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Life Cycle Assessment for Sustainable Design of Precast Concrete Commercial Buildings in Canada

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Abstract: A life cycle assessment (LCA) was conducted on a typical five-storey commercial building with five variations of exterior wall system and two variations of climate and location. The goal of the LCA was to gain a better understanding of precast concrete's environmental performance in the context of whole buildings. LCA is an analytical tool to comprehensively quantify and interpret the energy and material flows to and from the environment over the life of a product, process, or service. The energy and material flows are the environmental emissions to air, land, and water, and the consumption of energy and material resources. This paper presents the cradle-to-grave LCA of precast concrete commercial buildings with precast structure and precast wall envelope, relative to alternative wall envelope systems. Because the LCA includes a public comparative assertion, the study was critically reviewed by an independent external committee of LCA experts to ensure the LCA is consistent with the requirements of international ISO standards on LCA. The results show that over the full life cycle, the buildings with precast concrete walls have less environmental impact than the buildings with masonry brick veneer walls and those with glass and aluminum curtain wall, all other factors being equal.

1. Introduction

Life cycle *assessment* (LCA) is an analytical tool to comprehensively quantify and interpret the energy and material flows to and from the environment over the life of a product, process, or service. LCA is not the same thing as life cycle costing, which is a procedure for determining life cycle cost. The confusion arises because life cycle costing is often called life cycle analysis in some industries. In LCA, the energy and material flows include environmental emissions to air, land, aand water, as well as the consumption of energy and material resources. LCA evaluates the *potential* environmental impacts of these flows throughout the life cycle. Because LCA considers the full life cycle, it provides a comprehensive view of environmental attributes and a more accurate picture of environmental trade-offs than typical and simple "green" measures such as recycled content or product transportation distance. There are four phases in LCA: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. Each of these stages is described below.

LCA is a relative approach based on a *functional unit*. The functional unit defines the product being studied in terms of the function it provides and all inputs, outputs, and analysis are relative to the functional unit. This ensures that comparisons between alternative products, processes, or services are made on an equivalent basis—a so-called "apples-to-apples" comparison.

2. Background and Goal

The data and results in this paper are an excerpt of a cradle-to-grave comparative LCA of precast concrete commercial buildings with five variations of building envelope wall system (CPCI 2012). The study was commissioned by the Canadian Precast Prestressed Concrete Institute (CPCI). The goal was to get a better understanding of precast concrete's environmental performance in Canadian mid-rise precast concrete buildings. The reason for doing this work was to disseminate information on the LCA of precast concrete that is based on the most complete and up-to-date life cycle inventory data for cement and concrete products. The intended audience is architects, engineers, specifiers, academia, governments, and other interested parties who require reliable information on sustainable building design practices. An independent critical review committee ensured that the study complies with the requirements in LCA standards ISO 14040:2006 and ISO 14044:2006 for methodology, data, interpretation, and reporting, and that the study is consistent with the principles in the referenced international standards.

3. Scope

The scope of an LCA shall consider and clearly define the functional unit, system boundary, allocation procedures, environmental impact categories, impact assessment methodology, data requirements, assumptions, limitations, data quality requirements, type of critical review, and type of report. The functional unit for this study is a five-story commercial office building that meets the minimum prescriptive requirements for R_{SI}-value (R-value) and provides conditioned office space for approximately 130 people. The functional unit includes both the physical building and the service the building provides, which is conditioned space for occupants. Conditioned space consists of maintaining thermostat set points of 21°C (70°F) for heating, 24°C (75°F) for cooling, 2°C (4°F) throttling range, and night setback temperatures of 13°C (55°F) for heating and 37°C (99°F) for cooling. The service life of the buildings is 60 years. The system boundary defines the limits of the LCA as shown schematically in Figure 1. The LCA determined the environmental impacts from each stage of the buildings' life cycle, from extracting natural resources from the ground and processing through each subsequent stage of manufacturing, transportation, construction, product use, occupancy, recycling, and ultimately, disposal.

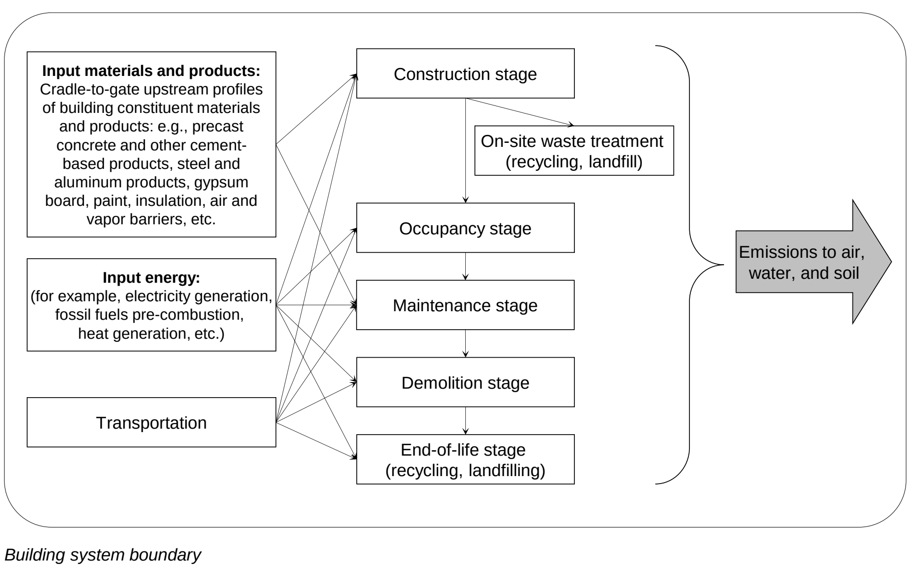

Figure 1: The system boundary defines the limits of the life cycle assessment and it applies to all buildings in this study.

The five variations of exterior wall envelope systems were; glass and aluminum curtain wall (CW), brick on steel stud backup (S), conventional precast concrete (P), insulated precast concrete (Pi), and insulated precast concrete with brick veneer (Pib). Each building envelope was insulated to meet *minimum* energy code requirements. Within a given city, all other physical parameters were the same.

The environmental impact categories selected are the required categories in ISO 21930:2007; global warming, acidification, respiratory effects, eutrophication, photochemical smog, solid waste, water use, non-energy abiotic resource depletion, ozone depletion, total primary energy, and the constituents of total primary energy (non-renewable fossil; non-renewable nuclear; renewable solar wind, hydro, and geothermal (SWHG); renewable biomass; feedstock fossil; and feedstock biomass). The impact assessment methodology selected is the U.S. EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). As defined by the scope, where a choice of data was available, preference was given to recent Canadian data representing an average level of technology. More information on data allocation, data quality, reporting, and references can be found in the referenced CPCI study.

4. Inventory Analysis of Precast Concrete Products And Other Products

Precast concrete products are fabricated in a precast manufacturing plant and transported to a job site where they are erected and assembled. Precast operations offer economies of scale and manufacturing in a controlled environment that makes it economical to achieve high levels of quality control. The LCA process began with conducting a life cycle inventory (LCI), which included collecting data directly from operating precast concrete plants. LCI data were obtained from surveys of three Canadian precast concrete plants in Quebec, Ontario, and British Columbia. LCI data for other materials and construction processes were taken from the Athena Institute™ proprietary LCI database for building materials and construction processes and from third-party sources, such as the World Steel Association, the International Aluminum Institute, and the Aluminum Extruders Council. Section 8, Life Cycle Impact Assessment, will describe how these LCI data were combined with a model of a building to calculate the potential environmental impact of building components and processes that together constitute a complete building from cradle-to-grave.

5. Building and Location

The prototype building chosen for the study is based on the “medium office building” in the U.S. Department of Energy’s commercial reference buildings. These reference buildings were created as a common baseline for research to assess new technologies, optimize designs, develop energy codes and standards, conduct studies to reduce energy use, etc. (Deru 2011). The prototype building is a five-storey commercial building with plan dimensions 27.4 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 by 12.2 m.

For this study, the building with conventional precast concrete wall and precast concrete structure was chosen to be the baseline building and it is given the abbreviation “P-P”. It consists of conventional architectural precast concrete exterior walls, precast concrete beams and columns, precast concrete hollow-core floors, and cast-in-place footings and slab on ground. The five buildings evaluated in the study are shown in Table 1. 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. The brick veneer of the “insulated precast concrete with brick veneer” is thin bricks that are 13 to 16 mm thick cast into the precast concrete panels. The facade of each storey has a band of windows each measuring approximately 1.5 by 1.5 m, for an overall window-to-wall ratio of 0.40.

Table 1: The Five Precast Buildings

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

Since energy use and thermal mass effects vary with climate, the buildings were modelled in two cities representing by two distinct Canadian climates: Vancouver, British Columbia, a cool climate (ASHRAE Climate Zone 5C) and Toronto, Ontario, a cold climate (ASHRAE Climate Zone 6A). These cities were also intentionally chosen to be consistent with cities used in other North American LCA studies.

6. Thermal Performance of Exterior Envelope

The criteria for thermal performance of the exterior envelope are based on the prescriptive 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 because it is a commonly used baseline to ensure consistent comparisons of buildings within a particular location, such as in the Canadian Leadership in Energy and Environmental Design (LEED®) rating system (LEED 2010).

The prescriptive requirements for fenestration (meaning windows) and insulation are shown in Table 2. Overall heat transfer coefficients (U-factor) and solar heat gain coefficients (SHGC) requirements are maximums, whereas thermal resistance (RSI-values) requirements are minimums. U-factor is a measure of thermal conductance and represents the *overall* rate of heat loss of a given assembly (such as in a window), whereas RSI-value is a measure of thermal resistance and generally represents the thermal resistance for a given thickness of material. U-factor is expressed in SI units as W/(m^2•K), and RSI-value is expressed in SI units of (m^2•K)/W.

Table 2: Minimum Prescriptive Requirements for Building Envelope in Vancouver and Toronto*

Climate zone and city	Fenestration		Roof RSI-value	CW wall RSI-value	Mass wall RSI-value	Slab RSI-value & depth
	U-factor	SHGC				
5C, Vancouver	2.56	0.40	3.5	2.3 + 1.3 ci	2.0 ci	None req'd
6A, Toronto	2.56	0.40	3.5	2.3 + 1.3 ci	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 RSI-value in (m^2·K)/W.
Note: CW = curtain wall; ci = continuous insulation across structural members without thermal bridges other than fasteners and service openings; and "2.3 + 1.3" = RSI-2.3 cavity insulation plus RSI-1.3 ci.

The modelled rate of air infiltration is based on the typical rate of 0.5 L/s•m^2 of envelope area in Canadian buildings when measured at a pressure difference of 75 Pa. Solely for comparison purposes, each building envelope is assumed to be designed and constructed as equally airtight. In addition the modeled thermal performance of the wall accounts for 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 the as-modelled thermal *performance* is less than the *prescriptive* requirement. The as-modeled U-factors (and overall effective RSI-values) are shown in Table 3.

Table 3: As-Modelled U-factor and overall effective RSI-value (1/U) of walls, W/m^2•K (m^2•K/W)

City	Curtain wall, CW	Brick on steel Stud, S	Conventional precast concrete, P	Insulated precast concrete, Pi	Insulated precast concrete with brick veneer. Pib
Vancouver	0.433 (2.31)	0.498 (2.01)	0.424 (2.36)	0.430 (2.33)	0.428 (2.34)
Toronto	0.433 (2.31)	0.444 (2.25)	0.372 (2.69)	0.376 (2.66)	0.374 (2.67)

7. 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. The buildings were modelled with EnergyPlus™ whole-building energy simulation software. The prototype building dictated that the heating system be a combination of natural gas furnace and electric reheat. Older or larger commercial buildings would typically only have a fossil-fuel boiler for heating. Therefore, even though more energy is used for heating than cooling, most of the heating energy is from electricity.

Annual energy use, as determined by the energy simulation software, is presented in Table 4. The results for both cities show relatively similar site energy use regardless of exterior wall type, but the precast envelope scenarios (P-P, Pi-P, and Pib-P) have lower overall site energy use by approximately 1% compared to curtain wall (CW-P) and brick and steel stud (S-P). The environmental impacts associated with site energy—where the upstream and downstream impacts of site energy are included—are presented in Section 8.

Table 4: Annual Site Energy Use, GJ

Energy source	Buildings in Vancouver					Buildings in Toronto				
	CW-P	S-P	P-P	Pi-P	Pib-P	CW-P	S-P	P-P	Pi-P	Pib-P
Electricity	2537	2519	2512	2501	2498	2802	2787	2764	2756	2755
Natural gas	69	73	71	73	73	189	197	194	197	197
Total	2606	2592	2583	2574	2571	2991	2984	2958	2953	2952

8. Life Cycle Impact Assessment (LCIA)

The LCI and LCIA modelling software used was SimaPro (PRé Consultants 2011). Each building constituent element (material, product, or process) was modelled independently from cradle-to-grave. These elements were then combined to comprise a complete building subassembly (for example, precast concrete walls subassembly, windows subassembly, and roof waterproofing subassembly). Each of these subassemblies was then combined to model the complete building structure and envelope as constructed on-site. A sample of the construction phase material quantities is shown in Table 5. The energy use from operating the buildings over 60 years was input into the SimaPro models. Maintenance and replacement of components as they wear out were also modelled. Finally, end-of-life demolitions, recycling, and landfilling were modelled.

8.1 Baseline Building Toronto

The whole building "cradle to grave" LCIA results for the baseline building in Toronto (precast envelope on precast structure, P-P) by life cycle stage (manufacturing, construction, maintenance, operating energy, and end-of-life) are presented in Table 6.

Table 5: A Sample of Construction Phase Material Quantities

Subassembly and constituent elements	Volume, m^3	Mass, kg
Slab on ground		
Concrete	152.6	352,895
Reinforcing steel	0.3	2,449
Underslab vapour barrier	…	389
Insulation (Toronto only)	4.0	140
Curtain wall		
Aluminum	…	35,335
Steel backpans	…	10,614
Glass	…	65,408
Rockwool insulation in Vancouver	184	10,292
Rockwool insulation in Toronto	184	10,292
Vapour retarder foil	0.1	154
Sealant and gaskets	…	584
Fasteners	…	1,570
Steel studs	…	3,402
Gypsum board	23.5	18,915
Paint, interior	…	1,193
Insulated precast concrete walls		
Precast concrete, exterior wyth	75.3	175,087
Insulation, extruded polystyrene in Vancouver	173	6,051
Insulation, extruded polystyrene in Toronto	203	7,103
Precast concrete, interior wyth	112.9	262,290
Steel studs	…	3,402
Gypsum wallboard	23.5	18,915
Backer rod	…	5
Sealant	…	91
Water repellent exterior coating	0.5	1,151
Paint, interior	…	1,193
Brick and steel stud		
Brick	122.9	245,847
Mortar	13.6	25,809
Steel ties	…	1,814
Steel angles	…	25,129
Weather barrier	30.0	3,005
Rockwool insulation in Vancouver	101	5,671
Rockwool insulation in Toronto	120	6,721
Exterior sheathing	23.5	18,915
Steel studs	…	6,190
Gypsum wallboard	23.5	18,915
Fiberglass batt insulation in Toronto	234.1	3,751
Paint, interior	…	1,193
Windows (all envelopes except curtain wall)		
Aluminum	…	5,010
Glass	…	31,790
Sealant and gaskets	…	316
Steel fasteners and anchors	…	282

Table 6: Whole-Building LCIA Results for P-P Toronto 60 years

Impact category	Total	Manufacturing	Construc-tion	Mainten-ance	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+ mol 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, kg 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
Feedstock, biomass, MJ	0	0	0	0	0	0

Total global warming potential (GWP) is 15,877,690 kg CO_2 eq. Of this, 89% of the GWP is from operating energy, which includes 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% of GWP and maintenance is responsible for 2%. Construction and end-of-life are less than 1%.

Total primary energy is 547,806,690 MJ, which consists mostly of 92% non-renewable energy and 8% renewable energy. Non-renewable energy consists of 45% fossil and 53% 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.

The study also evaluated the results over a 73-year life cycle, and these show the same order of magnitude and same ranking. See the referenced CPCI study for details (CPCI 2012).

The whole building "cradle to grave" LCIA results for the baseline building in Vancouver (precast envelope on precast structure, P-P) by life cycle stage (manufacturing, construction, maintenance, operating energy, and end-of-life) are presented in Table 7.

Table 7: Whole-Building LCIA Results for P-P Vancouver 60 years

Impact category	Total	Manufacturing	Construc-tion	Mainten-ance	Operating energy	End-of-life
Global warming, kg CO_2 eq	3,382,905	1,288,868	12,285	386,593	1,704,361	-9,202
Acidification, H+ mol 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 eg.	491	224	5	127	120	16
Photochemical smog, kg NOx 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, m^3	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, kg 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	13,519,153	173,016	6,281,615	30,061,636	-89,100
Non-renewable, nuclear, MJ	705,052	247,779	1,413	350,248	109,642	-4,031
Renewable (SWHG), MJ	152,907,093	892,319	50,431	111,667	151,874,794	-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

Total GWP 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%. This is due to the fact that the electricity grid in Vancouver has lower carbon emission intensity than Toronto, since most of the electricity in Vancouver comes from hydroelectric power. 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 75% renewable energy and 25% 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 and is responsible for more than 80% of the impacts only in water use, total primary energy, and renewable energy.

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.

8.2 Global warming potential (GWP) LCIA results

Table 8 shows the GWP summary of all of the precast buildings for each wall envelope system. 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. Increasing the service life in Toronto to 73 years 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 and steel stud envelope (S-P).

The GWP of the buildings in Vancouver varies from 3.27 to 3.39 million kg CO_2 eq. The GWP of operating energy is much lower in Vancouver compared to Toronto and the GWP of the other stages (manufacturing, construction, maintenance, and end-of-life) have a proportionately larger impact. Increasing the service life to 73 years 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 8: LCIA results: Global Warming Potential (GWP), kg CO_2 eq.

Scenario	60-year life cycle		73-year life cycle	
	Toronto	Vancouver	Toronto	Vancouver
CW-P	15,926,743	3,274,561	19,104,461	3,723,954
S-P	15,897,894	3,312,647	19,092,395	3,793,663
P-P	15,877,690	3,382,905	19,048,444	3,864,569
Pi-P	15,817,229	3,358,278	18,982,276	3,839,953
Pib-P	15,846,474	3,388,527	19,010,436	3,869,601

8.3 Total Primary Energy (TPE) LCIA results

The total primary energy (TPE) results for all of the precast buildings and wall envelope systems, in both cities, are shown in Table 9. The TPE of the buildings in Toronto varies from 546 to 553 million MJ. 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 and steel stud envelope (S-P).

The primary energy of the buildings in Vancouver varies from 203 to 204 million MJ. 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 and steel stud envelope (S-P).

Table 9: LCIA results: Total Primary Energy (TPE), MJ

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

8.4 Other Significant Comparative Observations

The LCA report also included the other environmental impacts described above. However, given the length limitations for this paper, these results cannot be presented here. Please refer to the reference CPCI report for a comparison of the LCA results on acidification, respiratory effects, eutrophication, photochemical smog, solid waste, water use, non-energy abiotic resource depletion, ozone depletion, and the constituents of total primary energy (CPCI 2012).

The referenced CPCI study also included modelling the same five envelope systems described above on a steel structure and on a cast-in-place concrete structure. However, given the length limitations for this paper, these results cannot be presented here. Please refer to the reference CPCI report for a comparison of the LCA of buildings with different structural framing systems (CPCI 2012).

The potential reduction in TPE of changing from curtain wall to insulated precast concrete is significant. For example, going from a curtain wall building with precast concrete structure (CW-P) to an insulated precast concrete building with precast concrete structure (Pi-P), reduced the total primary energy by a range of 6.8 to 8.4 million MJ in Toronto and a range of 1.3 MJ in Vancouver (the range is due to the different service life assumptions, 60 and 73 years).

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 TPE. 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 TPE are even less than hollowcore by approximately 8%. Similarly, precast panels are significantly less than hollowcore by 40%.

A sensitivity analysis on the thermal performance of walls was conducted. Although the study modelled thermal performance of insulated precast sandwich wall panels according to minimum ASHRAE requirements, RSI values of RSI-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, RSI-1.8, to the existing Pi walls on the precast building in Toronto, bringing the total overall *effective* RSI-value of the opaque portion of walls to 4.29 m^2•K/W. This represents an increase in overall effective wall RSI-value of 61%, that is (4.29-2.66)/2.66 = 61%. A 61% increase in overall effective wall RSI-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 RSI-value does not affect cooling energy use, 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. Discussion

Key factors when reviewing an LCA for any product or assembly include: a clear definition of function unit to ensure that comparisons are on an equivalent basis, an understanding of the goal and scope of the study, interpretation of the results in relation to the stated goal and scope, and use of a standard LCA methodology. It is important to distinguish cradle-to-gate life cycle inventories (LCI) from cradle-to-grave life cycle assessments (LCA). This study collected cradle-to-gate LCI data from precast concrete plants and used this data to conduct a cradle-to-grave LCA of precast concrete buildings. Products and assemblies should only be compared if they have they perform the same function. Therefore the choice of functional unit must recognize the function a product provides. In the case of precast concrete, its thermal mass can reduce life cycle energy use and associated environmental impacts. Therefore, any comparison of precast concrete with other building products, such as curtain wall of brick on steel stud, should include the products in a whole-building context, included operating energy over the life of the building. Further, this study highlighted the importance of considering geographic considerations in LCA. Two sets of very similar buildings (in Toronto and Vancouver) have very different environmental impacts because of differences in climate and make of regional electricity grids.

Some of the major conclusions are that the occupancy stage (operating energy) can be responsible for up to 90% of the environmental impacts in a given impact category, but the exact amount depends on many factors, such as the severity of climate and the upstream profile of energy carriers.

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 all 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. The goal and scope have been reviewed and accepted by an independent external critical LCA review committee.

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