Ozone Depletion	CFC-11 eq.	4.4E-08	4.3E-08
Total primary energy	MJ	5460	4589

Product: 1 m³ - Precast Structural, Columns, Beams - Cradle-to-Gate - Environmental Data Summary

Impact category	**Unit**	**1 m³ - Precast Wall Panel, Columns, Beams - Toronto**	**1 m³ - Precast Wall Panel, Columns, Beams - Vancouver**
Global warming	kg CO_2 eq.	515	481
Acidification	H+ moles eq.	139	123
Respiratory effects	kg PM2.5 eq.	0.922	0.849
Eutrophication	kg N eq.	0.075	0.071
Photochemical smog	kg NOx eq.	0.755	0.664
Solid waste	kg	94	93
Water use	m3	0.914	0.914
Abiotic resource depletion (non-energy)	kg Sb eq	3.0E-04	3.0E-04
Ozone Depletion	CFC-11 eq.	2.1E-07	2.1E-07
Total primary energy	MJ	5817	4917

Product: 1 m³ - Conventional architectural wall panels - Cradle-to-Grave - Environmental Data Summary

Impact category	**Unit**	**1 m³ - Conventional panel (Thickness- 150 mm) - Toronto**	**1 m³ - Conventional panel (Thickness- 150 mm) - Vancouver**
Global warming	kg CO_2 eq.	522	488
Acidification	H+ moles eq.	140	124
Respiratory effects	kg PM2.5 eq.	0.931	0.858
Eutrophication	kg N eq.	0.089	0.085
Photochemical smog	kg NOx eq.	0.772	0.682
Solid waste	kg	94	93
Water use	m3	0.962	0.962
Abiotic resource depletion (non-energy)	kg Sb eq	3.1E-04	3.1E-04
Ozone Depletion	CFC-11 eq.	1.2E-06	1.2E-06
Total primary energy	MJ	6018	5118

Product: 1 m^3 - Insulated wall panel - Cradle to Grave - Environmental Data Summary

Impact category	**Unit**	**1 m^3 insulated panel (75 mm interior, 50 mm exterior, 70 mm XPS insulation)- Toronto**	**1 m^3 insulated panel (75 mm interior, 50 mm exterior, 60 mm XPS insulation)- Vancouver**
Global warming	kg CO_2 eq.	866	782
Acidification	H+ moles eq.	208	183
Respiratory effects	kg PM2.5 eq.	1.218	1.103
Eutrophication	kg N eq.	0.113	0.105
Photochemical smog	kg NOx eq.	1.056	0.924
Solid waste	kg	94	93
Water use	m3	1.294	1.246
Abiotic resource depletion (non-energy)	kg Sb eq	3.1E-04	3.1E-04
Ozone Depletion	CFC-11 eq.	6.7E-03	5.7E-03
Total primary energy	MJ	9717	8275