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Life Cycle Assessment Overview And Application: Comparison Of Structural Frame Alternatives For Office Buildings

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LIFE CYCLE ASSESSMENT OVERVIEW AND APPLICATION: COMPARISON OF STRUCTURAL FRAME ALTERNATIVES FOR OFFICE BUILDINGS

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LIFE CYCLE ASSESSMENT OVERVIEW AND APPLICATION: COMPARISON OF STRUCTURAL FRAME ALTERNATIVES FOR OFFICE BUILDINGS

Master of Building Science, 2013

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Abstract

The objective of this project was to provide an overview of Life Cycle Assessment (LCA) and to demonstrate its application as a tool to provide a scientific comparison of alternative construction options for a commercial building in the Canadian context. The work entailed a quantitative assessment of the embodied environmental impacts of typical office buildings using a steel frame, and a concrete frame alternative (and associated components) in Toronto. Through the use of four assessment strategies, this study has indicated that the steel framed building performs better than the concrete building in most impact indicators, excepting primary energy and eutrophication potential. However, additional buildings should be assessed in order to confirm this finding. Furthermore, it was found that the manufacturing phase represents over 90% of the embodied impacts of the whole building. The study also advises caution when comparing different LCA studies and identifies its difficulties.

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Table of Contents

List of Tables

List of Figures

Abbreviations

AP	Acidification Potential
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BEES	Building for Environmental and Economic Sustainability
CaGBC	Canadian Green Building Council
CISC	Canadian Institute of Steel Construction
EC	Athena Eco-Calculator
EIE	Athena Environmental Impact Estimator
EP	Eutrophication Potential
EPA	United States Environmental Protection Agency
FFC	Fossil Fuel Consumption
GaBi	“Ganzheitliche Bilanzierung” in German
GWP	Global Warming Potential
HHR	Human Health Respiratory effects potential
ISO	International Standards Organization (International Organization of Standardisations)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCEA	Life Cycle Energy Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Social Assessment
LEED	Leadership for Energy and Environmental Design
NRCan	National Resources Canada
ODP	Ozone Depletion Potential
OWSJ	Open-web Steel Joists

PEC	Primary Energy Consumption
SP	Smog Potential
SSEF	Steel Structures Education Foundation
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
VOCs	Volatile Organic Compounds
WF	Wide-flange
WRU	Weighted Resources Use
WSA	World Steel Association

1. Introduction

1.1. Background

A growing awareness of the environmental impact of buildings throughout their life cycle has led the construction industry to shift the analysis of inherent environmental impacts from just the operational life stage, to include a more comprehensive understanding of the full life cycle of whole-buildings and materials. Hence, there is a move to evaluate the embodied impacts of materials and components that comprise a building using “cradle to grave” methodologies (or “cradle to cradle” when considering reuse or recycling aspects). This evaluation and quantification must be developed systematically through a consistent framework with the intention of locating major trade-offs and understanding potential areas of improvement. Life cycle assessment (LCA) methodology, established by the International Organization of Standardization (ISO 14040), is a scientific tool that provides such complex evaluation (Bare, et al., 2005; Fava, J., 2005; EPA, 2006; Malin, N., 2005).

Life cycle assessment evaluates all environmental impacts cumulatively stage by stage over the entire life span of a product or process providing a more accurate spectrum of environmental trade-offs and avoiding shifting environmental burdens between each life cycle stage. LCA assists improving the sustainability of products and processes by identifying “greener” opportunities over the life stages, and therefore is a tool useful for decision makers. LCA is used by government agencies in order to develop policies and regulations and to ensure that governmental regulations are being met. Private and public sectors can use LCA to provide a better understanding of environmental consequences of different choices. Furthermore, LCAs can help to change a company’s mind-set to more environmentally friendly aspirations (Heijungs, R., Huppes, G., and Guinée, J., 2009; Ortiz, O., Castells, F., and Sonnemann, G., 2009).

In summary, the use of LCA facilitates the investigation of various environmental impact indicators, such as global warming potential, primary energy use and other emissions to air, water and land, through all the building’s life cycles (cradle-to-grave and cradle-to-cradle). It also helps to understand the embodied impacts (from manufacture of materials, transport, etc.) compared to operational impacts. Furthermore, the comparison shows the various trade-offs of all components for each evaluated building.

In the U.S., this process of evaluation was first used in the late 1960’s by Coca-Cola to assess the environmental impacts of switching from glass to plastic bottles. Nowadays, the ISO 14040 family of LCA standards (Environmental management – LCA – Principles and framework & Requirements and guidelines) are considered the starting point for system development within the building industry sector (Fava, 2005; Malin, 2005).

1.2. Research objective

The main objective of this project research was to evaluate the environmental impacts of buildings using alternative structural framing systems through a Life Cycle Assessment (LCA), in an attempt to provide a fair comparison between steel and concrete. The study focused in answering the following main questions:

- How to provide a fair comparison between steel and concrete structural systems using LCA? – main topic of the study
- Which LCA tools are the most relevant in North America?
- How these LCA tools perform regarding their Life Cycle Inventory (LCI) database and methodologies?
- What are the implications in comparing results from various LCA studies?
- How accurately Athena Environmental Impact Estimator (EIE) evaluates impacts for steel and concrete structural systems?
- How does compare results from different LCA tools evaluating the same building?
- What are the major considerations in the comparison between embodied and operational environmental impacts?

This project study intended to provide an overview of LCA and to demonstrate its use as a tool to provide a scientific comparison of alternative construction options for a commercial building in the Canadian context. The work entailed a quantitative assessment of the embodied environmental impacts of using alternative structural materials (and associated components) for a typical office building located in Toronto. The aim was to provide a more reliable and consistent source of information on comparative environmental benefits of material selection putting the environmental impacts in a like for like analysis.

In order to answer the proposed questions, the study included a review of international LCA methodologies used for buildings including the UK Envest tool, the Dutch EcoQuantum system and the North American Athena Environmental Impact Estimator (EIE). Since Athena EIE was developed as a recognised LCA software tool in North America to carry out LCA studies of whole buildings, this study was based on the Athena EIE software, but also investigated other alternatives. The focus of the work was to undertake an analysis of a regular office building using alternative structural specifications through the EIE tool. Moreover, the study looked beyond the regular outputs from EIE and compared the impacts using Athena Eco-Calculator (EC) and GaBi LCA software, which broadened the comparison range of the study.

The main focus of the analysis was on global warming emissions (equivalent carbon dioxide emissions) and embodied energy, but air and water emissions, solid waste, and raw resources use were also considered. These measures are used as indicators of the environmental loadings that can be caused by the construction industry in Canada. Even though the indicators do not directly address the ultimate human or ecosystem health effects, which is a much more difficult and uncertain task, they do provide good measures of environmental performance, allowing professionals to understand and minimise these effects (Bare, J., and Gloria, T., 2005).

The project involved the following steps:

1. A literature review was carried out of LCA methodologies for building assessment regarding concrete, timber and steel frame structures. This considered national and international LCA tools to investigate various methodologies used to evaluate the steel recycling and reuse application in LCA studies. Furthermore, it also included a review of literature of LCA case studies comparing alternative structural systems in order to understand the major differences in results while identifying relevant aspects that were considered in this research.

2. Appropriate life cycle inventory (LCI) data for materials was identified. For initial analysis the Athena EIE LCI database was used. For comparison purposes a database for steel products was collected from the World Steel Association (WAS). This includes data collected from many steel producing sites around the world and was developed using appropriate methodologies to address recycling and reuse of construction materials in LCA. For comparative analysis the WSA data for steel was used in conjunction with Athena EIE datasets for other construction materials.

3. The typical design for a steel framed office building was identified by the CISC and its alternative in concrete was developed by the Department of Architectural Science. The building was assumed to be located in southern Ontario and follows Ontario's construction standards.

4. An LCA analysis was developed for the steel framed and concrete framed buildings using Athena EIE software, which provided the base comparison data for the study focused on embodied impacts such as material extraction, transportation, manufacture, assembly, maintenance and demolition.

5. A series of sensitivity analyses were carried out to test assumptions in Athena and to identify the impacts of such assumptions. In this phase, alternative approaches to carry out an LCA of the same buildings were considered. This involved the Athena Eco-Calculator models and GaBi software using LCI data from WSA.

6. This research was prepared consisting of:

    - A brief background on LCA and its importance for the construction industry, including its framework and general terminologies

    - A summary review of the existing literature in LCA case studies and methodologies, including general description of the LCA tools used in this research

    - The characterisation of the steel and concrete buildings, and methodology applied to develop the LCA models, also including modeling limitations

    - A summary of the LCA results and comparisons

    - Observations, discussion and conclusion

2. Review of Life Cycle Assessment Methodologies

Life cycle assessment as defined by ISO 14040 and 14044 (2006) is the compilation and evaluation of inputs and outputs of a product system and their potential impacts on the environment during the products lifetime. In other words, it is a scientific framework that evaluates the inherent environmental impacts of products over its life span, including resource extraction, manufacturing, use and disposal, therefore allowing the identification of hot-spots and improvement of products in each life cycle phase. Regarding the construction industry, a whole building life cycle can be summarised as shown in Figure 1 (EPA, 2006; Fava, 2005; Jameel, F., Daystar, J., and Venditti, R., n.d.; Malin, 2005):

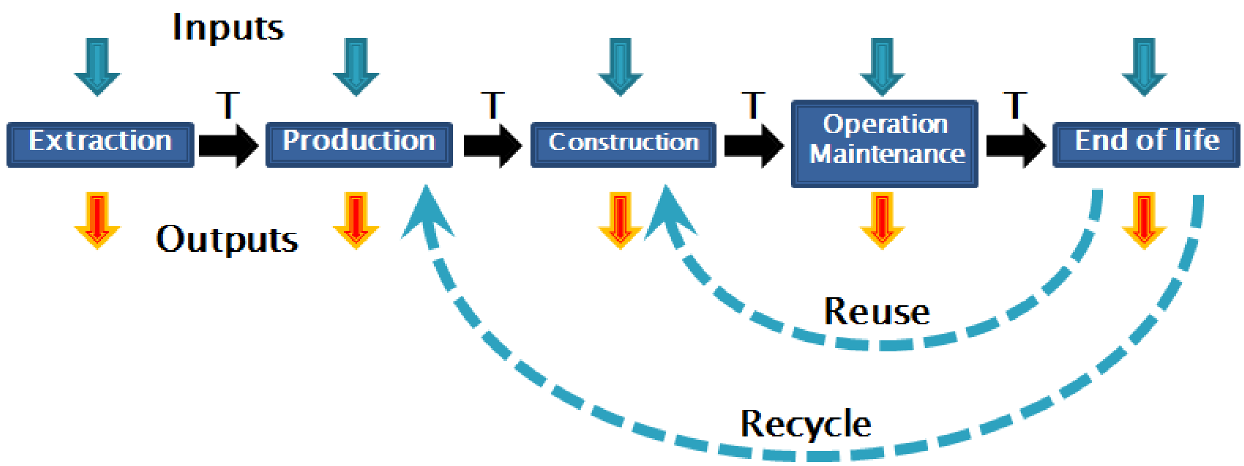


Figure 1 - Life cycle stages of a whole building

The life-cycle stages of a product are mainly resource extraction, manufacturing, use and disposal. Each phase has many processes that require inputs of resources (including energy) which then generate outputs as the main product (also co-products and by-products) and other emissions to land, air and water. Figure 1 exemplifies a whole building's cradle-to-grave life cycle stages, or cradle-to-cradle if considering aspects such as reuse and recycle. A cradle-to-gate life cycle considers only the extraction and production phases when a product is ready from its manufacturing processes. LCA therefore is the compilation of every input and output within a system boundary and its evaluation and interpretation as environmental impact indicators (EPA, 2006; Fava, 2005; Nebel, 2006). Moreover, embodied impacts are associated to every life-cycle stage of the product besides its operation. Recurring embodied impacts are all impacts related to the maintenance of the product and should not be included as operational.

Between specialists and practitioners of LCA, two types of assessment have been distinguished, the attributional LCA and the consequential LCA. Attributional LCA was defined as a study focused on the environmental impacts (inputs and outputs) "to and from the life cycle and its subsystems". Consequential LCA on the other hand was defined as a study focused on how environmental impacts will change as a consequence of possible decisions (Finnveden, et al., 2009, p. 3). In other words, attributional LCA intend to evaluate the actual (or historical) environmental burdens over the life cycle of a product, while consequential LCA evaluates the changes caused by future trends and choices over the life cycle. The study presented in this report is an example of attributional LCA since the environmental impacts of a steel building were compared to a concrete building based on data for current manufacturing methods and energy intensities. A consequential LCA therefore could be the assessment of same building if no landfill was possible at the end of life, or if the recycled content of steel was assumed to increase, and also varying the energy source for steel component production. Attributional LCAs are the most broadly applied, although some authors argue that consequential LCAs are more relevant for decision makers (EPA, 2006; Finnveden et al., 2009; Sandén, B., and Karlström, M., 2007).

2.1. ISO framework and definitions

Up to the 1990s, many LCAs studies were developed and also many critics emerged with regard system boundary and especially data source credibility. Therefore ISO 14040 series of standards were developed in order to provide an established framework and guideline to perform an LCA study. It also provides common ground for LCA practitioners in order to achieve consistency and transparency within LCA studies. ISO 14044 – Requirements and Guidelines defines 4 phases required to perform an LCA study as shown in the diagram and described below (ISO, 2006):

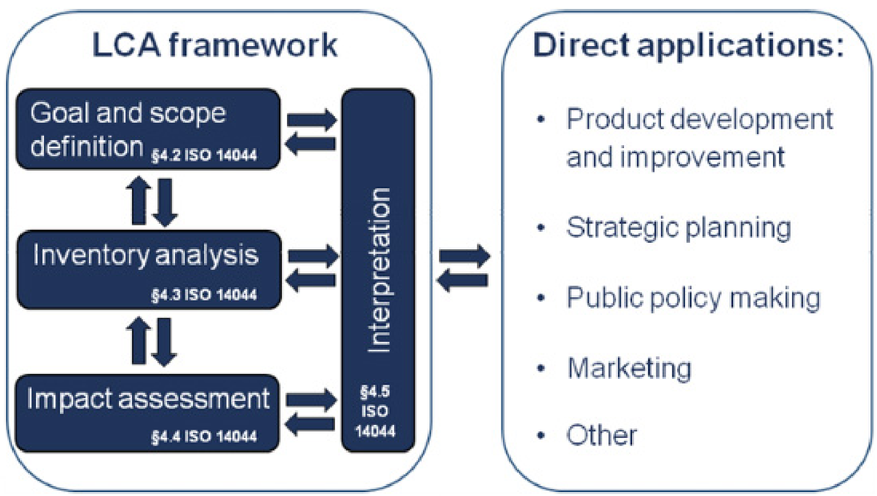


Figure 2 - ISO standards LCA phases (ISO 14044, 2006)

- Goal and scope definition: identify the purpose and audience describing the object of the study and its boundaries, including methodology and assumptions and also defining the functional unit.

- Life cycle inventory (LCI) – Inventory analysis: compilation of all inputs and outputs for every process included in the system boundaries. Data collection varies according to methodology and purpose of study and is defined quantitatively and qualitatively. Collected data must be validated regarding the functional unit. Inputs and outputs must be allocated accordingly, and the system boundaries can be redefined in order to keep a valid functional unit. Figure 3 shows a sample unit process as used for LCI data collection.

- Life cycle impact assessment (LCIA): identifies and evaluates the amount and significance of the potential environmental impact of a product system; used to reach midpoint or endpoint environmental impact indicators. It consists of classifying physical flows to its respective scientifically defined impact category (such as global warming potential) and then converting each physical flow to its respective impact category unit (such as kg CO_2 eq. for global warming potential) by applying scientifically defined characterization factors. An example of this phase is represented by Figure 4.

- Results interpretation: results are analysed while identifying limitations and assumptions to determine the environmental hot-spots, deriving conclusions and providing recommendations. If the LCA study is to be published as ISO compliant, a peer review of the study is required in order to guarantee transparency and consistency of the LCA.

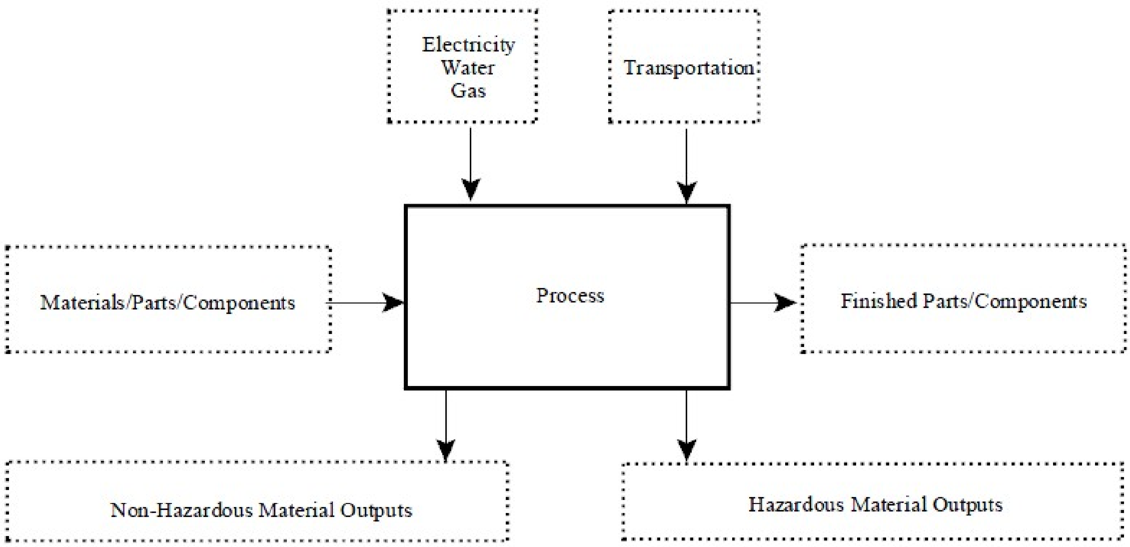


Figure 3 - Sample unit process for LCI data collection (EPA, 2006)

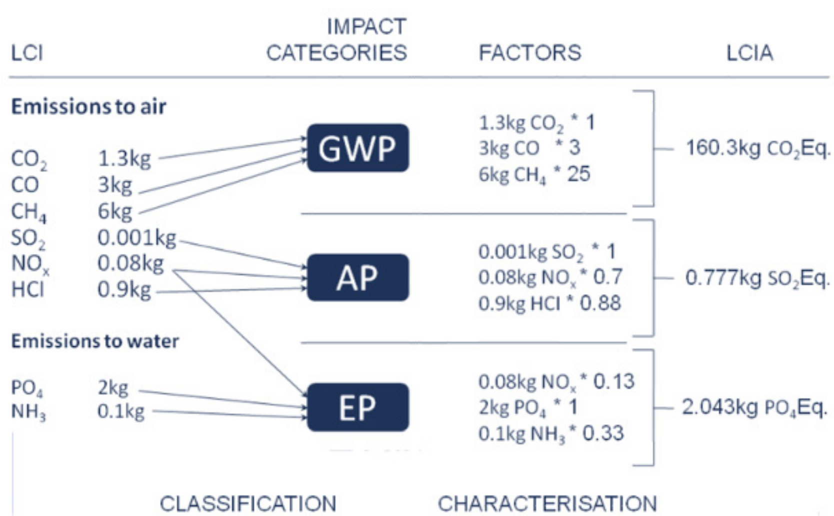


Figure 4 - LCIA classification and characterisation example (GaBi, 2010)

2.1.1. Goal and Scope Definition & functional unit

It is during the goal and scope definition that the object of study is described according to its function, demand and functional unit. The 'functional unit' sets the boundaries or scope, ensures consistency and validates the fairness of the study (EPA, 2006; Finnveden, et al., 2009). Taking wall insulation as an example, comparing fiberglass batt-insulation (with a thermal conductivity of 0.043 W/m.K) to polyurethane foam (0.026 W/m.K), both materials have the same function, to provide insulation for a wall assembly. However, if the batt-insulation is to be applied in one square metre of 2x4 framed wall, its maximum thermal resistance value is R_{si} 2.07 (m^2.K)/W (R 11.75). On the other hand, the foam insulation can reach R_{si} 3.42 (m^2.K)/W (R 19.42). Thus the 'functional units' are not the same. For any fair LCA comparison the thermal performance of each wall should be equivalent, and similarly for other performance factors such as permeability, air tightness, structural performance, etc.

In this report the functional unit is an office building located in Toronto in which the only design variation is the structural systems. Further design details are discussed later.

2.1.2. Life Cycle Inventory & data problems

The life cycle inventory (LCI) phase is the most work intensive and time consuming of all phases. This is due to the difficult task of compiling all physical flows (inputs and outputs) for every process within the system boundary. Although LCA studies have been used for over 30 years, there is still considerable data scarcity, especially for the building industry in North America (EPA, 2006; Finnveden, et al., 2009; Malin, 2005). Another complex task during the LCI phase is the correct allocation of the physical flows to each finished part/component of all processes involved within the system boundaries. Furthermore, there is the problem of allocating the physical flows for recyclable content, recyclability potential and reuse aspects of products within same life cycle stage or between different stages (which is particularly relevant for steel). Figure 5 below is an example for reuse and recycling aspects of a system boundary. Various methodologies have been developed to address this complex task of properly allocating physical flows. Although these methodologies can significantly affect the results for a same product, they are accepted by ISO standards if they are applied consistently and transparently throughout an LCA study.

Buildings consist of many interconnected components with multiple functions and different life spans, which make the LCA of buildings particularly challenging. Consequently, the LCA for buildings requires many assumptions that, if not clearly presented and reported, can invalidate the study. Data collection becomes a difficult task since there are many products to consider, and so the definition of a clear and consistent functional unit becomes critical (EPA, 2006; Finnveden, et al., 2005; Malin, 2005). For additional information on LCI and methodologies for integration of recycling aspects in LCA tools, see Appendix A.

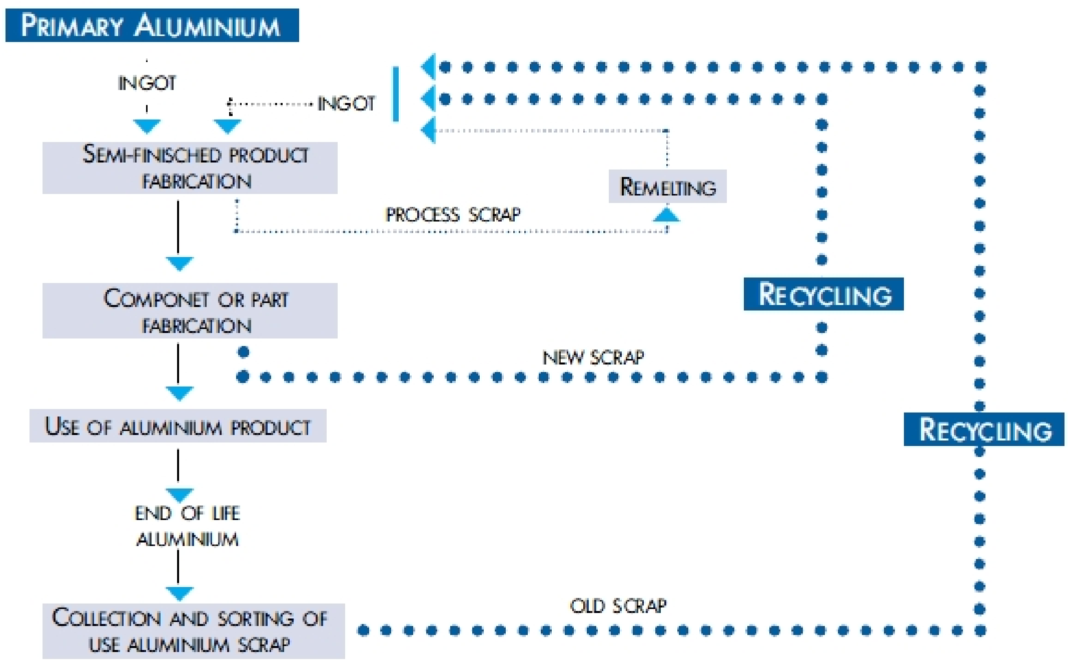


Figure 5 - Example of system boundaries for aluminum products life cycle (EAA, n.d.)

2.1.3. Life Cycle Impact Assessment

In Life Cycle Impact Assessment (LCIA) phase of an LCA study, all elementary flows are divided into environmental impact indicators and then aggregated by applying a characterization factor. Elementary flows are all physical flows that enter the system boundary from nature (such as resources and energy) and all physical flows that leave the system boundary to nature (emissions to air, water and land). Characterization factors are determined by different scientific groups based on various methodologies and philosophical views of the environmental impact indicators. The most common characterization factor methodology in North America is the US EPA Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) and in Europe the methodology developed by the Center for Environmental Sciences (Centrum voor Milieukunde Leiden – CML). Also within the LCIA phase, depending on the methodology being used, such as TRACI or CML, the results will vary. Similarly to allocation issues regarding different methodologies, ISO standards accept both LCIA methodologies if they are consistently applied throughout an LCA study (Bare, et al., 2005; EPA, 2006; Finnveden, et al., 2009; Jameel, et al., n.d.; Nebel, 2006).

There are two levels of impact indicators within LCIAs, the midpoint and endpoint impacts. Endpoint impacts are directly related to the areas of main concern of protection (human health, natural environment, manmade environment and natural resources), therefore much more complex to be defined. Midpoint categories on the other hand is the intermediate level between the endpoint and the actual emissions from a product in LCA. Midpoint model reflects the relative potency of an environmental impact “at a common midpoint within the cause-effect chain”, minimizing forecasting effect modeling, and also minimizing assumptions and value choices that simplifies communication (Bare et al., 2005; EPA, 2006; Jameel, et al., n.d.;

Finnveden et al., 2009; Nebel, 2006). Figure 9 shows various impact indicators as discussed above.

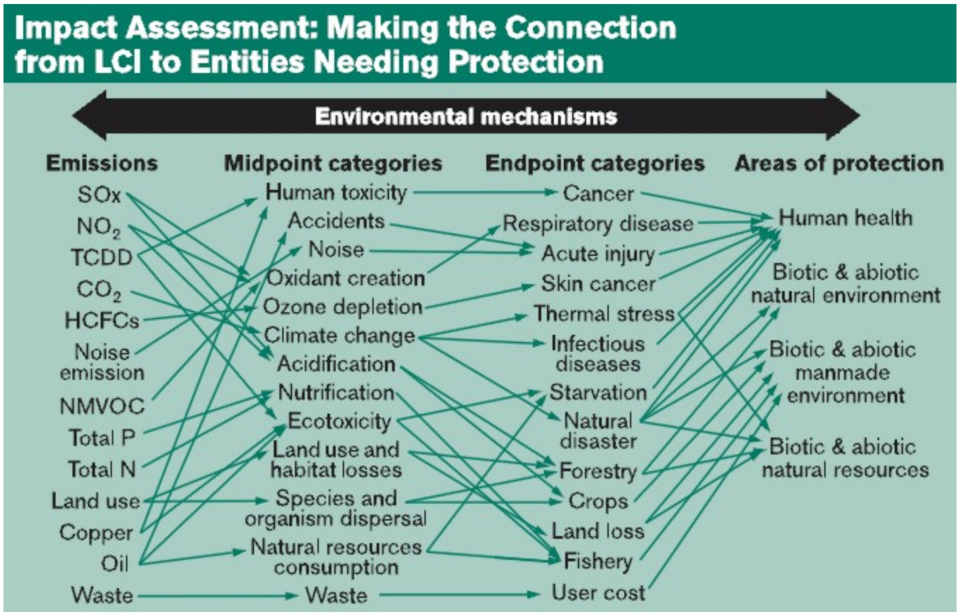


Figure 9 - LCIA environmental mechanisms (Bare, et al., 2005)

It is important to stress here that ISO restricts the LCIA to environmental impact only, which restricts the evaluation of the total sustainability aspects of a product or process that are dependent on the social and economic dimensions. There are seven major steps in performing an LCIA, however ISO states that only the first three steps are mandatory steps (Finnveden, et al., 2009; EPA, 2006; Daystar et al., n.d.; Bare et al., 2005):

- First, selecting and defining the impact categories, which are predetermined in the initial goal and scope phase and that assist the LCI process. The impacts are considered as consequences from the emissions and materials use (LCI) on human health, ecological health and resource depletion.

- Second step is the classification, in which all the emissions and resources identified in the inventory analysis are assigned to the predetermined impact categories. If an LCI result must be assigned to multiple impact categories, it can be partitioned if its effects are dependent on each other category; or all the LCI results can be assigned to all related categories if the effects are independent.

- The third step is the characterization of each impact, one of the most important steps because it makes possible the comparison of LCI results at each impact category, translating the inventory into comparable impact indicators as a quantitative model. The calculation of the impact indicators takes the inventory results and multiplies by a science-based conversion factor called characterization factor.

- The forth step is the normalization of results, relating them to reference values, facilitating the comparison between impact categories, which helps the interpretation of the results.

- The fifth step is grouping the impact categories into sets of similar impacts or ranks, which may help the interpretation and presentation of the results.

- The sixth step is weighting LCIA results, but is considered a subjective process and must be documented. It is a way for grouping by assigning values to impacts and allowing the integration of the different impact categories.

- The final step is the evaluation and reporting the LCIA results, where the accuracy of the results is verified according to the scope of the study.

Additionally to all these concerns that might arise in an LCA study regarding data availability and credibility, time/budget, consistency of methodologies applied and transparency of assumptions, is the complexity of performing an LCA study for a whole building. As Malin points out (2005), to perform a perfect LCA of a whole building, or to have the right tool to enable this complex task is like "seeking the holy grail". Buildings consist of many interconnected components with multiple functions and different life spans, which make the LCA of buildings almost an impossible task. Consequently, the LCA for buildings requires more assumptions that, if are not well presented and reported, can invalidate the study. Data collection becomes an even more difficult task since there are many products, and also making difficult to elaborate a consistent functional unit (EPA, 2006; Finnveden, et al., 2005; Malin, 2005).

2.2. LCA tools for the building industry

The challenge of collecting consistent LCI data has led several research entities to develop local, regional and international databases of LCI data on materials, such as the U.S. EPA, the Canadian Athena Institute and the UK Environmental Profiles. Furthermore, the complexity of performing an LCA study has led several companies and organizations to develop software tools to assist practitioners in processing data. These tools include a set of methodologies and assumptions that encompass the LCI and LCIA phases of LCA and are applied consistently in order to perform valid studies. Although they somewhat vary in methodologies and assumptions, they follow the ISO standards and comply with the requirements to perform LCA studies. In order to characterize the application of LCA software tools, it is important to explain the methodology in which those tools are defined. Generally, building simulation tools are classified in three levels (Nebel, 2006; Malin, 2005; Trusty, W., n.d.; Ortiz et al., 2009):

- Level 1 tools are focused on individual products or simple assemblies, often used to make comparisons regarding environmental impacts or economic criteria, i.e. product comparison tool

- Level 2 tools are focused on the whole building, and assist in design decision making regarding specific areas such as operational energy use and lighting simulation, LCC and LCA effects

- Level 3 tools are "whole building assessment framework or systems", and includes a wider range of environmental, economic and social concerns, which assist the evaluation of sustainable development or sustainability property of the building

The main software tool used in this research was the Athena Environmental Impact Estimator (EIE) because it is the leading building LCA tool in North America designed to facilitate easy modeling of whole building assemblies. Athena Eco-Calculator (EC) is a simplified tool that was developed based on EIE and was used in this research as comparison to EIE models. Another common LCA tool in North America is BEES (Building for Environmental and Economic Sustainability), which can be used by Green Building Rating Systems such as LEED for material selection credits. However, BEES is a level 1 tool while EIE and EC are level 2 tools. There are other LCA tools available that are still under development or do not have the same relevance of those described here for the construction industry in North America. The Table 1 is a summary of the LCA tools that were investigated.

Table 1 - Summary of LCA tools for construction industry

LCA tool	Developer	LCI database	Region application	Classification Level	LCA phases considered	Criteria concerns
Athena	Athena Sustainable Material Institute, Canada	Athena Institute	North America	whole building	cradle-to-grave recycling	environment
BEES	US National Institute of Standards and Technology (NIST), USA	Generic data and brand specific	USA	building products	cradle-to-grave	environment and economic
Eco-Quantum	IVAM, Netherlands	Compilation of public available generic sources data and LCA's performed by IVAM	Netherlands	building products	cradle-to-grave recycling reuse	environment
Envest 2	Building Research Establishment (BRE), UK	UK based data and benchmarking, LCA data for material and Ecopoints	UK	whole building	cradle-to-grave recycling	environment and economic
SimaPro	PRé, Netherlands	various databases including the North American Franklin US	not specific	all purposes professional LCA tool	can be used widely considering any life cycle	environment
GaBi	PE International, Germany	various databases including the North American Franklin US	not specific	all purposes professional LCA tool	can be used widely considering any life cycle	environment and economic
Source: Environment Australia, n.d.; Haapio, A., & Viitaniemi, P., 2008; Seo, S., 2002						

Internationally, there are two LCA software tools important to ne mentioned related to the construction industry: Eco-Quantum from Netherlands and Envest 2 from UK (Anderson, J., Shiers, D., and Steele, K., 2009; Haapio, A., & Viitaniemi, P., 2008; Seo, S., 2002).

- Eco-Quantum - Netherlands:

LCA software that helps designers to identify the environmental burdens for the full life cycle, and provides four impact indicators, namely resource depletion, emissions (to air and water), energy consumption and waste.

- Envest 2 - UK:

LCA software that calculates the life cycle environmental effects and costs based on the building's geometry and element choices. The environmental results are expressed in a single score, the EcoPoint, which are derived from the impacts caused by one typical UK citizen over one year (equals to 100 EcoPoints), in which 1 EcoPoint corresponds to each of:

  - 320 kWh electricity use;
  - 83m^3 water use (approximately 1000 baths);
  - 63 miles transport by articulated truck;
  - 1.3 tonnes of landfilled waste;
  - Manufacturing of 250 bricks approximately;
  - 540 tonne km by sea freight;
  - 1.38 of minerals extraction

In North America, the two most used and best developed LCA software tools focused in the construction industry are the Athena EIE (discussed later) and BEES:

- BEES:

Building for Environmental and Economic Sustainability (BEES) is an LCA tool focused in building products, and enables direct comparison of products based on life cycle assessment and life cycle costing, combined in a single score weighted by the user.

Additionally, it is important to mention two other LCA tools, Sima-Pro and GaBi. These LCA software tools provide a wide range of LCI datasets. These generic LCA software tools are considered open based because they compiled many different methodologies and allow users to develop their LCA from scratch, practitioners must develop their own framework within the software. It is possible to create new LCI data or modify existing databases, and they can be used to develop LCA of almost any product and process. These tools are very complex since the user must develop the entire framework for the system boundary and create process by process to reach the final object of study.

2.2.1. Athena's Environmental Impact Estimator

The Athena Sustainable Materials Institute is a non-for profit institute that developed the Athena Environmental Impact Estimator (EIE) to facilitate the assessment of environmental impacts of industrial, institutional, office and residential building designs. This tool is regionalized, therefore the results are affected by the building location. The software covers eight regions in Canada and seven regions in US (an eighth considers US average). It allows varying the buildings life span, providing easy comparison and understanding of material maintenance and replacement. Annual operational energy consumption by fuel type can be entered and then the software makes possible the comparison between embodied and operational impacts. The software simulates over 1,000 different assembly combinations for envelope and structure systems and is considered to be able to model about 95% of the building stock in North America. It can provide cradle-to-grave LCI data for the building design including primary energy use, solid waste, global warming, air and water pollution indexes and resource use as impact measures. Moreover, since the incorporation of the EPA TRACI LCIA formulations within version 4, the software also provides results for acidification, human health respiratory effects potential, eutrophication, smog potential, ozone depletion and fossil fuel consumption. The results can be shown by assembly groups or by life cycle stages, which includes construction impacts as a separate stage (Trusty, W., n.d.; Athena, 2008).

The impact indicators described above as defined by Athena are (Athena EIE):

- Primary energy consumption (PEC): reported in mega-joules (MJ), is all energy, direct or indirect, used to transform and transport raw materials into products and buildings, also including indirect energy use associated with processing, transporting, converting and delivering energy and the operating energy

- Fossil fuel consumption (FFC): same as above, although considering only non-renewable fossil fuel consumption and feedstock fossil

- Global warming potential (GWP): reported in kilograms of carbon dioxide equivalence (kg CO_2 eq), is the aggregation of all greenhouse gases into carbon dioxide equivalent by applying TRACI's characterization factors

- Acidification potential (AP): reported in moles of hydrogen equivalence (moles H^+ eq), is the aggregation of concentrations of NO_x and SO_2 by applying TRACI's characterization factors

- Human health respiratory effect potential (HHR): reported in kilograms of 2.5µm particulate matter equivalence (kg $PM_{2.5}$ eq), is the aggregation of particulate matter of various sizes using TRACI's characterization factors

- Eutrophication potential (EP): reported in kilograms of nitrogen equivalence (kg N eq), is the fertilization of surface waters by nutrients that were previously scarce leading to proliferation of aquatic photosynthetic plant life

- Smog potential (SP): reported in kilograms of nitrogen oxides equivalence (kg NO_x eq), is a product of interactions of volatile organic compounds (VOCs) and NO_x with the presence of sunlight, producing photochemical smog

- Ozone depletion potential (ODP): reported in milligrams of chlorofluorocarbon -11 equivalence (mg CFC-11 eq), is the aggregation of ozone depleting substances (CFCs, HFCs, and halons) by applying TRACI's characterisation factors

- Weighted resource use (WRU): reported in kilograms, is the conversion of normal resource use to a mass quantity applying Athena's expert panel ranking of the effects of extraction activities

The general system boundaries used in Athena EIE can be seen in the Figure 5. Athena EIE methodologies consider recycling and reuse when applicable such as with materials that are not currently being land-filled at the end-of-life of the building (e.g. steel). The methodology assumes impacts for on-site building disassembly of those materials and transportation. The results provided by the software are all midpoint indicators and LCI emissions over the life cycle span of the building (Athena, 2008).

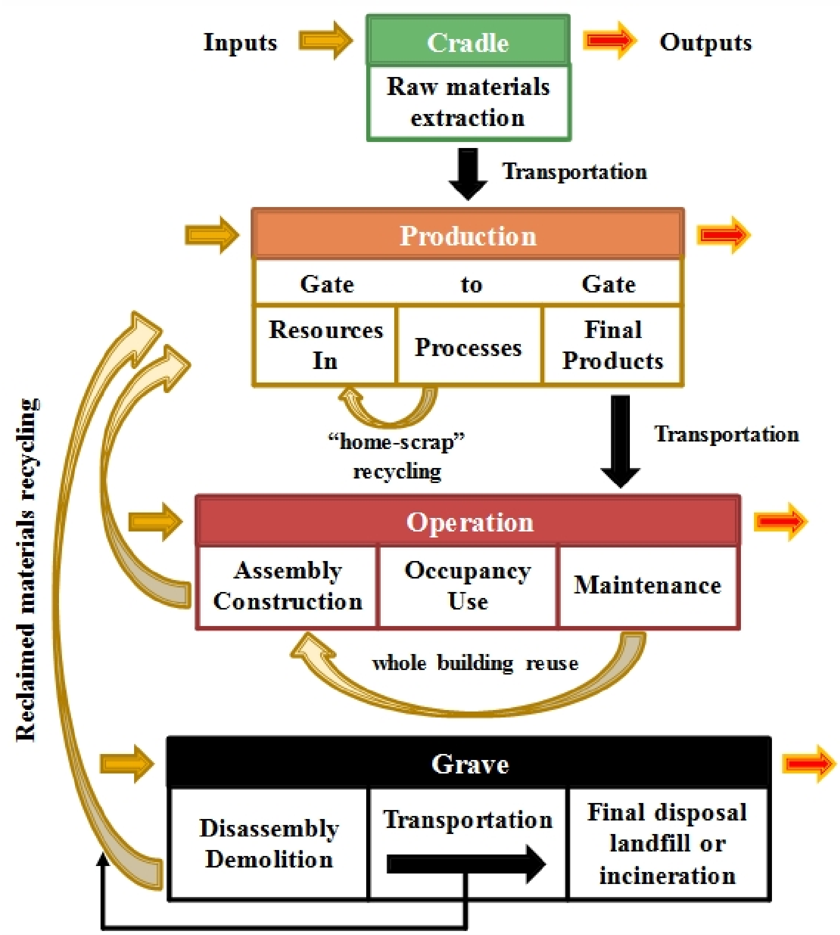


Figure 6 - Example of system boundaries for whole building life cycle

There are two methods of modeling a building using Athena EIE. The first method is the most conventional, by using the assembly dialogues predefined by Athena (by assemblies). This method is user-friendly and the software builds a tree to help track entries. The software has a series of predefined assemblies which are divided into foundations, walls (exterior and interior), roofs, columns and beams and floors. The user can select many envelope characteristics for each assembly group in order to most accurately represent the whole building design. Once the user has developed the model for the building or its parts, the software can provide all the results discussed before, and also a bill of materials considered as material quantity take-off. Athena Institute (2008) compared these bills of materials to detailed manual take-off quantities and suggested that the materials on the take-off list are within a range of 10%. Athena Institute also considers that any comparative impact measure differences of 15% or less are equal or insignificant. This is due to a series of uncertainties in the LCI database and various assumptions used in the software LCA's system.

The second method to model a building in Athena EIE is 'by quantities'. This requires providing material input data by units of weight, area or volume (in the case of concrete). It is the inverse of the first method as in this case it is the user who calculates the material quantity take-off list and inputs this data as basic extra materials. The software will then calculate those materials and provide similar results. There are a few limitations with this second method when getting results. Since the model does not use the assembly dialogues, Athena EIE does not know what belongs to each assembly group and also cannot account for environmental impacts under construction life cycle stage, but only the transportation of the material inputs. However, this limitation can be solved by applying a series of calculations based on proportions between the results from models by assemblies and quantities.

2.2.2. Athena Eco-Calculator

Athena Eco-calculator (EC) is a web based simplified building LCA tool developed in association with the University of Minnesota and Morrison Hershfield Consulting Engineers and commissioned by the Green Building Initiative™ (BI) for the use in Green Globes™ environmental assessment and rating system. It was developed using Athena EIE software and the Athena Institute's LCI databases and with data from the US LCI database (Athena, n.d.). It consists of a simplified web base spreadsheet tool that allows a designer to choose between pre-specified constructions and build up a whole building, but is limited to the available assemblies. The software allows users to model their building designs much faster than the EIE software through a series of predefined assemblies on a spreadsheet. These assemblies are divided into foundations & footings, columns & beams, intermediate floors, exterior walls, windows, interior walls and roofs. The only input data for each chosen assembly is the area that each assembly has in the overall building design. Every predefined assembly (which also includes envelope characteristics) has a fixed value (per unit of area) for each environmental impact indicator and is multiplied by the area input. Athena EC is also a regionalized LCA tool for North America, but its intent is to provide only estimates of embodied impacts of the building. The software does not include recurring embodied impacts and operational impacts. It can be considered as a first step LCA study for a building design development.

The environmental impact results provided by Athena EC includes primary energy use, weighted resource use, global warming potential, acidification potential, human health respiratory effects potential, eutrophication potential, ozone depletion potential and smog potential. The results are divided also by each assembly group, and are represented in absolute values for each summary measure and also in pie charts showing the proportion of inherent environmental impact related for each assembly group. The software is easy to use and provides instant results. Although it is limited to fewer sensitivity analyses possibilities, is a good source for comparison of different choices during the design process.

2.2.3. GaBi

GaBi (Ganzheitliche Bilanzierung) was developed in Germany, by PE International, and consists of a generic LCA tool that allows modeling any process or product. The software has various methodologies and access to many LCI databases around the world. Practitioners must develop their LCA studies process by process or altering existing processes in order to get to final results. The software also allows developing Life Cycle Costing (LCC) and Life Cycle Social Assessment (LCSA) as a complement to LCA aspects of various processes and products, which makes the software an efficient tool to estimate and evaluate sustainability. The GaBi tool was used in this project to model the data provided by WSA. Further detail on the methodology is discussed later.

3. Literature review of building LCA studies

Since 1990s, LCA practitioners have developed more complex methodologies for the analysis of building products and components to whole building evaluation. These studies assess complete systems such as structure, envelope and even building services. Due to the complexity and data availability, many of the early studies focused only on energy consumption and CO_2 emissions of buildings.

The following is a review of a series of case studies comparing commercial buildings over their life-cycle. They also cover a range of building types including, warehouse buildings, various office buildings and many houses, and including analysis of structural frame alternatives and in a few cases envelope systems. In order to organize the results found, the first step was to determine a reference number to each case study and present them with the respective analyzed buildings, the functional unity, assumptions and limitations with actual results. In sequence, the results are grouped to each reference number and presented in graphs, which facilitates the comparison and analysis of results.

3.1. Characterization of case studies

3.1.1. Commercial buildings

1 – Environmental audits of alternate structural systems for warehouse buildings (Cole, Rousseau and Taylor, 1992):

This study was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC). An environmental audit was defined as the evaluation of impacts in terms of inherent energy consumption and environmental emissions from cradle-to-gate following the International Federation of Institutes for Advanced Studies (IFIAS) level II standard set. These standards are considered to capture 90% of energy required to manufacture a product, and include all steps required in raw material extraction, primary processing, secondary processing and transportation to gate. Every building system and components were disaggregated into each individual material by mass and multiplied by unit factors related to five fuel types.

The analyzed building is a single-storey industrial style building, typical for warehouse or light industry, and also as a retail mall if used in a more finished form. It has a simple slab on grade floor of $3240m^2$ with a 15x9m or 15x6m bay size. The building is designed for a climate applicable to Vancouver. Energy, energy-related and non-energy-related emissions were calculated for four alternate structural systems: 1a – concrete masonry, 1b – tilt-up wall, 1c – steel system and 1d – wood.

Table 2 - Summary of results for warehouse structural alternatives

Building type	Life Span/LCA Stages	Embodied Energy	Embodied CO_2	Air Toxicity
Units	years/stages	(GJ/m^2)	($kg\ eCO_2/m^2$)	(volume unit/m^2)
1a - concrete	cradle-to-gate	1.57	103.80	4,185.00
1b - tilt-up wall	cradle-to-gate	1.65	108.60	4,345.00
1c - prefabricated steel	cradle-to-gate	1.10	66.50	2,653.00
1d - timber frame	cradle-to-gate	1.17	51.10	3,608.00

1a and 1b are considered massive structural system while 1c and 1d lightweight structural system and it was identified that the lightweight components are 25-33% lower in energy and 14-39% lower in air pollution indices than massive buildings. Comparing the lightweight buildings, their embodied energy is fairly close with timber being 6% higher, although emissions to air are much higher, about 26%. This high air pollution index is due to production techniques of laminated timber which burns wood waste. The research also found that the hydrocarbon emissions for steel and wood are high and it is due to protective paint coating. On the other hand, the particulate emissions of concrete are much higher. The major component that account for the highest environmental costs were the roof joists with 26-31% of energy, 28-57% of CO_2 and 20-56% of the air emissions index.

2 – Life cycle energy use in office buildings (Cole and Kernan, 1996):

This research was part of the Athena Institute project and funded by the Natural Resources Canada (NRCan), in which the authors have developed an Life Cycle Energy Assessment (LCEA) for a 4620m^2 three-storey office building comparing 2a – wood, 2b – steel and 2c – concrete structural systems in Vancouver and respectively 2d, 2e and 2f in Toronto, with and without underground parking. The objective was to identify the differences between initial embodied energy, also comparing total embodied to operational energy in order to understand the effects when decreasing the operational energy use.

The key categories evaluated in the LCEA were the energy to produce the building (including site work, structure, envelope and service systems, finishes and construction) using industry data, the recurring embodied energy (refurbishment and maintenance) available in Howard and Sutcliffe (1994) and operational energy (required for heating, cooling and ventilation, lighting and equipment) using the DOE-2.1D energy simulation program. Energy to demolish and dispose of the building were also considered, although, because of high complexity and uncertainties regarding its implication, the research used values found in U.S. Advisory Council on Historic Preservation (1981).

Table 3 - Summary results for LCEA of office buildings

Building type	Life Span/LCA Stages	Embodied Energy	LCEA
Units	years/stages	(GJ/m^2)	(GJ/m^2)
2a - wood frame with parking VA	50	10.86	63.36
2b - steel frame with parking VA	50	11.69	64.18
2c - concrete with parking VA	50	11.24	63.74
2a - wood frame no parking VA	50	10.58	58.54
2b - steel frame no parking VA	50	11.46	59.40
2c - concrete no parking VA	50	10.94	58.89
2d - wood frame with parking TO	50	10.86	98.91
2e - steel frame with parking TO	50	11.69	99.73
2f - concrete with parking TO	50	11.24	99.29
2d - wood frame no parking TO	50	10.58	92.39
2e - steel frame no parking TO	50	11.46	93.25
2f - concrete no parking TO	50	10.94	92.74

The study has shown that wood alternative has slightly lower impacts when compared to steel or concrete, and due to high energy use during steel production, the final impacts for steel were the highest, about 4-8%. The study also identified that envelope systems in this case represented the most significant proportion of energy compared to total embodied impact, between 26-30%. The embodied energy for main structural systems represented 20.3-28.9% with underground parking and 15.7-25.2% without underground parking. Furthermore, it was concluded that when buildings improve their energy efficiency decreasing the operational energy use over a 75 years span, the embodied energy impact becomes most significant.

3 – A comparative life-cycle assessment of steel and concrete framed office buildings (Amato and Eaton, 1997):

In this study funded by the British Steel (Now Corus) and the Department of the Environment, Construction Sponsorship Directorate, the authors have calculated the energy consumption and CO_2 emissions during the lice-cycle stages of the building, including building services operational impacts. The building is a four-storey office building with $2592m^2$ and analyzed over 60 year life span. Within the two structural options, 5 structural alternatives were analyzed: 3a – steel frame, slim floor beams with precast concrete slabs, 3b – steel frame, composite beams and composite slabs, 3c – in-situ reinforced concrete frame and slabs, 3d – steel frame, cellular beams with composite slabs and 3e – concrete frame, precast concrete hollow core units.

The study focused on various structural systems, envelope and heating, ventilating and air-conditioning (HVAC). It also considered in each option periodic refurbishment, replacements and improvements. Construction stage and demolition stage were not included because the impacts of these stages were considered insignificant compared to other stages. Transportation impacts were included from gate-to-construction site using average data for U.K. In the study it was also incorporated the recycling and reuse aspects of steel, in which the material embodied energy for steel is reduced. The figures used for U.K. industry are: 25.5GJ/tonne (primary steel), 17.3GJ/tonne (recycled steel) and 18.9GJ/tonne (multi cycle steel). The study also pointed that the main structural system (frame, foundation and floors) are in average 29% and 33.33% for embodied energy and embodied CO_2 emissions respectively. The remaining impacts are divided in building envelope, partitions, services and finishes.

Table 4 - Summary results for office building in UK

Building type	Life Span/LCA Stages	Embodied Energy	LCEA	Embodied CO_2	CO_2 Emissions
Units	years/stages	(GJ/m^2)	(GJ/m^2)	(kg eCO$_2$/m^2)	(kg eCO$_2$/m^2)
3a - steel frame/precast slabs	60	2.60	38.50	251.00	2,484.00
3b - steel frame/composite slabs	60	2.60	38.60	241.00	2,480.00
3c - in-situ reinforced concrete	60	2.50	38.40	286.00	2,520.00
3d - steel frame/cellular beams	60	2.90	38.90	259.00	2,499.00
3e - concrete frame, precast hollow	60	2.70	38.50	333.00	2,565.00

The study shows that the embodied energy for steel frames is higher than concrete frames about 7-14%, and the opposite when comparing CO_2 emissions about 10-28% lower than concrete. When the operational impacts are added, the embodied impacts are almost insignificant, therefore the differences between both systems are negligible. In regarding refurbishment of envelope systems, the study shows that the steel alternative provides more flexibility for major retrofit renovations, which can theoretically achieve negative energy consumption during operational life and consequently shift the focus to embodied impacts.

4 – LCA of concrete and steel building frames (Jönson, Björklund and Tillman, 1998):

The research was partially funded by the cement industry of Sweden, Norway and Finland, and involved the evaluation of environmental impacts of seven buildings with concrete and steel frames. In this report only the three office buildings will be presented. The study utilized the attributional LCA methodology and a functional unit of one average square metre of each building. The main objective was to describe the average situation and not to quantify the effects for potential improvement. The three buildings chosen were: 4a – in-situ cast concrete frame office, 4b – precast concrete frame office, 4c – steel/concrete frame office.

The study required the elaboration of LCI data for steel and concrete production, building site construction, service life, demolition and final disposal. Subjective issues such as accidental spills, personal-related effluents and human resources were not included in the analysis. The environmental impact indicators were assessed in three different Life Cycle

Impact Assessment (LCIA) tools in order to define direct impact of the buildings over a 50 year life span. The boundaries of study include the raw material extraction and use, building materials productions, building components fabrication, building site assembly construction, service life, demolition and final disposal.

Table 5 - Summary results for office buildings in Sweden

Building type	Life Span/LCA Stages	Embodied Energy	Embodied CO_2	Air Toxicity	Water Toxicity	Weighted Resource Use	Solid Waste
Units	years/stages	(GJ/m^2)	(kg eCO_2/m^2)	(volume unit/m^2)	(volume unit/m^2)	(kg/m^2)	(kg/m^2)
4a - in-situ cast concrete	cradle-to-gate	1.20	125.00	650.00	10.00	850.00	15.02
4b - precast concrete	cradle-to-gate	1.05	110.00	675.00	12.00	700.00	10.15
4c - steel and concrete slabs	cradle-to-gate	0.95	90.00	650.00	15.00	500.00	15.12

Results presented in Table 5 are an approximation of graphical values from the respective study and including only cradle-to-gate impacts. The study has shown that the major part of resource use is related to concrete frames with 25-41% higher than mixed steel concrete frame. Concrete frames also awarded higher CO_2 emissions about 18-28% and embodied energy about 10-21%. On the other hand, water toxicity and solid waste are higher for mixed steel and concrete frame building, about 20-33% and 1-33% respectively.

5 – Comparison of environmental effects of steel- and concrete-framed buildings (Guggemos and Horvath, 2005):

In this research, the authors have quantified the energy use and environmental emissions of 5a – concrete and 5b – steel framed building during the construction phase, and also included the overall impacts during the entire life-cycle of the buildings. The two buildings have 4,400m^2 and five-storey representing a typical office building in Midwestern US considering 50 years life span. They have concrete foundations, aluminum-framed glass panel curtain walls and built-up roofing. It included interior finishes as painted partition walls, acoustical drop ceilings and carpet or ceramic tile flooring. Building services included were mechanical system providing heating and cooling.

In this study two LCA methods were used, the process-based LCA and the economic input-output analysis-based LCA (EIO-LCA). To assess the environmental impacts during construction phase, Guggemos developed and used the Construction Environmental Decision Support Tool (CEDST). Process data were used for maintenance and demolition phases. In this study were also included supply-chain environmental effects associated to direct material and energy use and emissions. The boundaries of study included materials extraction and manufacturing, through and process detailed building construction, building use, building maintenance and end-of-life. The benefit of recycling steel and concrete were applied, and on average were 25% scrap steel and 10% crushed concrete.

Table 6 - Summary of LCI applied to steel and concrete frame buildings

	Energy (10 TJ)	CO_2 (Gg)	CO (Mg)	NO_x (Mg)	PM_{10} (Mg)	SO_2 (Mg)
Steel-frame building	36	26	38	72	9	100
Concrete-frame building	36	26	34	76	9	98

Table 7 - Summary results for office buildings in US

Building type	Life Span/LCA Stages	Embodied Energy	LCEA	Embodied CO_2	CO_2 Emissions
Units	years/stages	(GJ/m^2)	(GJ/m^2)	($kg\ eCO_2/m^2$)	($kg\ eCO_2/m^2$)
5a - concrete frame	50	8.30	81.82	550.00	5,909.09
5b - steel frame	50	9.50	81.82	620.00	5,909.09

Results presented in Table 7 are an approximation of graphical values from the respective study and including cradle-to-gate and operational impacts. During the construction phase, the study has shown that concrete has higher energy use, CO_2, CO, NO_2, particulate matter smaller than 10μm (PM_{10}), SO_2 and hydro-carbon (HC) emissions due to temporary materials use, more transportation and longer installation process. Considering the steel frame, it has higher volatile organic compound (VOC) and heavy metal (Cr, Ni, Mn) emissions due to paint, torch cutting and welding. Once again, when the operational impacts are considered in the overall life-cycle of the buildings, the environmental impact difference becomes insignificant. Therefore, when the authors subtracted operational impacts, it has shown that steel components accounted for higher energy and CO_2 emissions, about 12.5% and 11% respectively, because of high energy use in steel production.

3.1.2. Residential buildings

As this report focuses in commercial buildings, the following papers are only a summary of major concerns regarding the residential case studies looking into structural alternatives. Both papers used the Athena Environmental Impact Evaluation (EIE), LCA tool that was developed with Life Cycle Inventories (LCI) for the North American construction industry context.

6 – Building life cycle assessment: residential case study (Trusty and Meil, 1999):

The Athena Institute was commissioned by the Canadian Wood Council (CWC) to investigate initial environmental impacts (from cradle-to-gate and on-site construction) of three alternate structural systems of a custom 223m^2 single-family home built in Toronto. The three alternatives are: 6a – softwood lumber and engineered wood I-joist framing, 6b – light frame steel and 6c – insulated concrete forms (ICF) for basement and exterior walls and a HAMBRO floor system. Because the concrete structural design is not included in the Athena Environmental Impact Evaluation (EIE) tool, the study require complete LCI profiles for all six key measures evaluated, initial embodied energy, ecologically weighted raw resource use, greenhouse gas emissions, and other emissions to air and water and soil wastes. The functional unit of the study was the whole-building in order to achieve true equivalence between all alternatives. The results are presented in Table 8.

7 – Life cycle environmental performance of renewable building materials in the context of residential construction (CORRIM, 2004):

In this research, the Consortium for Research on Renewable Industrial Materials (CORRIM) has developed a large life cycle inventory (LCI) database for wood products, partially funded by the USFS Forest Products Laboratory. In conjunction to Athena Institute, the LCI data was included in the Athena EIE tool in order to improve the data quality of the LCA tool for the North American context. With the new LCI data for wood, the Athena Institute carried out an investigation using the EIE tool to analyze two different buildings (from cradle-to-gate plus construction phase): a single-family detached house with 200m^2 no basement in warn climate of Atlanta using 7a – a wood structure and 7b – a concrete structure; and a different 192m^2 single-family detached house with basement in cold climate of Minneapolis using 7c – a wood structure and 7d – a steel structure. The results are presented in Table 8.

The results suggested that 6a (timber option) scored the lowest environmental impacts for all the six measures besides solid waste production which was slightly higher than 6b. 6c scored the highest environmental impacts in all cases other than water toxicity. The results also showed that the wood alternative has considerably lower impacts in both cases considering all the index measures with two exceptions. It was detected that the 7d (steel) has lower solid waste production, and that there was no significant difference in the water pollution index between 7a (timber option) and 7b (concrete option).

Table 8 - Summary results for residential buildings in North America

Building type	Life Span/LCA Stages	Embodied Energy	Embodied CO_2	Air Toxicity	Water Toxicity	Weighted Resource Use	Solid Waste
Units	years/stages	(GJ/m^2)	(kg eCO$_2$/m^2)	(volume unit/m^2)	(volume unit/m^2)	(kg/m^2)	(kg/m^2)
6a - wood frame	cradle-to-gate + construction	1.09	278.85	14.51	1,828.64	546.21	48.19
6b - steel frame	cradle-to-gate + construction	1.67	342.84	25.24	6,339.84	621.08	39.90
6c - concrete frame	cradle-to-gate + construction	2.52	419.61	31.26	3,929.10	1,053.79	63.03
7a - Atlanta wood frame	cradle-to-gate + construction	1.99	106.84	24.47	0.04	not provided	37.21
7b - Atlanta concrete frame	cradle-to-gate + construction	2.31	140.02	30.04	0.04	not provided	56.35
7c - Minneapolis wood frame	cradle-to-gate + construction	3.39	192.95	44.61	0.09	not provided	71.70
7d - Minneapolis steel frame	cradle-to-gate + construction	3.98	243.89	50.67	0.36	not provided	71.05

3.2. Analysis of results for the commercial buildings

Before presenting the comparison of the results, it is important to stress the complexity of this task due to the different methodologies, assumptions, tools and LCI data used for each study. These differences can be identified in the figures and table below. Since the results of each study encompass different environmental impacts, in this research only those impacts possible to be grouped to the same indicator were collected and presented. The impacts were: embodied energy, total energy consumption, embodied CO_2 and total CO_2 emissions. Other impacts such as water and air toxicity, resource use and solid waste production are more complicated to group, and not all the presented case studies evaluated those impacts. For this comparison all the results were grouped using the functional unit of one square metre ($1m^2$) of floor area of the building.

Most of the cases presented in Figure 7 and Table 9 the steel frame structure appears to have the highest embodied energy consumption from cradle-to-gate (i.e. from raw material extraction to fabrication of components). However, when the analysis of the energy consumption incorporates the operational life cycle stage of a building (a Life Cycle Energy Assessment – LCEA), the results in every case study for the various alternatives become equivalent (see Figure 8). This happens because the operational life cycle has the biggest percentage of the total environmental impacts when compared to embodied impacts.

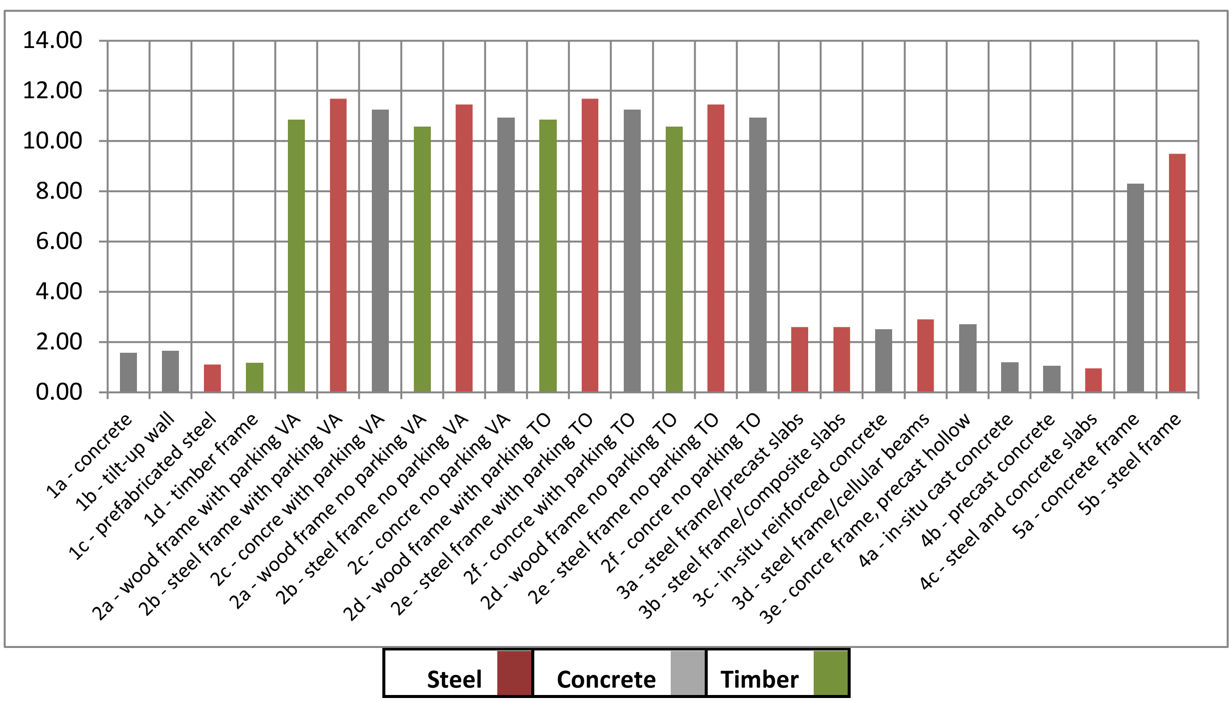


Figure 7 - Embodied energy (GJ/m2) comparison for commercial buildings

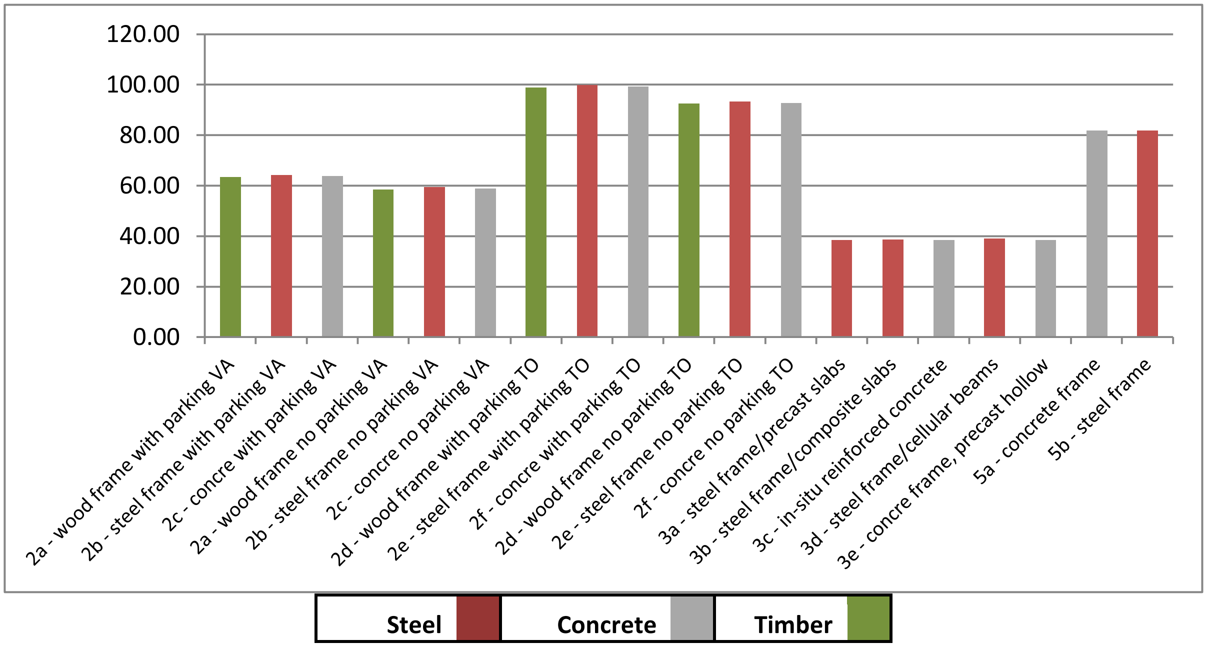


Figure 8 - LCEA (GJ/m2) comparison for commercial buildings

Embodied CO_2 emissions are the best example to illustrate the differences of results found for each case study and the complexity of comparing absolute values as can be seen in Table 9 and Figure 9. Nevertheless, the results points that steel has lower CO_2 emissions for all studies with exception from the timber frame on 1d case and the concrete on the 5a case. The authors for the US office buildings, 5a concrete and 5b steel, found much higher CO_2 emissions for steel because of intensive energy use from fossil fuel during production stage.

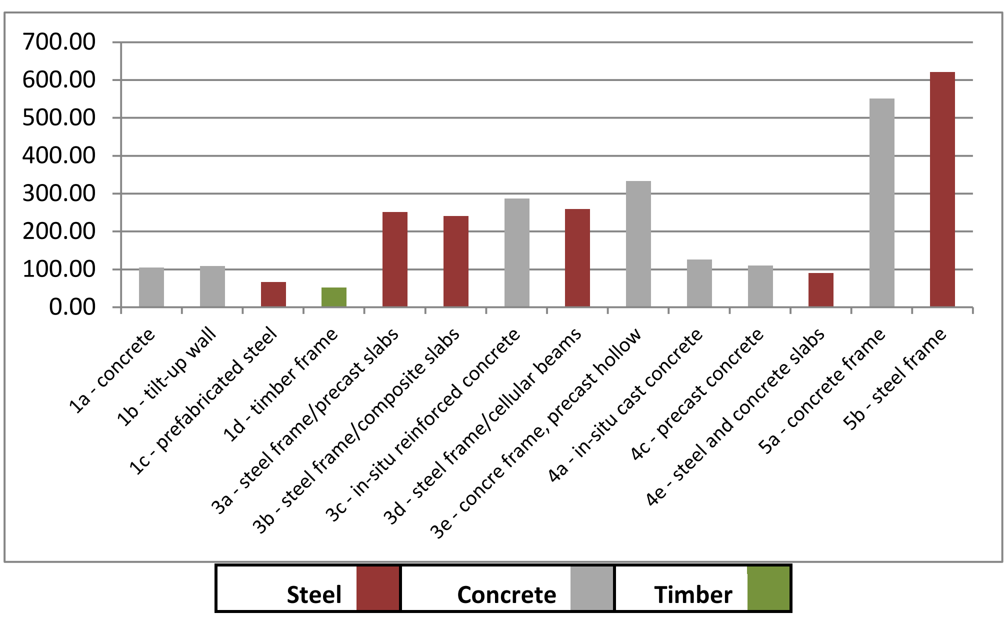


Figure 9 - Embodied CO2 (kg eCO2/m2) emissions for commercial buildings

Table 9 - Summary results of commercial buildings case studies

Case	Building Characteristics				Life cycle span	Embodied PEC	Total PEC	Embodied GWP	Total GWP
Units	Size (m^2)	No. of storeys	Main Structure Type	Location	years cycles	GJ/m^2	GJ/m^2	kg eCO_2/m^2	kg eCO_2/m^2
1a	3,240	Typical Warehouse 1 storey	concrete	Vancouver, Canada	cradle to gate	1.57	not provided	103.80	not provided
1b			tilt-up wall			1.65		108.60	
1c			prefabricated steel			1.10		66.50	
1d			timber			1.17		51.10	
2a	4,620	3	timber	Vancouver, Canada	50	10.58	58.54	not provided	not provided
2b			steel			11.46	59.40		
2c			concrete			10.94	58.89		
2d			timber	Toronto, Canada		10.58	92.39		
2e			steel			11.46	93.25		
2f			concrete			10.94	92.74		
3a	2,592	4	steel frame/precast slabs	UK	60	2.60	38.50	251.00	2,484.00
3b			steel frame/composite slabs			2.60	38.60	241.00	2,480.00
3c			in-situ reinforced concrete			2.50	38.40	286.00	2,520.00
3d			steel frame/cellular beams			2.90	38.90	259.00	2,499.00
3e			concrete frame, precast hollow			2.70	38.50	333.00	2,565.00
4a	not provid ed	not provided	in-situ cast concrete	Sweden	cradle to gate	1.20	not provided	125.00	not provided
4b			precast concrete			1.05		110.00	
4c			steel and concrete slabs			0.95		90.00	
5a	4,400	5	concrete	Midwestern US	50	8.30	81.82	550.00	5,909.09
5b			steel			9.50	81.82	620.00	5,909.09

3.3. Discussion on literature review

There is a consensus from all the case studies about the importance of comparing the operational impacts over embodied impacts. This is due to the high impacts generated during operational life cycle. However, as the construction industry focuses on decreasing the environmental impacts in operation, the embodied impacts become a much more significant portion of the overall impacts. Although end-of-life accounts for very little impacts compared to the entire life of a building, further development considering the waste management and current technologies to reuse and recycle, especially for steel components and materials, can decrease environmental impacts. In the steel case, it is extremely important to address recycled content during production stage, which is not well considered or even neglected in some studies. It is also during the operational life cycle stage that refurbishment occurs and it is important to calculate its impacts especially for commercial buildings studies. Although frame structures last the entire life-span of a building, each structure requires different integrated materials, such as protective coatings for steel and timber. Moreover, it was also pointed the importance to analyze the mechanical systems and its flexibility of application for the different structural alternatives. Therefore, to reach a consistent and valid functional unit, these complementary materials must be accounted for with each structural alternative.

Another important consideration is the evaluation of different environmental impact indicators in order to better portray the environmental impact of each structural system. As an example, if the analysis shows only GWP, the overall result can be misleading. However, improved LCA analysis with a variety of environmental impact indicators makes the research more complicated due to availability of data and consequently the assumptions required to generate results. When alternatives are presented using the same material, in the case studies the precast concrete compared to in-situ cast concrete, LCA can suggest which life cycle stage accounts for the highest environmental impact and identify trade-offs of different components.

4. Research methodology and limitations

For this study, four different methods were used to calculate the LCA of an office building using a steel frame, and an alternative using a concrete frame structure. These alternative methods are listed in Table 10 and described in detail below. In addition, to develop a better evaluation of the building alternatives, two modeling subtypes were used: (a) whole building, and (b) structure only models. Whole building analysis consists of building envelope, structural system and interior partitions, while structural models evaluate above and below ground structural systems only (including fire protection for steel components).

Table 10 - LCA models for steel and concrete buildings

Model	LCA models	Steel	Concrete
1	Athena Eco-Calculator (EC)	a - whole building model	a - whole building model
2	Athena EIE software using the predefined assembly dialogs (EIE by assemblies)	a - whole building b - structural models	a - whole building b - structural models
3	Athena EIE using material weights and volume (EIE by quantities)	a - whole building b - structural models	a - whole building b - structural models
4	GaBi + Athena EIE software using World Steel Association and Athena data	a - whole building b - structural models	n/a

Model 1 – Athena Eco-Calculator

For comparison purposes, the web-based Athena Eco Calculatior (EC) tool (see section 2.2.2) was used to model the building. The Athena EC's version that best suited this research was the EC high-rise commercial buildings in Toronto. According to EC models, the respective assembly categories areas are shown in Table 11. These values are reference to all areas used to develop the model as calculated by the software. The differences in results presented later are based on the different structural system used for columns, beams, intermediate floors and roof structure that vary for the steel and concrete buildings (see section 5).

Table 11 - Assembly categories areas from Eco-Calculator

ASSEMBLY	Total area (m^2)
Foundations & Footings	1,499
Columns & Beams	8,740
Intermediate Floors	7,314
Exterior Walls	1,174
Windows	2,272
Interior Walls	3,824 (steel) 2,595 (concrete)
Roof	1,426

Models 2 & 3 – Athena EIE by assemblies and by quantities

This research was developed using Athena EIE 2009 software version. Alternative Athena EIE models were developed using the two methodologies described in section 2.2.1: first using the predefined assembly dialogs within the program (Model 2 in Table 11 – EIE by assemblies), and second using a materials take-off list (Model 3 – EIE by quantities). Since the focus of interest was the structural materials, the "by quantities" models were developed using hand calculated values for structural materials and Athena EIE's bill of materials quantity list for other materials. For the "by assemblies" method the software automatically accounts for material losses during construction (see Table 12 for waste ratio values of each material). Thus for the "by quantities" method, the waste ratio was applied to the appropriate materials input values used in the model in order to be consistent and account for the likely materials wastage for both models. Furthermore, structural materials weights were hand-calculated in order to assess how accurately the Athena EIE software represents steel and concrete structures using its predefined assembly dialogs. Model 3 (Athena EIE by quantities) are considered the most accurate in this research, therefore these will be used as base results to compare to other model results as shown in Section 6 and beyond.

Table 12 - Waste ratio materials list from Athena EIE LCA tool

CONCRETE	Unit	Waste Ratio
Concrete materials	m^3	95.24%
STEEL	Unit	Ratio
Galvanized Decking	Tonnes	99.01%
Galvanized Sheet	Tonnes	99.01%
Galvanized Studs	Tonnes	99.01%
Hollow Structural Steel	Tonnes	99.01%
Nails	Tonnes	97.09%
Open Web Joists	Tonnes	99.01%
Rebar, Rod, Light Sections	Tonnes	99.01%
Screws Nuts & Bolts	Tonnes	97.09%
Welded Wire Mesh / Ladder Wire	Tonnes	98.04%
Wide Flange Sections	Tonnes	99.01%
GYPSUM BOARD	Unit	Ratio
Gypsum board materials	m^2	90.91%
Joint Compound	Tonnes	93.46%
Paper Tape	Tonnes	95.24%
INSULATION	Unit	Ratio
Batt. Fiberglass	m^2 (25mm)	95.24%
Expanded Polystyrene	m^2 (25mm)	95.24%
Extruded Polystyrene	m^2 (25mm)	95.24%

ROOFING	Unit	Ratio
EPDM membrane (black, 60 mil)	kg	97.09%
Modified Bitumen membrane	kg	97.09%
OTHER	Unit	Ratio
Aluminum	Tonnes	100.00%
Glazing Panel	Tonnes	100.00%
Water Based Latex Paint	L	98.04%

Model 4 – GaBi + Athena EIE with WSA steel data

A major limitation with the LCA research presented here is the LCI data used for the input materials. The Athena Institute has developed a large LCI database for the construction materials in North America, including data collected from manufacturers in Canada and the EPA LCI databases for US. Although Athena's databases are well recognized, they are approximately 10 years old for steel and concrete products. Therefore, to provide a comparison to the Athena steel data, the World Steel Association (WSA) was contacted to provide more up to date LCI data for steel products. WSA has developed the most recent and recognised LCI database for the steel industry. Their LCI allocation methodology is considered the most advanced in order to best define steel products into LCA studies (FWI, 2007). Although the WSA's LCI database for iron and steel products are a good source for LCA studies, the database is still in development, therefore WSA was not able to provide regionalized, North American LCI data for this research. The data provided by WSA is the world average cradle-to-gate LCI data for steel products (including recycling) used in construction. The WSA LCI data for those materials were developed including an end of life recycling rate of 85%. Their recycling methodology takes into consideration the steel scrap that is recycled from a product at the end of life and the steel scrap that goes into the steel making process. The LCI data included:

- hot rolled coil
- electro galvanized steel
- hot dip galvanized steel
- organic coated steel
- steel plates
- steel rebars
- steel sections
- steel pipes

This LCI data was used to model the impact of the steel using GaBi LCA software (see section 2.2.3). Results were collected using US EPA's TRACI's methodology (EPA, n.d.) in order to reach consistency between Athena and GaBi models. These results were then integrated with the Athena EIE data for other materials and results to provide an alternative LCA model based on WSA steel data. GaBi results replaced the results for cradle-to-gate steel products within Athena EIE model by quantities. All other life cycle phases were modeled with Athena EIE.

5. Characterization of the buildings' design

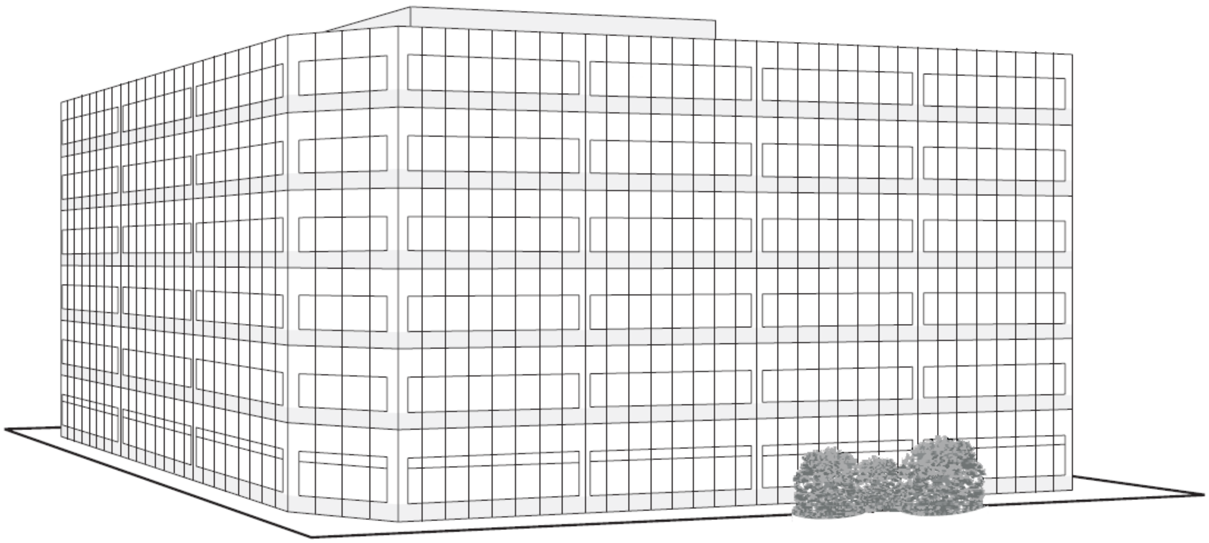


Figure 10 - Steel building 3d model (CISC, 2009)

The Canadian Institute of Steel Construction (CISC) provided the steel structure building design and the Department of Architectural Science at Ryerson University developed an equivalent concrete structure building design. In order to ensure a consistent functional unit, both buildings were designed following the same characteristics as follows:

- Building location: Toronto, Ontario, Canada.
- Height: 26.2m with 6 storeys + penthouse (lower roof + upper roof).
- Built area: 1426m^2 ground floor plan and 8740m^2 total area.
- Foundation: 100mm concrete slab on grade + footings (footings vary for each building design).
- Envelope - curtain-wall: curtain-wall designed with 70% glazing area and 30% insulated metal spandrel area (100mm batt insulation).
- Envelope - roofing: conventional built-up roof including 2 ply standard modified bitumen and 200mm expanded polystyrene insulation.
- Interior walls and finishes: each floor has a total of 150 linear metres of wall with 2x4 steel studs, ½" gypsum board, painted.

When modeling the building using EIE by assemblies (Model 2), the software provided its automatic bill of materials take-off list which is shown in Table 13 for the common elements (excluding foundation and structural materials). The values on the list were used as input data to develop the EIE models by quantities (Model 3) applying the waste ratio values from Table 5.

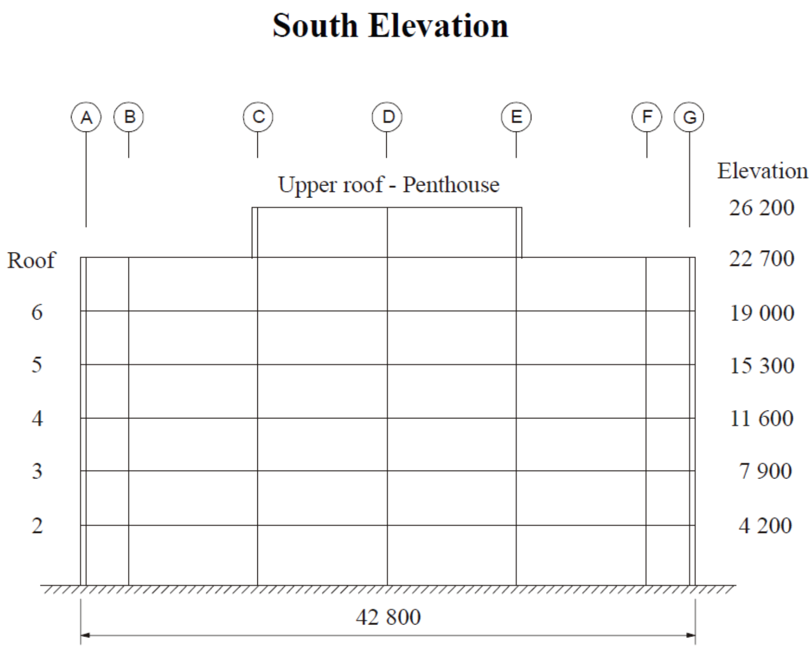


Figure 11 - Steel building, south elevation (CISC, 2009)

Table 13 - Bill of materials take-off list from EIE models by assemblies

EIE by assemblies take-off list for non-structural materials		
Curtain wall	Quantity	Unit
Aluminum	47.328	Tonnes
Batt. Fiberglass	9706.5471	m^2 (25mm)
EPDM membrane (black, 60 mil)	567.9504	kg
Galvanized Sheet	7.9909	Tonnes
Glazing Panel	83.1649	Tonnes
Roofing	Quantity	Unit
Expanded Polystyrene	11318.966	m^2 (25mm)
Modified Bitumen membrane	12248.636	kg
Interior walls and finishing	Quantity	Unit
1/2" Fire-Rated Type X Gyp. Board	11705.62	m^2
1/2" Regular Gypsum Board	5709	m^2
Galvanized Studs	11.6861	Tonnes
Joint Compound	17.3821	Tonnes
Nails	0.2488	Tonnes
Paper Tape	0.1994	Tonnes
Water Based Latex Paint	1873.1799	L
Foundation insulation	Quantity	Unit
Extruded Polystyrene	118.9928	m^2 (25mm)

The only variation to the buildings' design was the structural systems, namely for columns and beams, floor slabs/decks, roof slabs/decks and footings. In order to achieve a valid functional unit, fire protection was added for steel structures (columns, beams and decks). The following is a description of the buildings' design including modeling input data and modeling limitations. For more details on the buildings description refer to Appendix B.

5.1. Steel building design

According to the design provided by the Canadian Institute of Steel Construction (CISC), the floor plan consists mostly of 9m x 9m and 9m x 12m bays, with the central service core at the center of the building (Figure 12). The non-composite floor system consists of a composite steel deck with concrete topping supported by wide-flange girders, beams and open-web steel joists (OWSJ). The beams are supported by wide-flange columns and the central core columns bays are braced by hollow sections. The structural components of the roof system consists of steel deck (without concrete topping), supported mainly by 9m long OWSJs and 12m long girders. This steel building structural design is appropriate for Toronto conditions, and was developed to provide resistance against strong winds and to withstand earthquakes.

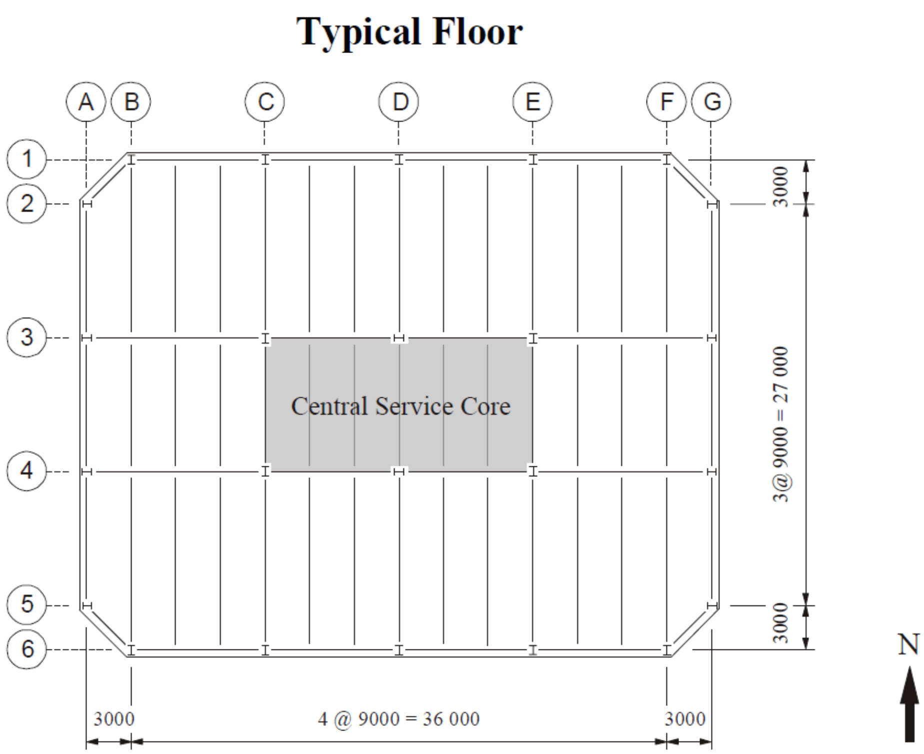


Figure 12 - Steel building, typical floor plan (CISC, 2009)

Table 14 – Steel design above grade structural materials take-off list from EIE by assemblies (Model 2) and hand calculated variation for EIE by quantities (Model 3)

	EIE by assemblies (Model 2) material list for above grade structural materials (provided by EIE)			EIE by quantities (Model 3) take-off list (hand calculated)		Ratio of EIE by assemblies over EIE by quantities
Material	Unit	Quantity	per area	TOTAL	per area	
Concrete 20 MPa (flyash av 9%)	m^3	655.30	0.09	730.48	0.10	90%
Galvanized Decks	Tonnes	83.92	0.01	95.42	0.01	88%
OWSJs	Tonnes	62.77	0.01	53.05	0.01	118%
Rebar, Rod, Light Sections	Tonnes	6.41	0.00	10.15	0.00	63%
Screws Nuts & Bolts	Tonnes	21.82	0.00	21.82	0.00	n/a
Wide Flange Sections	Tonnes	385.39	0.05	248.47	0.03	155%
HSSs	Tonnes	n/a	n/a	8.82	n/a	n/a
TOTAL STEEL	Tonnes	560.31	0.07	437.73	0.05	128%

Notes:
The values presented for EIE by quantities did not include the waste ratio included on values from EIE by assemblies.
Detailed table including the different types of materials (decking, OWSJs, WF sections and HSSs can be found on Appendix B.

The Table 14 represents values for the above grade structural materials from the EIE model by assemblies (on the left side) and input data to the EIE model by quantities (on the right side). As mentioned previously, structural materials were hand-calculated in order to assess how accurately the Athena EIE software represents steel and concrete structures using its predefined assembly dialogs. The right most column of Table 7 shows how well EIE by assemblies estimated the materials quantities compared to the hand calculations. Values below 100% indicate where EIE has underestimated the amount of material, and values above 100% suggest that EIE has allowed for too much of the respective material. The values suggest that Athena EIE underestimated the mass of steel decking and rebar, but significantly overestimated the amount of steel required for wide flange (WF) sections. The value for WF sections used by EIE when using its predefined dialogs is nearly double the value when calculated by hand using the actual steel sizes. Since WF sections are approximately 50% of the total weight of steel in the building, this difference means that the EIE software overestimated the steel structure by approximately 28%, which has a significant impact on the overall results.

Table 15 - Steel building above grade by quantities (Model 3) specification and EIE by assemblies (Model 2) assumptions

ASSEMBLY CATEGORY Non-composite Steel Building	Components / Location	Material	Athena EIE by quantities (Model 3) design specifications	Athena EIE by assemblies (Model 2) software assumptions
Columns	inner columns 4.8KPa (central services)	wide flange	W310x179 from 1st to 3rd floor W310x86 from 4th to 6th floor W250x49 at penthouse	WF columns of 41kg/m
	outer columns 2.4KPa	wide flange	W310x129 from 1st to 3rd floor W310x74 from 4th to 6th floor	WF columns of 26kg/m
	braces	hollow structural steel	HSS203x203x6.4 at 1st and 2nd floors HSS152x152x6.4 at 3rd and 4th floors HSS152x152x4.8 at 5th and 6th floors HSS102x102x3.2 at penthouse	there is no option to add braces (braces can be added as extra material by weight as in Model 3 by quantities which defeats the purpose to use assemblies option, therefore not included)
Beams	floor	open-web steel joists	750mm x 12m long 25.3kg/m @ 3m o.c.	OWSJs of 7.41kg/m @ 1.2m o.c.
		girders	W610x113 x 9m long (perimeter) W760x147 x 9m long W760x173 x 12m long	WF beams of 205kg/m
		other beams	W410x46 x 9m long W360x45 x 9m long W360x33 x 9m long (5th floor)	WF beams of 206kg/m for central core structure and WF beams of 141kg/m for other spaces
	roof	open-web steel joists	700mm x 9m long 14.7kg/m @ 1.2m o.c. average	OWSJs of 6.13kg/m @ 1.2m o.c.
		girders	W760x147 x 12m long	WF beams of 205kg/m
		other beams	W410x46 x 9m long W360x33 x 9m long	WF beams of 141kg/m
Intermediate Floors structure	floor	galvanized decking	Canam P2532 composite 20 gauge (0.91mm) 76mm deep 11.5kg/m^2 of steel deck	22 gauge (0.76mm) 39mm deep 9.9kg/m^2 of steel deck
		concrete topping	103mm poured concrete topping*	89mm poured concrete topping*
		rebar	152x152mm MW 11.1x11.1 with 2 layers above girders 1.13kg/m^2 of rebar	150x150mm #10 steel mesh single layer all floor 0.9kg/m^2 of rebar
Roof structure	roof	galvanized decking	20 gauge (0.91mm) 38mm deep 10kg/m^2 of steel deck	22 gauge (0.76mm) 39mm deep 9.9kg/m^2 of steel deck

Notes:
The specified live loads of the design are 2.4KPa for office space and 4.8KPa for central core services area.
The weights for steel structural materials from Athena assembly dialogs were collected by a series of test analysis and averaged for the steel design.
The assumed weights for steel beams from Athena assembly dialogs vary if bay and span values are changed.
Athena EIE considers the depth of the decking to calculate the concrete topping thickness. The real thickness of the concrete topping for the steel design (Model 3 by quantities) is 65mm.
Athena Eco-Calculator software uses assumptions from Athena EIE.

The major differences in material quantities shown in Table 14 are described in Table 15 which includes Athena EIE's assumptions for above grade steel structural products. The Athena EIE by quantities column in Table 15 shows the exact steel building design specifications which were hand-calculated to develop the model by quantities. The Athena EIE by assemblies column on the other hand shows all assumptions from the main assembly dialogs in the EIE software related to the specific steel building design of the research.

Table 16 – Final materials take-off list for steel building models by quantities (Model 3)

MATERIALS	Unit	EIE model by quantities Whole building	EIE model by quantities Structural
Concrete 20 MPa (flyash av)	m^3	902.12	902.12
Concrete 30 MPa (flyash av)	m^3	132.02	132.02
Galvanized Decking	Tonnes	95.42	95.42
Galvanized Sheet	Tonnes	7.91	0
Galvanized Studs	Tonnes	11.57	3.74
Hollow Structural Steel	Tonnes	8.82	8.82
Nails	Tonnes	0.24	0.11
Open Web Joists	Tonnes	53.05	53.05
Rebar, Rod, Light Sections	Tonnes	12.76	12.76
Screws Nuts & Bolts	Tonnes	21.19	21.19
Welded Wire Mesh / Ladder Wire	Tonnes	1.26	1.26
Wide Flange Sections	Tonnes	248.47	248.47
1/2" Fire-Rated Type X Gypsum Board	m^2	10,641.47	10,641.47
1/2" Regular Gypsum Board	m^2	5,190	0
Joint Compound	Tonnes	16.24	10.92
Paper Tape	Tonnes	0.19	0.13
Batt. Fiberglass	m^2 (25mm)	9,244.33	0
Expanded Polystyrene	m^2 (25mm)	10,779.97	0
Extruded Polystyrene	m^2 (25mm)	113.33	0
EPDM membrane (black, 60 mil)	kg	551.41	0
Modified Bitumen membrane	kg	11,891.88	0
Aluminum	Tonnes	47.33	0
Glazing Panel	Tonnes	83.16	0
Water Based Latex Paint	L	1,836.45	1,234.41
Note: Values for concrete volume and rebar differ from Table 7 because in this table it includes foundation materials. Table 7 refers to above grade structural materials.			

Table 16 shows the final take-off materials list used to develop the EIE models by quantities for the steel building: values on the left for the whole building model and values on the right for the structure only. Note that the boxes highlighted relate to structure and so were hand-calculated, others were taken from EIE. The values on the structural model column that are 0 or less than the value for the whole building model refers to non-structural materials. The only non-structural materials included on structural model are those included in fire rated protection walls for columns, beams, steel decks and central core services.

5.1.1. Steel building composite floor system for sensitivity analysis

In order to provide a sensitivity analysis of the results presented in section 6.1. (Steel building models comparison), the structural steel building (Model 3 by quantities) was modified to account for 10% and 20% less steel weight. The Department of Architectural Science at Ryerson University adapted the steel building design provided by the CISC with a composite floor system. The new design has shown a decrease in 10% of the total weight of steel for the structural building (detailed description of the steel building with composite floor system can be found on Appendix B). In addition a model was created to assess the potential benefit of a steel design with 20% reduction in steel weight. Table 17 shows a comparison of the materials take-off list (Model 3 EIE by quantities structural building) for the original non-composite floor system, a composite floor system with 10% less steel and a speculative composite floor system with 20% less steel.

Table 17 - Comparison of the above grade structural materials take-off list quantities (Model 3 structural building materials) for the non-composite and composite floor systems

Model 3 – EIE by quantities Above grade structural steel building sensitivity analysis		EIE by quantities take-off list for non-composite system		EIE by quantities take-off list for composite system (10% less steel)		Ratio of non-composite floor system over "10% less steel sensitivity"	EIE by quantities take-off list for 20% less steel		Ratio of non-composite floor system over "20% less steel sensitivity"
Material	Unit	TOTAL	per area	TOTAL	per area		TOTAL	per area	
Concrete 20 MPa (flyash av 9%)	m^3	730.48	0.10	730.48	0.10	100%	730.48	0.10	100%
Galvanized Decks	Tonnes	95.42	0.01	95.42	0.01	100%	95.42	0.01	100%
OWSJs	Tonnes	53.05	0.01	53.05	0.01	100%	44.31	0.01	84%
Rebar, Rod, Light Sections	Tonnes	10.15	0.00	13.58	0.00	134%	15.23	0.00	150%
Screws Nuts & Bolts	Tonnes	21.82	0.00	21.82	0.00	100%	21.82	0.00	100%
Wide Flange Sections	Tonnes	248.47	0.03	199.39	0.02	80%	166.55	0.02	67%
HSSs	Tonnes	8.82	0.01	8.82	0.01	100%	8.82	0.01	100%
TOTAL STEEL (per total area)	Tonnes	437.73	0.05	394.37	0.05	90%	352.15	0.04	80%

It was found that the composite floor system design has 20% less weight for wide flange sections and 34% more weight of rebar (which also includes the studs for composite floor systems reinforcement). The speculative composite floor system with 20% less steel was defined by increasing the rebar weight by 50% and decreasing not only the wide flanges weight (by 33%) but also decreasing the open-web steel joists weight (by 16%).

5.2. Concrete building design

The concrete building has a similar layout to the steel building, and consists of reinforced concrete columns, suspended slabs and drop-down panels. Using the EIE software to model suspended concrete slabs by assemblies, it was found that the software assumes the slab as two way spanning suspended concrete slabs. Therefore, the steel building structural grid design could not be used for the concrete building as the steel building structural grid is not appropriate for a concrete building design. Consequently, the floor plan grid was modified to 7.5m x 9m and 9m x 9m mostly, which increased the number of columns of the design.

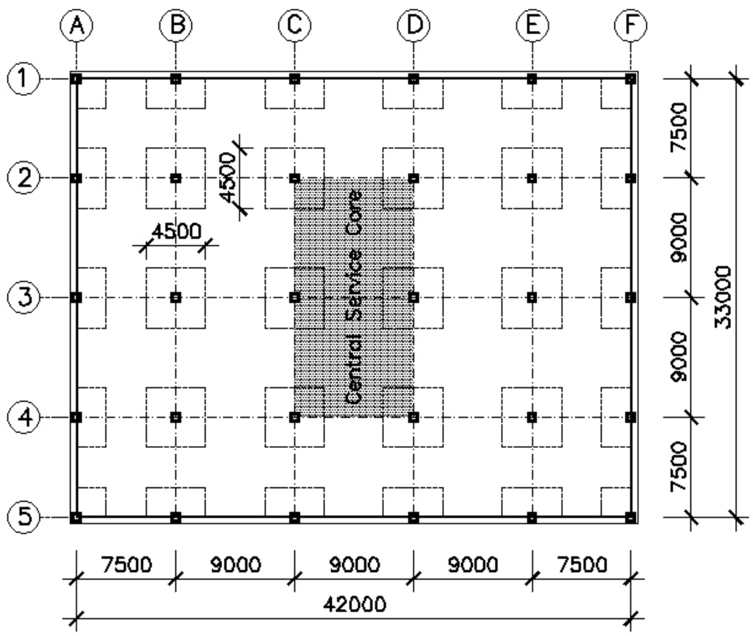


Figure 13 - Typical floor plan for the concrete building

Table 18 represents values for the above grade structural materials from the EIE model by assemblies and input data for the EIE model by quantities for the concrete building models. As with Table 14, the proportion values (right column) below 100% indicate where EIE has underestimated the amount of material, and values above 100% suggest that EIE has allowed for too much material. The values in this case suggests that the Athena EIE software significantly overestimated the volume of concrete and rebar weight for columns by 110% and 29% respectively. However, this has a relatively small impact on overall material use, and when the total volume of concrete and rebar weight are added the results imply that Athena EIE dialogs represented the concrete building design more accurately compared to steel building.

Table 18 – Concrete design above grade materials take-off list from EIE by assemblies (Model 2) and hand calculated variation for EIE by quantities (Model 3)

	EIE by assemblies (Model 2) material list for above grade structural materials (provided by EIE)		EIE by quantities (Model 3) take-off list (hand calculated)			Ratio of EIE by assemblies over EIE by quantities
Material	Quantity	Unit			TOTAL	
Concrete 20 MPa (flyash av) (roof)	380.5884	m^3	220 mm	1791m^2	394.02	97%
Concrete 30 MPa (flyash av) (slabs)	1973.738	m^3	220 mm	9158m^2	2014.76	98%
Concrete 30 MPa (flyash av) (columns)	418.8811	m^3	30 columns	6.64m^3	199.14	210%
Rebar, Rod, Light Sections (roof)	19.2999	Tonnes	11.83kg/m^2	1791m^2	21.19	91%
Rebar, Rod, Light Sections (slabs)	102.203	Tonnes	16.9kg/m^2 11.83kg/m^2	3848m^2 5310m^2	127.83	80%
Rebar, Rod, Light Sections (columns)	199.6996	Tonnes	221kg/m	702m	155.14	129%
Screws Nuts & Bolts	1.9569	Tonnes	n/a	n/a	1.9569	n/a
TOTAL CONCRETE	2773.207	Tonnes	n/a	n/a	2607.92	106%
TOTAL STEEL	323.1594	Tonnes	n/a	n/a	306.1169	106%
Notes: The values presented for EIE by quantities did not include the waste ratio included on values from EIE by assemblies.						

Table 19 - Concrete building above grade by quantities (Model 3) specification and EIE by assemblies (Model 2) assumptions

ASSEMBLY CATEGORY Concrete Building	Components / Location	Material	Athena EIE by quantities (Model 3) design specifications	Athena EIE by assemblies (Model 2) software assumptions
Columns	inner columns 9x9m grid with 2.4KPa and 4.8KPa (central services)	concrete	30MPa concrete average flyash (9%) 532x532mm columns	30MPa concrete average flyash (9%) 836x836mm columns and 856x856mm columns (central services)
		rebar	reinforcement included @ 221kg/m column	reinforcement included @ 334kg/m column and 346kg/m column (central services)
	outer columns 7.5x7.5m grid and 9x7.5m grid	concrete	30MPa concrete average flyash (9%) 532x532mm columns	30MPa concrete average flyash (9%) 673x673mm columns (7.5x7.5m grid) 752x752mm columns (9x7.5m grid)
	outer columns 7.5x7.5m grid and 9x7.5m grid	rebar	reinforcement included @ 221kg/m column	reinforcement included @ 217kg/m column (7.5x7.5m grid) and 270kg/m column (9x7.5m grid)

Table 20 cont.				
ASSEMBLY CATEGORY Concrete Building	**Components / Location**	**Material**	**Athena EIE by quantities (Model 3) design specifications**	**Athena EIE by assemblies (Model 2) software assumptions**
Intermediate Floors structure & Roof structure	9x9m slabs with 2.4KPa and 4.8KPa (central services)	concrete	30MPa concrete average flyash (9%) 220mm slab thickness with 4.5x4.5m x 220mm drop panel	30MPa concrete average flyash (9%) 317mm slab thickness (2.4KPa) and 337mm slab thickness (4.8KPa)
		rebar	reinforcement included @ 16.9kg/m^2 slab and drop panels	reinforcement included @ 16.27kg/m^2 slab (2.4KPa) and 19.43kg/m^2 slab (4.8KPa)
	7.5x7.5m and 9x7.5m slabs with 2.4KPa	concrete	30MPa concrete average flyash (9%) 220mm slab thickness with 4.5x4.5m x 220mm drop panel	30MPa concrete average flyash (9%) 252mm slab thickness
		rebar	reinforcement included @ 11.83kg/m^2 slab and drop panels	reinforcement included @ 12.66kg/m^2 slab

Notes:
The specified live loads of the design are 2.4KPa for office space and 4.8KPa for central core services area.
The suspended concrete slab assembly dialog from Athena EIE refers to a two way spanning concrete slab, and does not require beams.
The weights for structural materials from Athena assembly dialogs were collected by a series of test analysis and averaged for the concrete design.
The assumed weights for concrete and rebar from Athena assembly dialogs vary if bay and span values are changed.
Athena Eco-Calculator software uses assumptions from Athena EIE.

The major differences in material quantities shown in Table 18 are described in Table 19 which includes Athena EIE's assumptions for above grade concrete structure. The Athena EIE by quantities column in Table 19 shows the exact concrete building design specifications which were hand-calculated to develop the model by quantities. The Athena EIE by assemblies column on the other hand shows all assumptions from the main assembly dialogs in the EIE software related to the specific concrete building design of the research.

Table 21 - Materials take-off list for concrete building model by quantities (Model 3)

MATERIALS	Unit	EIE model by quantities Whole building	EIE model by quantities Structural
Concrete 20 MPa (flyash av)	m^3	565.66	565.66
Concrete 30 MPa (flyash av)	m^3	2,422.22	2,422.22
Galvanized Sheet	Tonnes	7.91	0
Galvanized Studs	Tonnes	7.83	0
Nails	Tonnes	0.22	0
Rebar, Rod, Light Sections	Tonnes	305.83	305.83
Screws Nuts & Bolts	Tonnes	1.90	1.90
Welded Wire Mesh / Ladder Wire	Tonnes	1.26	1.26

Table 22 cont.				
MATERIALS	Unit	EIE model by quantities Whole building		EIE model by quantities Structural
1/2" Fire-Rated Type X Gypsum Board	m^2	8,496.27		0
1/2" Regular Gypsum Board	m^2	5,190		0
Joint Compound	Tonnes	18.18		0
Paper Tape	Tonnes	0.16		0
Batt. Fiberglass	m^2 (25mm)	9,244.33		0
Expanded Polystyrene	m^2 (25mm)	10,779.97		0
Extruded Polystyrene	m^2 (25mm)	113.33		0
EPDM membrane (black, 60 mil)	kg	551.41		0
Modified Bitumen membrane	kg	11,891.88		0
Aluminum	Tonnes	47.33		0
Glazing Panel	Tonnes	83.16		0
Water Based Latex Paint	L	1,587.61		0
Note: Values for concrete volume and rebar differ from Table 10 because in this table it includes foundation materials. Table 10 refers to above grade structural materials.				

Table 20 consists of values used to develop the EIE models by quantities for the concrete building. The same methodology for the steel building was applied here as described above.

5.3. In-use phase modeling: Operations and maintenance

The main body of results presents initial embodied environmental impacts only. However for comparison the building models were also evaluated over a 60 years life span in order to include the operational phase of the buildings. The operational energy use by fuel type was determined from typical office energy use data from National Resources Canada statistics (NRCan, 2010), which estimates the average energy intensity of office buildings in Toronto to be approximately 420ekWh/m^2. Although high, this value is in general agreement with reports by Jarvis (2009) for average energy use of office buildings in Toronto as reported by CaGBC in 2008. In addition, Athena EIE software accounts for maintenance and replacement of components. Therefore, maintenance for glazing panels, painting and envelope roofing materials was assessed. The impacts from operational energy and maintenance are discussed in section 6.4.

5.4. Modeling limitations

A few modeling limitations were observed when the models for the steel and concrete buildings were developed. In this researh these observations are divided into assembly groups as used in the Athena EIE software modeling by assemblies:

- Foundation components:
  - Concrete slab on grade: the software does not allow to modify the thickness of the slab, the only options are 100mm or 200mm thickness
  - Concrete types: the only concrete types allowed to model are 20, 30 or 60MPa, with variation of flyash content as average (9% content), 25% or 30% (these concrete options are repeated for every component that uses concrete besides columns and beams modeling)
  - Grade beams/foundation walls: the software does not have a specific assembly dialog under foundation components to model grade beams or foundation walls. Therefore the grade beams from both steel and concrete designs were modeled by changing the footing assembly dialog to represent a linear footing
  - Footings: EIE software does not allow to model footings deeper than 500mm. The inner column footings for concrete and steel building are 600mm deep; therefore it was required to model them by volume of concrete using 500mm deep footings.
- Columns and beams:
  - As the software does not account for shared beams and columns between two adjacent slab plates, it is difficult understanding how the software interprets and calculates the structural design. The user must model columns and beams without repeating a column or beam that is shared between two slab plates.
  - Fire protection: the software does not provide the option for sprayed fire protection, therefore the only option was to use type-X gypsum boards.
  - Concrete types: the software does not give any option to vary concrete type for columns and beams, and it is automatically assumed 30MPa concrete with average flyash content.
- Floor assemblies:
  - Steel deck system: the software automatically assumes OWSJ at 1.2m o/c spacing to support steel deck. It does not allow for replacing OWSJ for wide flange beams. The software will always account for OWSJs in the case of steel deck modeling.

- Developing models by quantities:
  - o When modeling by quantities, the software does not account for environmental impacts during the construction phase of the building, only the transportation of materials to site (a solution methodology to this problem is presented in the results section)
  - o When modeling by assemblies the software automatically accounts for a waste ratio that varies by material type. This must be calculated into the materials list when modeling by quantities. The Waste Ratio values can be extracted from modeling by assemblies. If a value was extracted from the bill of materials of a model made by assemblies, the waste factor must be applied to this value. If a value was hand calculated then it must enter the model as is, since the software will apply the ratio automatically.

Additionally, a major limitation to modeling structural components using Athena EIE for high-rise buildings is that the software does not include variations for different floor levels. The software assumes the structure for every floor level to be the same. This is relevant with the steel model, in which the structural components can decrease in weight for higher floor levels (columns as an example). There were no major limitations or difficulties in modeling the concrete building because flat slab was adopted. A more complex concrete structure, for example one-way slab on two-way beams, may encounter further limitations and problems.

6. Modeling results: Observations and discussion

In the following sections, the results are based on the environmental impacts during extraction, manufacturing, construction and end of life phases, but do not include the impact from operating the building during its lifetime. Operational and maintenance impacts are discussed in section 6.4. The detailed modeling results can be found on Appendix D.

6.1. Steel building models comparison

Table 23 – Comparison of the embodied impacts for the steel building using different LCA tools

STEEL BUILDING - EMBODIED Whole building models	Model 1 - ECO-CALCULATOR	Model 2 - EIE BY ASSEMBLIES	Model 3 - EIE BY QUANTITIES	Model 4 - EIE + GABI
Primary Energy Consumption – PEC (GJ)	**20,444***	**24,243**	**22,114**	**18,111**
Weighted Resource Use – WRU (tonnes)	**4,642**	**4,346**	**4,504**	**6,253**
Global Warming Potential – GWP (tonnes CO_2 eq)	**1,556**	**1,306**	**1,264**	**1,381**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**1,037**	**891**	**866**	**800**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**12,066**	**7,604**	**7,520**	**7,326**
Eutrophication Potential – EP (kg N eq)	**798**	**927**	**763**	**256**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**1,794**	**1,658**	**1,720**	**1,718**
Smog Potential – SP (kg NOx eq)	**7,272**	**5,479**	**5,384**	**4,773**
Note: *Eco-Calculator software does not provide Primary Energy Consumption result; instead it shows Fossil Fuel Consumption.				

Table 21 shows absolute values for the embodied environmental impact indicators of the whole building models. Figure 14 is a proportional comparison of the results from Table 14 as compared to the results of EIE by quantities (Model 3 defined as 100%). The first observation is the difference of the results between models for the same building. This is due to the use of different LCA tools. Although Athena developed both Eco-Calculator and the EIE LCA tools, their modeling methodologies differ. Eco-Calculator has fixed values for each assembly component that are multiplied by the equivalent area of each component to generate the final results. It is a simplified version for the EIE software. EIE allows users to modify the assembly components of the building with more flexibility, which increases model variations and accuracy.

Furthermore, by applying a different LCI dataset, in the case of the EIE + GaBi model, some variation in the results can be expected. Nevertheless, the variation in results for weighted resource use and eutrophication potential are surprisingly large, namely 39% more and 66% less than the EIE model by quantities respectively. Regarding the results for weighted resources use, the reason is due to the different methodologies used to calculate this impact indicator. Athena Institute consulted with an expert panel in order to develop a ranking methodology to express a better understanding of the effects of extraction activities (Athena EIE software). On the other hand, GaBi's weighted resources use impact indicator uses the methodology called "Ecological Scarcity Method" that was developed by UBP (GaBi tool).

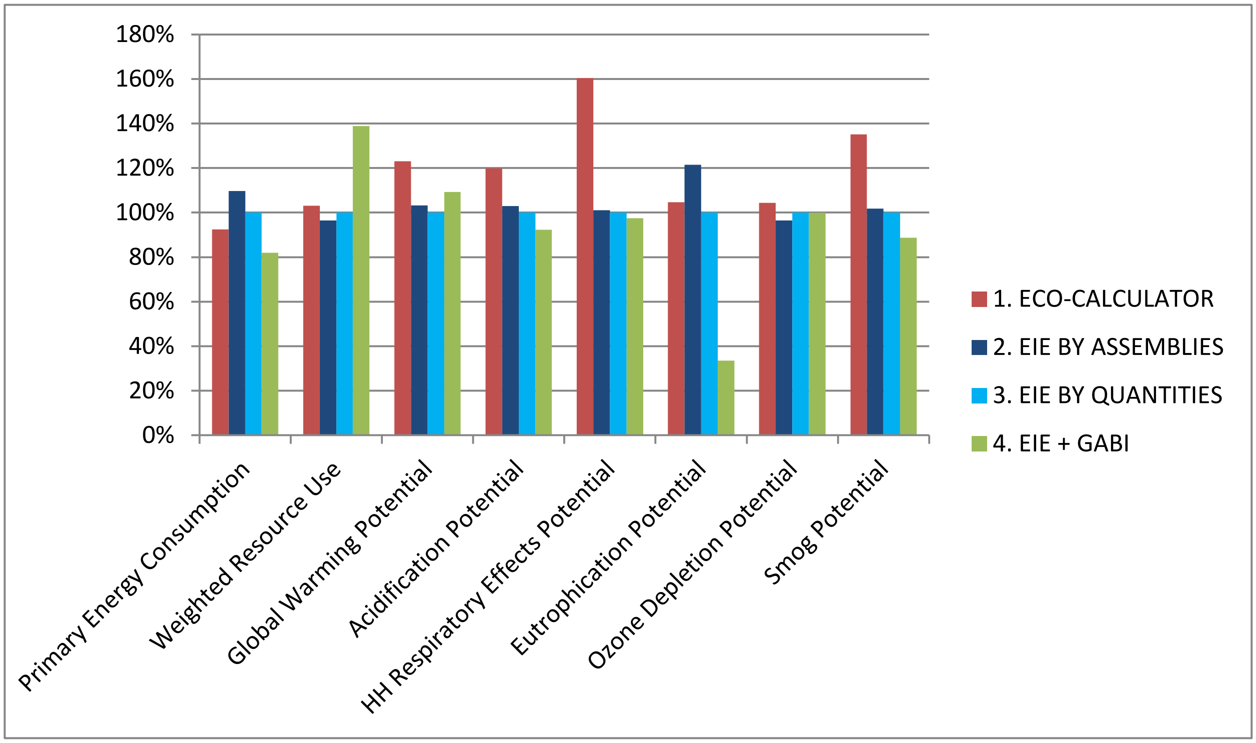


Figure 14 - Steel building models embodied impact results (relative to EIE by quantities)

With regards to the eutrophication potential impact results, both EIE and GaBi tools includes results using TRACI methodology. However, it was noted that WSA's LCI dataset presented low emissions to air and water of chemicals that increase eutrophication potential (such as nitrogenous matter). Additionally, it could also be a failure in the LCA model developed within GaBi software. Further investigation is required to determine more accurately this difference.

Table 24 – Comparison of the embodied impacts for the steel building structure only models

STEEL BUILDING – EMBODIED Structural building models	Model 2 - EIE BY ASSEMBLIES	Model 3 - EIE BY QUANTITIES	Model 4 - EIE + GABI
Primary Energy Consumption – PEC (GJ)	**16,190**	**14,115**	**9,820**
Weighted Resource Use – WRU (tonnes)	**3,811**	**3,974**	**5,205**
Global Warming Potential – GWP (tonnes CO_2 eq)	**817**	**778**	**860**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**282**	**258**	**186**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**1,729**	**1,649**	**1,410**
Eutrophication Potential – EP (kg N eq)	**755**	**594**	**98**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**581**	**642**	**640**
Smog Potential – SP (kg NOx eq)	**1,753**	**1,661**	**1,071**

Table 22 show the absolute values for the embodied impacts of the structural only and Figure 15 shows a proportional comparison to the EIE model by quantities (Model 3) which is set as 100%. By extracting the envelope materials for walls and roof and interior partition walls (except fire protection for steel components), the results for PEC and GWP decreased approximately 35%. The WRU and EP did not have a considerable decrease which suggests that these impacts are directly related to steel structural components. On the other hand, AP, HHR, ODP and SP impacts greatly decreased which suggests that these impacts are not directly related to steel structural components.

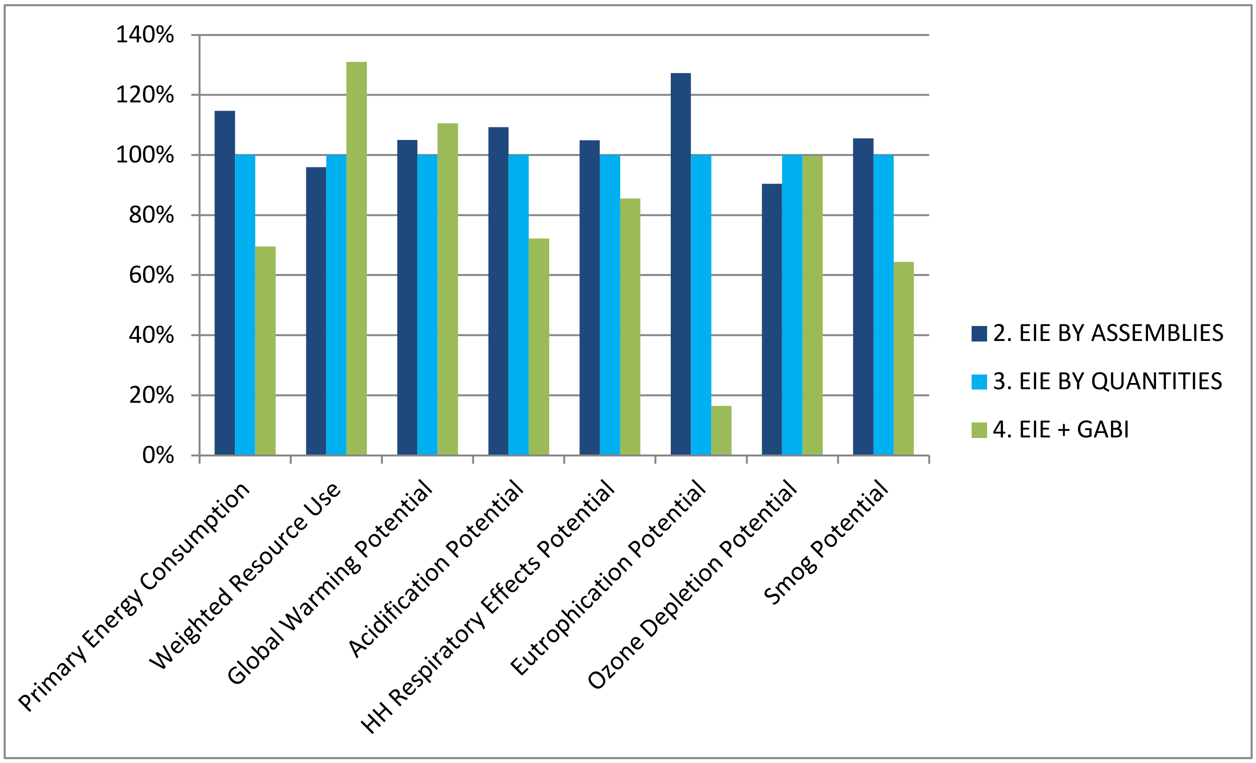


Figure 15 – Embodied impacts of the steel building structural models (relative to EIE by quantities)

6.1.1. Steel building models sensitivity analysis comparison

Table 23 shows absolute values for the embodied environmental impact indicators of the sensitivity analysis developed for the structural building models, including the non-composite and composite floor system designs (see section 5.1.1). Figure 16 is a proportional comparison of the results from Table 23 in which the non-composite floor system was defined as 100%. It was identified that only PEC and EP for the composite design with 20% less steel has a significant decrease (over 15% accuracy margin). All the other impacts have no relevant decrease, although the differences are proportional (e.g. PEC for composite design with 10% less steel decreased in 7% and the composite design with 20% less steel decreased in 14%). Since the structural building models include equal foundation, interior fire protection and roof assemblies, by decreasing the above grade structural materials shown on section 5.1.1, the environmental impacts did not generally decrease as much as the steel reductions.

Table 25 - Comparison of the emboied impacts of the sensitivity analysis for the structural steel building (Model 3)

MODEL 3 - STEEL BUILDING - EMBODIED Sensitivity analysis of structural building models	Non-composite floor system	Composite floor system (10% less steel)	Composite floor system (20% less steel)
Primary Energy Consumption – PEC (GJ)	**14,115**	**13,153**	**12,138**
Weighted Resource Use – WRU (tonnes)	**3,974**	**3,908**	**3,830**
Global Warming Potential – GWP (tonnes CO_2 eq)	**778**	**746**	**711**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**258**	**245**	**230**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**1,649**	**1,584**	**1,513**
Eutrophication Potential – EP (kg N eq)	**594**	**534**	**474**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**642**	**642**	**642**
Smog Potential – SP (kg NOx eq)	**1,661**	**1,593**	**1,522**

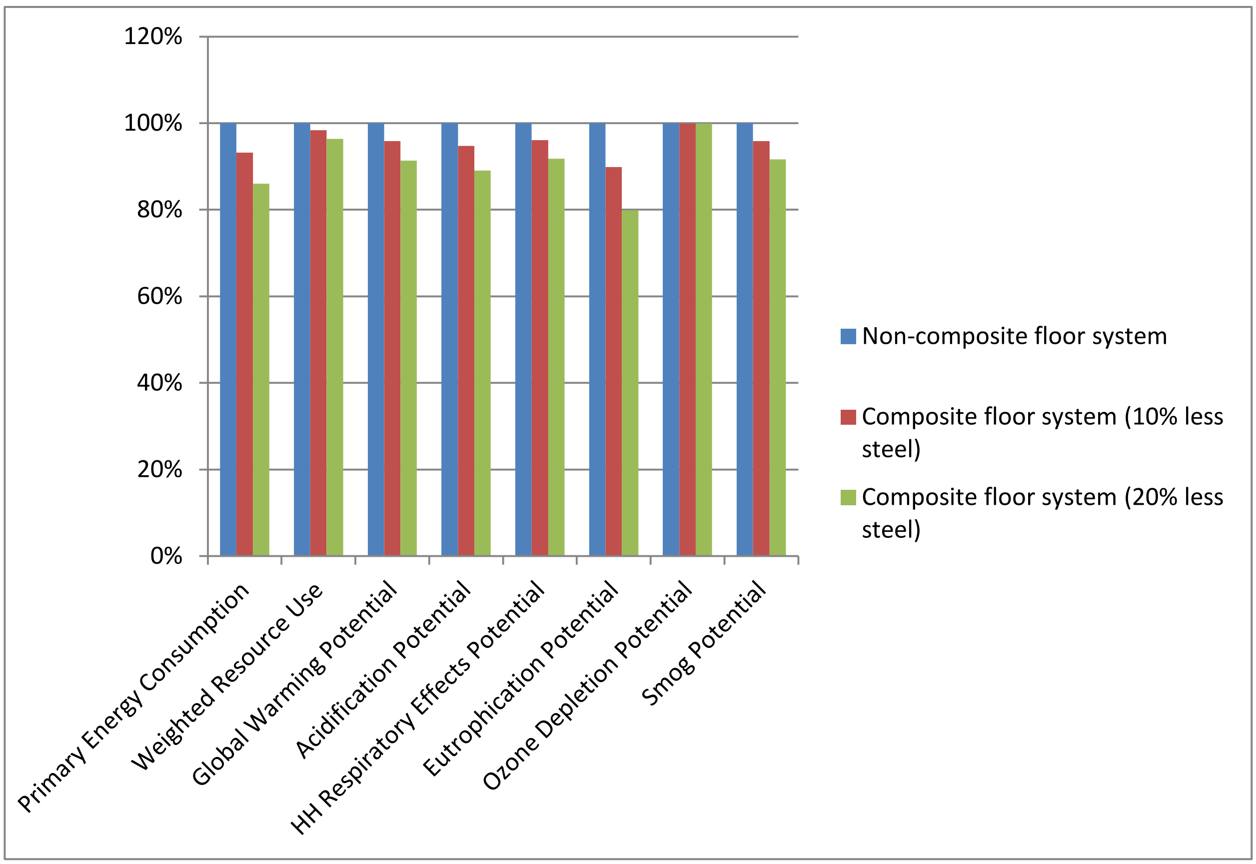


Figure 16 - Embodied impacts of the sensitivity analysis (Model 3) for the structural steel building (relative to non-composite floor system)

6.2. Concrete building models comparison

Table 26 - Comparison of the embodied impacts of the concrete building using different LCA tools

CONCRETE - EMBODIED Whole building models	Model 1 - ECO-CALCULATOR	Model 2 - EIE BY ASSEMBLIES	Model 3 - EIE BY QUANTITIES
Primary Energy Consumption – PEC (GJ)	**26,064***	**22,187**	**21,818**
Weighted Resource Use – WRU (tonnes)	**12,986**	**9,685**	**9,566**
Global Warming Potential – GWP (tonnes CO_2 eq)	**2,438**	**1,720**	**1,697**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**1,305**	**997**	**989**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**14,410**	**8,956**	**8,905**
Eutrophication Potential – EP (kg N eq)	**1,111**	**764**	**743**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**4,247**	**3,508**	**3,471**
Smog Potential – SP (kg NOx eq)	**10,537**	**7,484**	**7,422**
Note: *Eco-Calculator software does not provide Primary Energy Consumption result; instead it shows Fossil Fuel Consumption.			

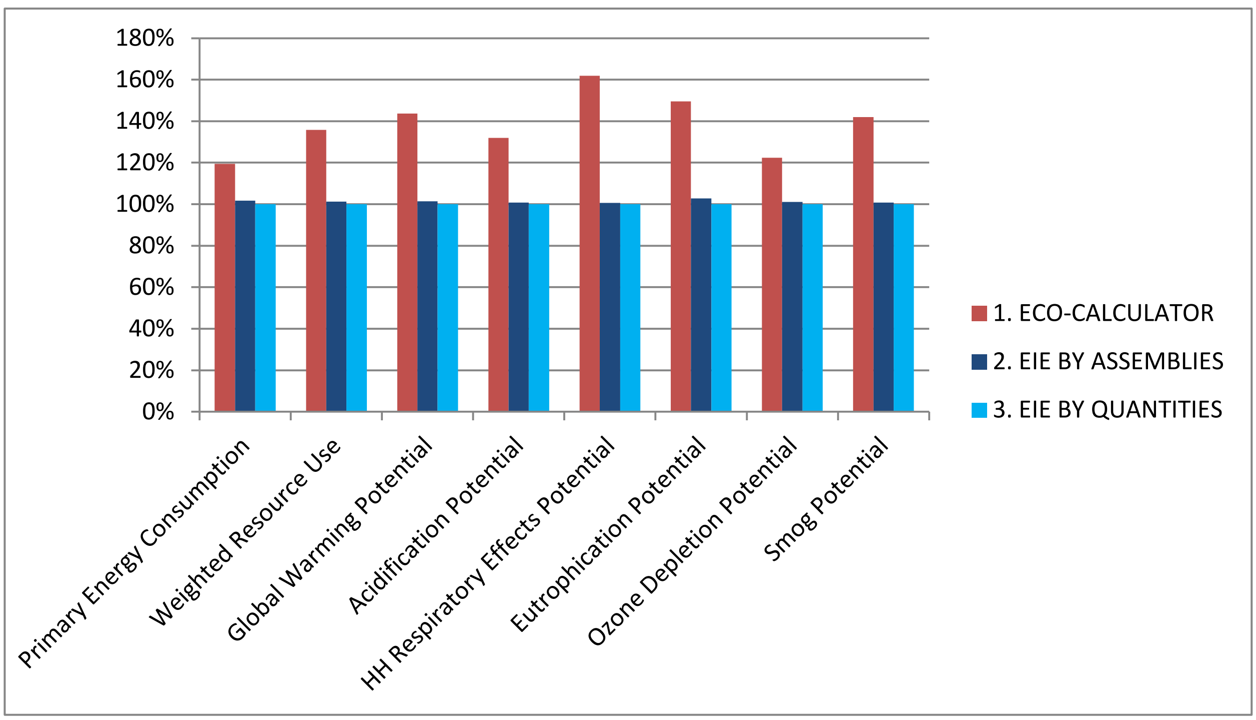


Figure 17 – Embodied impacts of the concrete building (relative to EIE by quantities)

Table 24 shows absolute values for the embodied environmental impact indicators of the whole building models. Figure 17 is a proportion comparison of the results from Table 24 in which EIE by quantities results were defined as 100%. Similarly to the steel building models' results comparison, the main observation is the difference between results from each LCA tools used. Besides the Eco-Calculator results, it is possible to recognize that the EIE tool has consistent results between both methods to model the concrete building. The difference in results between them is on average less than 5%, which can be considered insignificant. The same pattern can be detected on Table 25 for concrete structural models comparison below.

Table 27 – Comparison of the embodied impacts of the concrete building structural models

CONCRETE - EMBODIED Structural building models	Model 2 - EIE BY ASSEMBLIES	Model 3 - EIE BY QUANTITIES
Primary Energy Consumption – PEC (GJ)	**13,637**	**13,314**
Weighted Resource Use – WRU (tonnes)	**9,056**	**8,940**
Global Warming Potential – GWP (tonnes CO_2 eq)	**1,205**	**1,183**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**375**	**367**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**2,959**	**2,908**
Eutrophication Potential – EP (kg N eq)	**589**	**570**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**2,429**	**2,393**
Smog Potential – SP (kg NOx eq)	**3,695**	**3,633**

The difference in results shown in Tables 24 and 25 are related to the assembly components removed from the structural models (envelope materials for walls and roof, and interior partition walls). Table 25 results indicate that WRU is the only impact directly related to concrete structural components since there was only 7% decrease in the results, while PEU was reduced by 39%. AP, HHR and SP impacts were greatly reduced, suggesting that are not directly related to concrete. On the other hand, GWP, EP and ODP impacts are relatively related to concrete material since there was only 30%, 23% and 31% decrease in results respectively.

6.3. Comparison of steel and concrete buildings

Table 26 shows absolute values for the initial embodied (manufacturing, construction and end-of-life) environmental impact indicators from Eco-Calculator (Model 1) whole building models. Figure 18 is a proportion comparison of the results from Table 19 in which the concrete model results were defined as 100%. The results suggest that the steel building design has lower embodied impacts. Since these differences are 15% or more for every impact indicator, it is possible to conclude that this modeling tool suggests that the steel building design provides a better option for designers, especially if considering resources use and ozone depletion potential. However, the Eco-Calculator does not portray these impacts as accurately as the EIE tool. Nevertheless, the more detailed analysis from EIE suggests a similar pattern as will be discussed below.

Table 28 – Embodied impacts using Eco-Calculator (Model 1) for whole building models

Model 1 - ECO-CALCULATOR Whole building models	STEEL	CONCRETE
Fossil Fuel Consumption – FFC (GJ)	**20,444**	**26,064**
Weighted Resource Use – WRU (tonnes)	**4,642**	**12,986**
Global Warming Potential – GWP (tonnes CO_2 eq)	**1,556**	**2,438**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**1,037**	**1,305**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**12,066**	**14,410**
Eutrophication Potential – EP (kg N eq)	**798**	**1,111**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**1,794**	**4,247**
Smog Potential – SP (kg NOx eq)	**7,272**	**10,537**

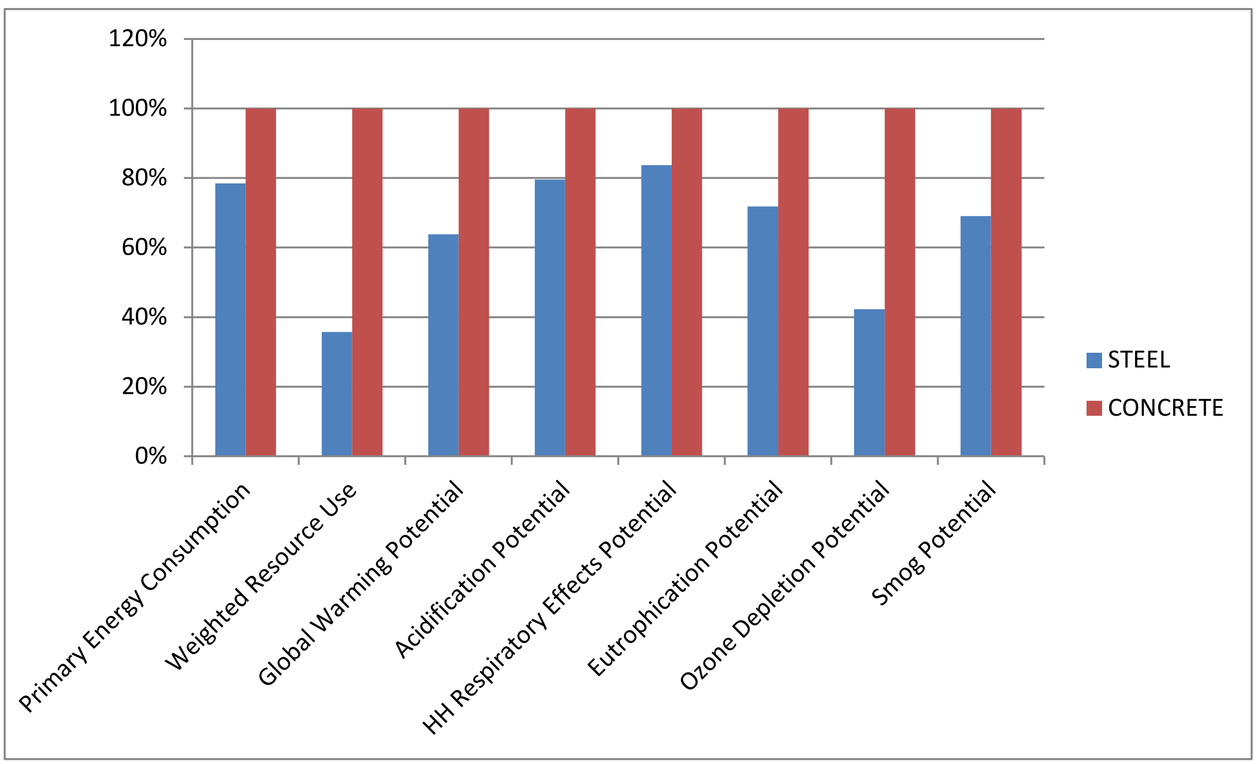


Figure 18 – Comparison of embodied impacts using the Eco-Calculator (Model 1) for whole building models (relative to concrete model results)

Table 29 – Embodied impacts using EIE by assemblies (Model 2) for the whole building models

Model 2 - EIE by assemblies Whole building models	STEEL	CONCRETE
Primary Energy Consumption – PEC (GJ)	**24,243**	**22,187**
Weighted Resource Use – WRU (tonnes)	**4,346**	**9,685**
Global Warming Potential – GWP (tonnes CO_2 eq)	**1,306**	**1,720**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**891**	**997**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**7,604**	**8,956**
Eutrophication Potential – EP (kg N eq)	**927**	**764**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**1,658**	**3,508**
Smog Potential – SP (kg NOx eq)	**5,479**	**7,484**

Table 27 presents a comparison of the results for the steel and concrete buildings using EIE by assemblies (Model 2). Figure 19 is a proportional comparison of the results on Table 27 in which the concrete model results were defined as 100%. This comparison suggests that PEC and EP did not follow the pattern shown in the previous comparison and are slightly higher for the steel building. Nevertheless, the difference for PEC is below 10% and so not significant, and the steel building design performs better in all other categories, particularly GWP, WRU and ODP, while in some categories the differences are small.

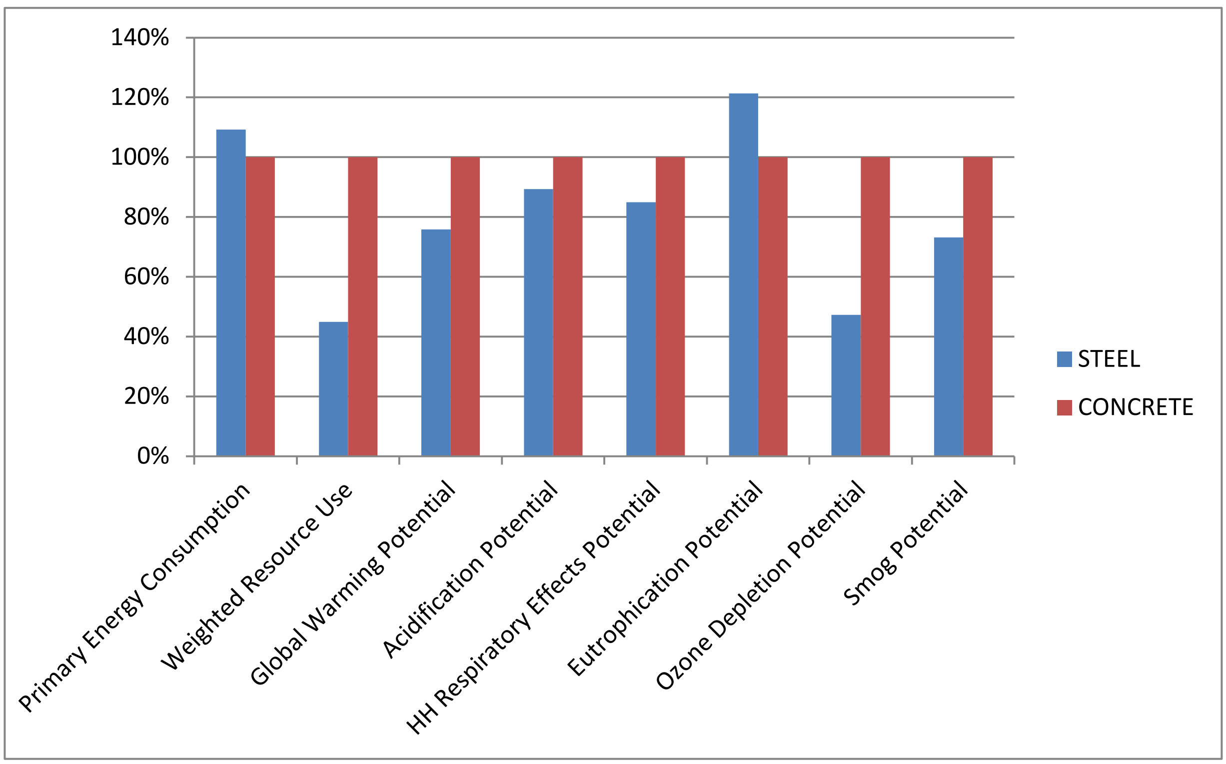


Figure 19 – Comparison of embodied impacts using EIE by assemblies (Model 2) for the whole building models (relative to concrete model)

Table 30 – Embodied impacts using EIE by assemblies (Model 2) for structure only models

Model 2 - EIE by assemblies Structural building models	STEEL	CONCRETE
Primary Energy Consumption – PEC (GJ)	**16,190**	**13,637**
Weighted Resource Use – WRU (tonnes)	**3,811**	**9,056**
Global Warming Potential – GWP (tonnes CO_2 eq)	**817**	**1,205**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**282**	**375**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**1,729**	**2,959**
Eutrophication Potential – EP (kg N eq)	**755**	**589**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**581**	**2,429**
Smog Potential – SP (kg NOx eq)	**1,753**	**3,695**

Table 28 and Figure 20 present embodied impacts as calculated by EIE by assemblies (Model 2) for the structural components only. This indicates that steel structure performs better in all categories other than PEC and EP. PEC difference between steel structure and concrete structure is higher than 15%. On the other hand, this comparison shows that GWP, WRU, ODP and SP are much higher for the concrete structure.

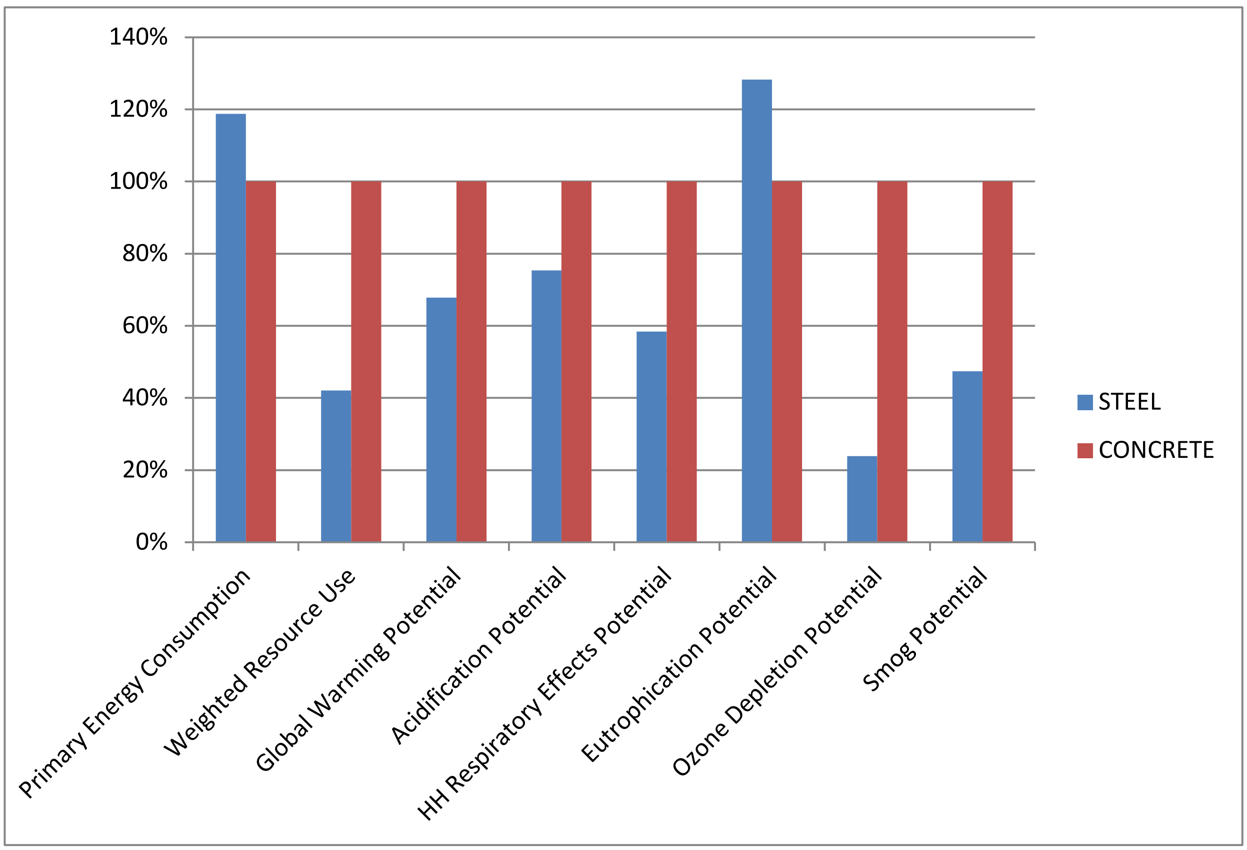


Figure 20 – Comparison of embodied impacts using EIE by assemblies (Model 2) for the structure only models (relative to concrete model)

Table 31 – Embodied impacts from EIE by quantities (Model 3) for the whole building models

Model 3 - EIE by quantities Whole building models	STEEL	CONCRETE
Primary Energy Consumption – PEC (GJ)	**22,114**	**21,818**
Weighted Resource Use – WRU (tonnes)	**4,504**	**9,566**
Global Warming Potential – GWP (tonnes CO_2 eq)	**1,264**	**1,697**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**866**	**989**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**7,520**	**8,905**
Eutrophication Potential – EP (kg N eq)	**763**	**743**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**1,720**	**3,471**
Smog Potential – SP (kg NOx eq)	**5,384**	**7,422**

Tables 29 and 30, and Figures 21 and 22 present the same data as above, but using the EIE by quantities (Model 3) method of calculation, which is considered the most accurate. In this case steel performs better for all impact categories with exception of PEC, although the difference shown is small (much less than 15% accuracy margin).

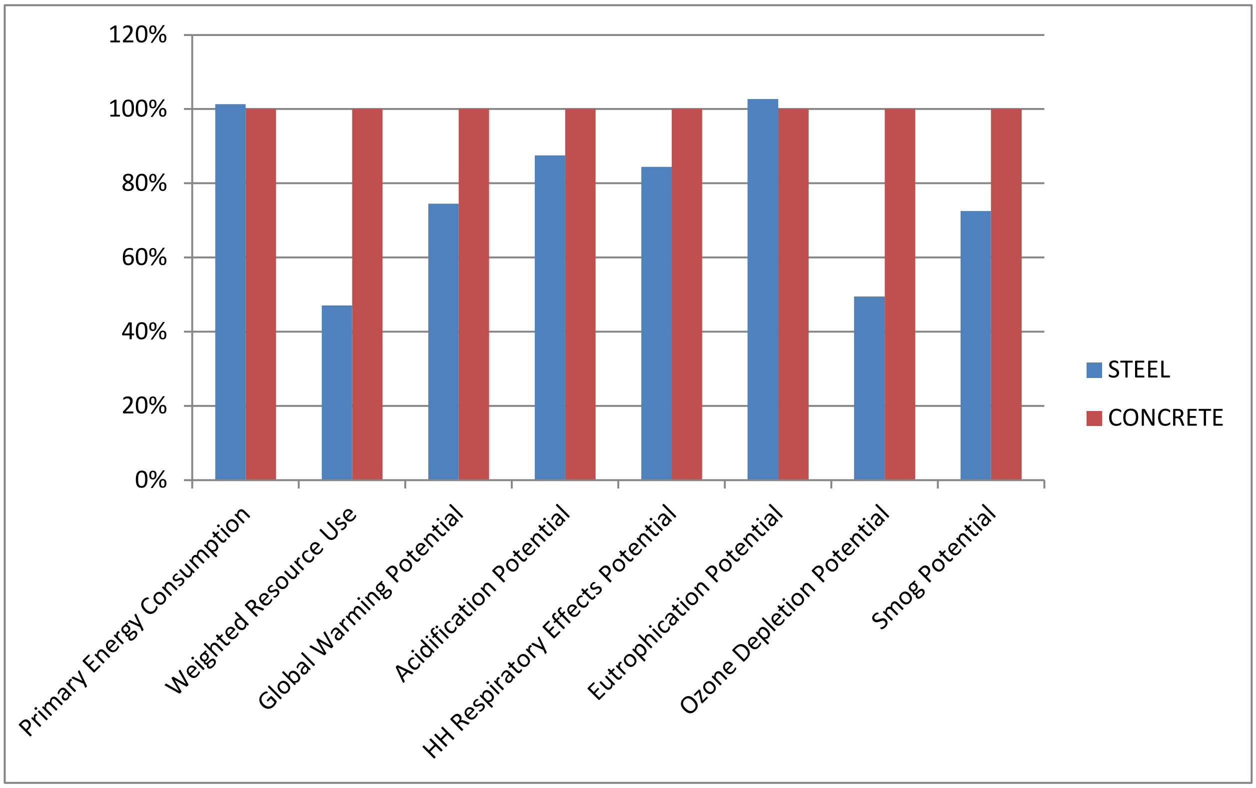


Figure 21 – Comparison of embodied impacts from EIE by quantities (Model 3) for the whole building models (relative to concrete model)

Table 32 – Embodied impacts from EIE by quantities (Model 3) for the structure only models

Model 3 - EIE by quantities Structural building models	STEEL	CONCRETE
Primary Energy Consumption – PEC (GJ)	**14,115**	**13,314**
Weighted Resource Use – WRU (tonnes)	**3,974**	**8,940**
Global Warming Potential – GWP (tonnes CO_2 eq)	**778**	**1,183**
Acidification Potential – AP (moles of H+ eq x 10^{-3})	**258**	**367**
HH Respiratory Effects Potential – HHR (kg PM2.5 eq)	**1,649**	**2,908**
Eutrophication Potential – EP (kg N eq)	**594**	**570**
Ozone Depletion Potential – ODP (mg CFC-11 eq)	**642**	**2,393**
Smog Potential – SP (kg NOx eq)	**1,661**	**3,633**

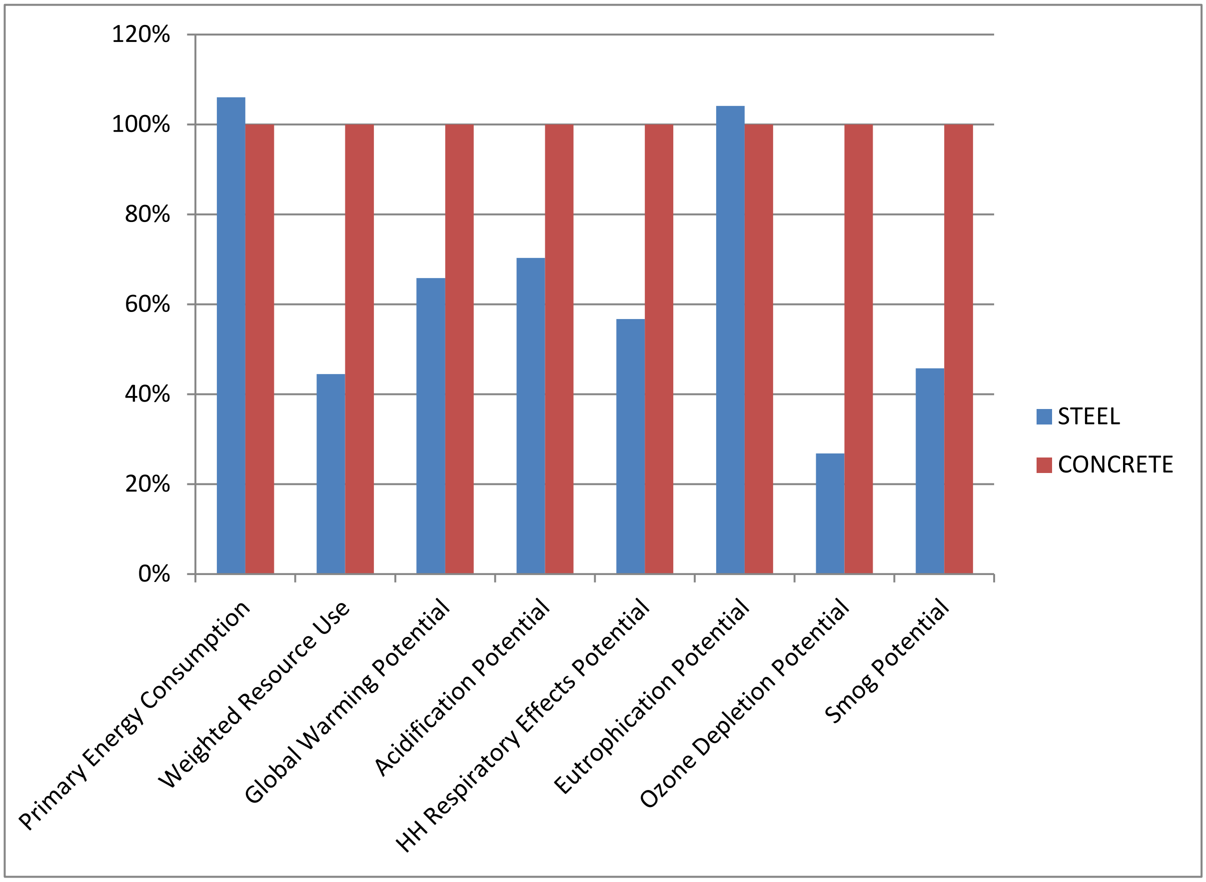
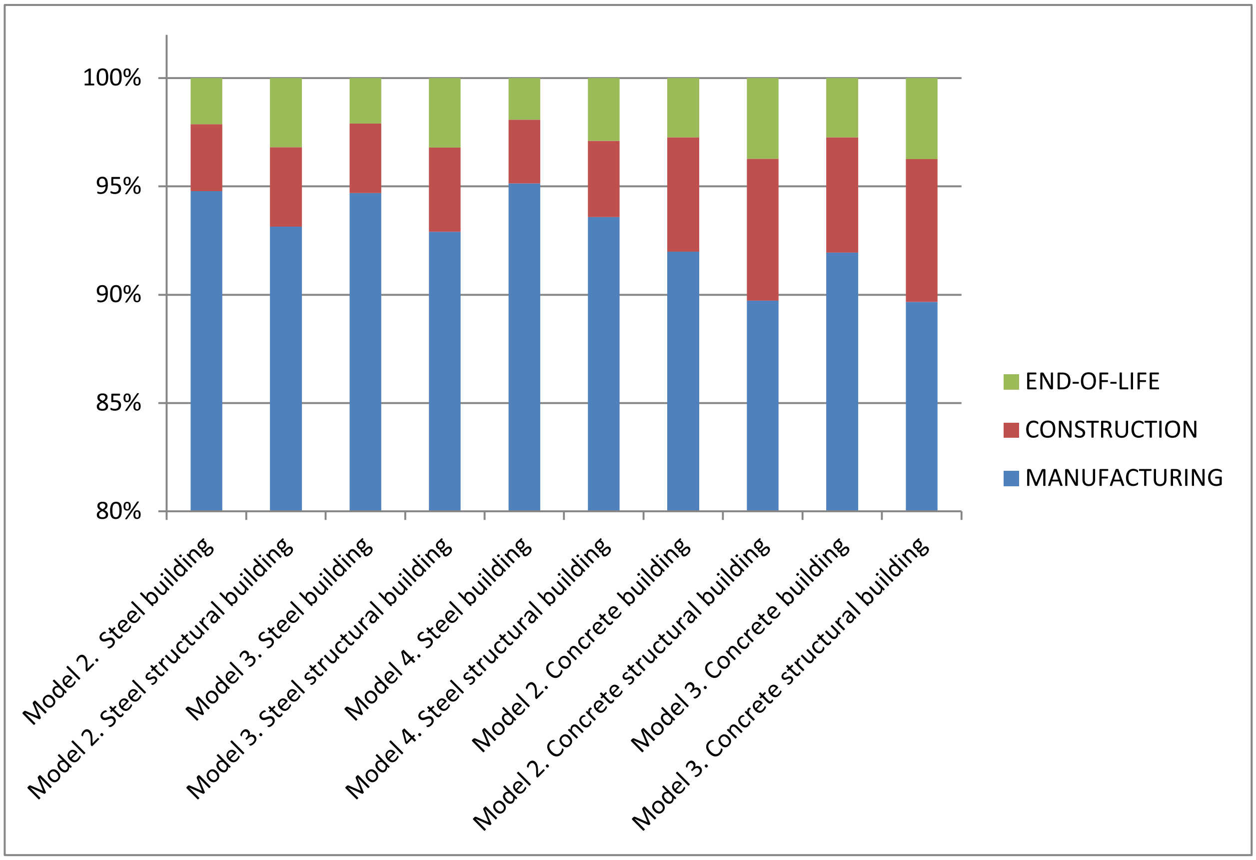


Figure 22 – Comparison of embodied impacts from EIE by quantities (Model 3) for the structure only models (relative to concrete model)

6.3.1. Detailed comparison of embodied global warming potential

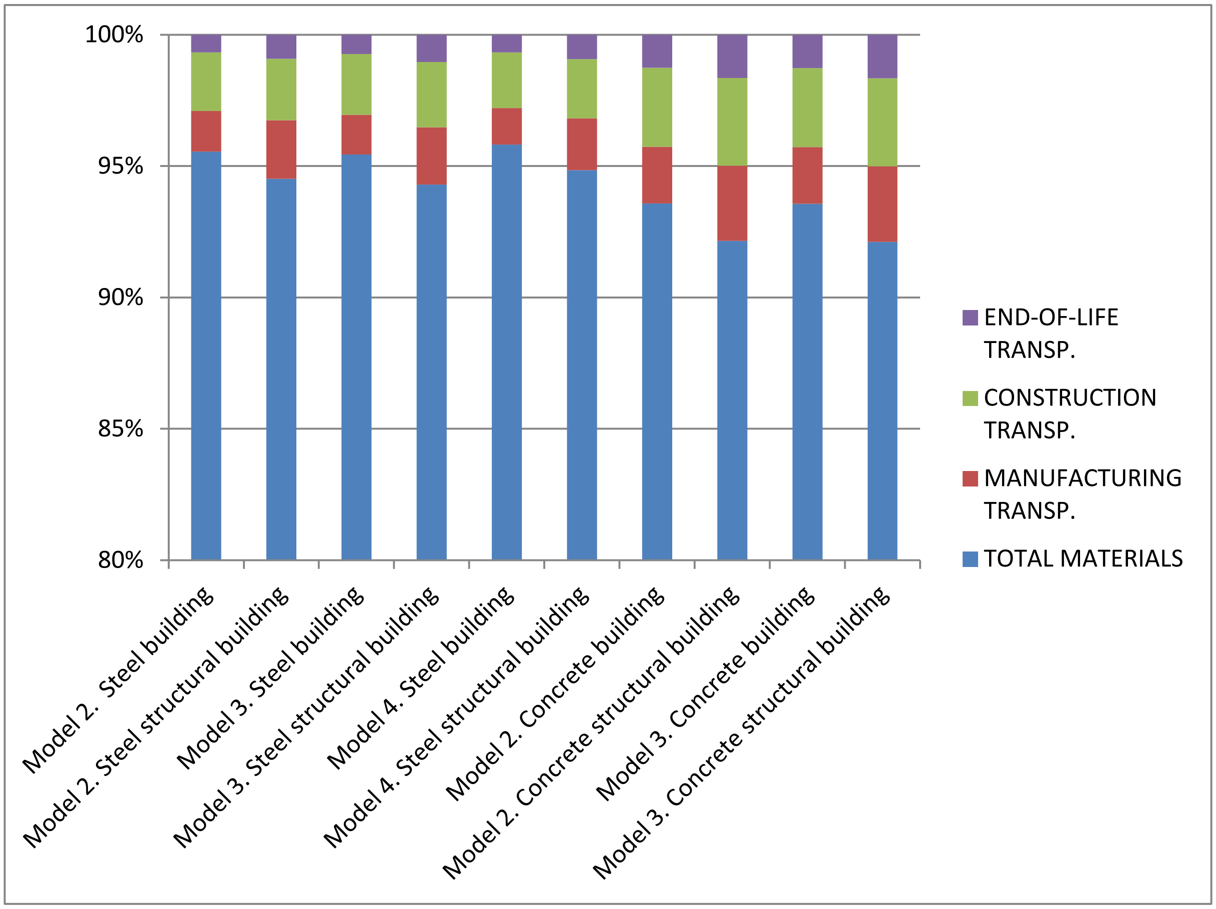
The Global Warming Potential (GWP) impact indicator was chosen to develop a more in-depth comparison between the steel and concrete building models. The first step was to understand the proportion of this impact within each life cycle phase as shown in Figure 23. As expected, the manufacturing embodied impacts outweigh construction and end-of-life phases significantly. Moreover, Figure 23 implies that the construction and end-of-life GWP impacts for the concrete buildings are more relevant than for the steel buildings. This is due to the use of heavy machinery and varying technologies between concrete and steel buildings construction and end-of-life phases. Athena EIE assumes a more intense use of machinery during construction and demolition for concrete buildings.



NOTE: The X-axis scale starts at 80% as the vast majority of the impact is manufacturing.

Figure 23 - Global Warming Potential proportion between life cycle phases

The second step was to understand the relevance of transportation compared to the other impacts of the materials used. This is shown in Figure 24. Although the concrete building models have much higher embodied GWP as shown in previous comparisons, Figure 24 shows that GWP produced during transportation in the concrete building life cycle phases is also higher than transportation in the steel building. Similarly to the comparison shown in Table 27, the major differences are within construction and end-of-life phases because Athena EIE considers more volume of materials being transported during construction of concrete building and end-of-life to land-filling sites. Steel products have a higher rate of recycling and reuse and lower weight/volume ratio decreasing transportation impacts. Further analysis of transportation impacts related to steel or concrete construction is not possible because the LCI data is aggregated.



NOTE: The X-axis scale starts at 80% as the vast majority of the impact is manufacturing.

Figure 24 - Global Warming Potential proportion between materials and transportation

The third step was to understand the GWP proportion between each assembly category as shown in Figures 25 and 26 which represent values for whole building models (Figure 25) and structural models (Figure 26). Figures 25 and 26 indicate that the columns, beams and floors for concrete structures carry more impact than in the steel structures. Interior and exterior walls for the steel building has a more relevant proportion in which interior fire rated protection is 2 to 5% of the total GWP embodied impact. Flooring structural systems are shown to carry the highest portion of GWP in all models. However it is important to mention the difference between concrete building models by assemblies and by quantities comparing columns and beams to flooring. The difference in use of concrete and steel rebar materials shown in Table 16 resulted in varying GWP proportions for these assembly categories.

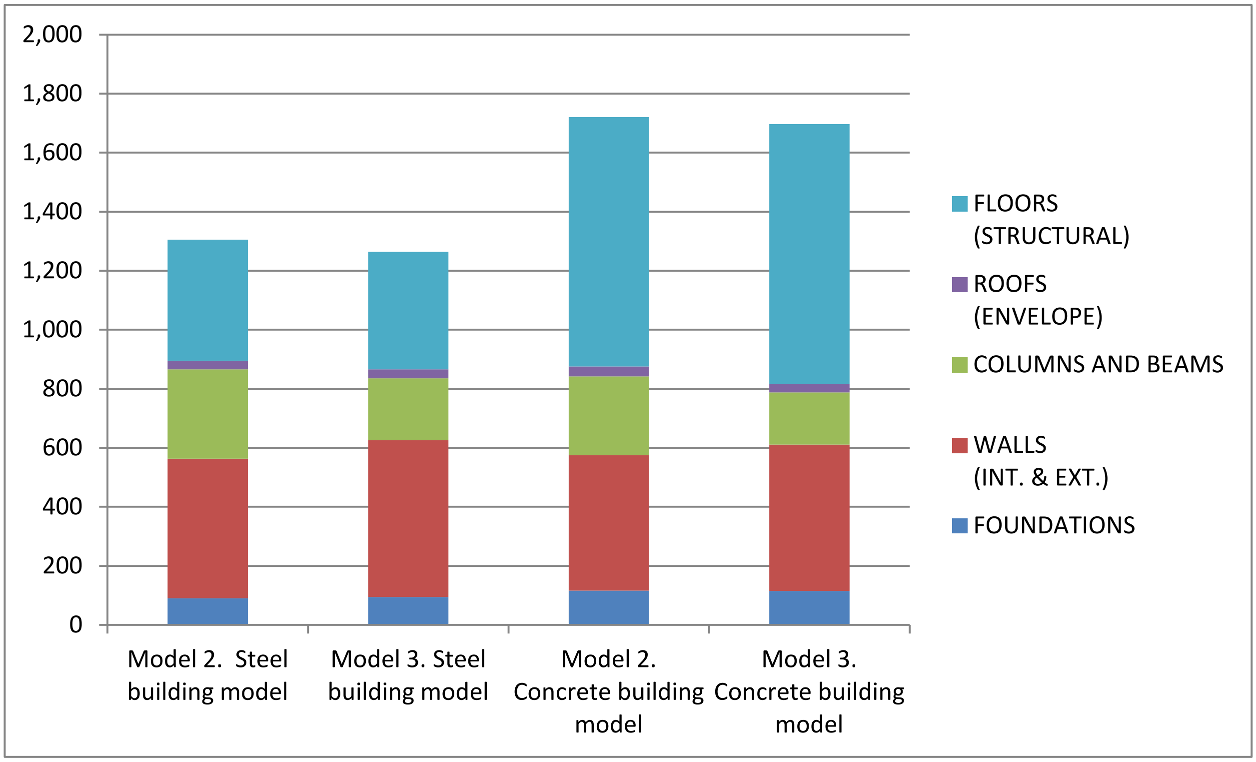


Figure 25 - Global Warming Potential (tonnes CO_2 eq) proportion between assembly categories for whole building

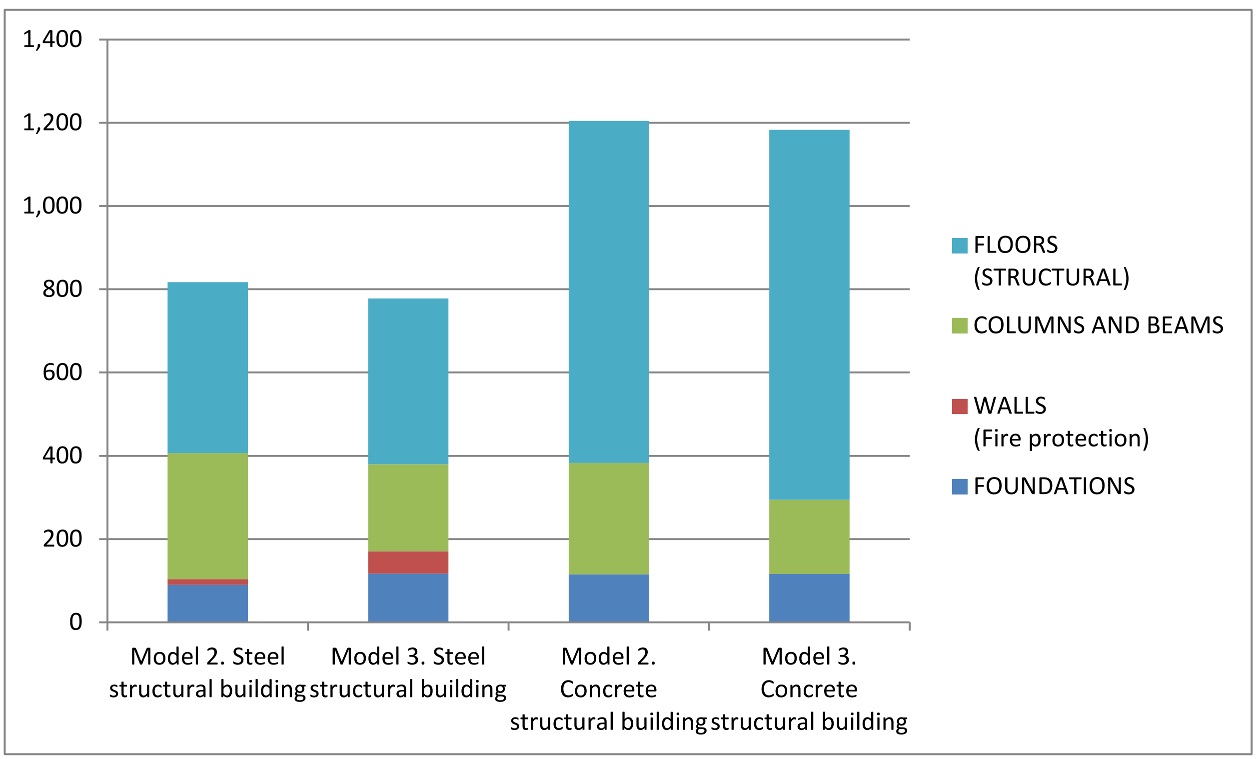


Figure 26 - Global Warming Potential (tonnes CO_2 eq) proportion between assembly categories for structure only

Finally, the GWP impact for the manufacturing phase (cradle-to-gate) for the super structure was compared (columns & beams and floor assembly). Figure 27 presents a comparison of the columns and beams only. All GWP results presented are in tonnes of carbon dioxide equivalent (tonnes CO_2 eq).

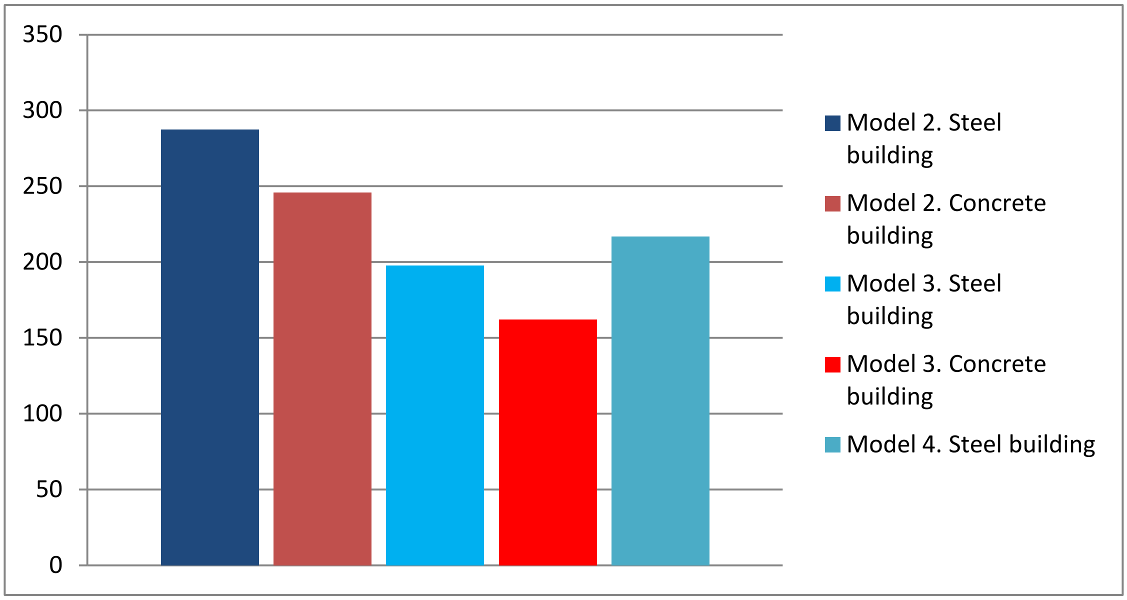


Figure 27 - Cradle-to-gate GWP (tonnes CO_2 eq) for columns & beams of whole building models

Figure 27 indicates that steel structures modeled by assemblies (Model 2) have in average 17% higher GWP impact compared to concrete structures modeled by assemblies (Model 2). On the other hand, the models by quantities (Model 3) show that the steel columns & beams are slightly lower, which can be considered an insignificant difference. Additionally, this comparison shows a great difference between EIE models by assemblies (Model 2) and by quantities (Model 3) for both building designs. This difference is in average 85% and 50% for the steel building models and concrete building models respectively. This is due to the assumptions that the Athena EIE software uses to model columns and beams as shown in Tables 15 and 19. Athena EIE assembly dialogs overestimate columns and beams materials.

When considering GWP of structural floor assembly group as shown in Figure 28, concrete structures have much higher impacts, with over 71% difference. This is due to the higher volume of concrete used for suspended concrete slabs and drop panels. Although EIE software underestimated values for floor assemblies, this comparison indicates that EIE software can model structural floor assemblies more accurately than columns & beams.

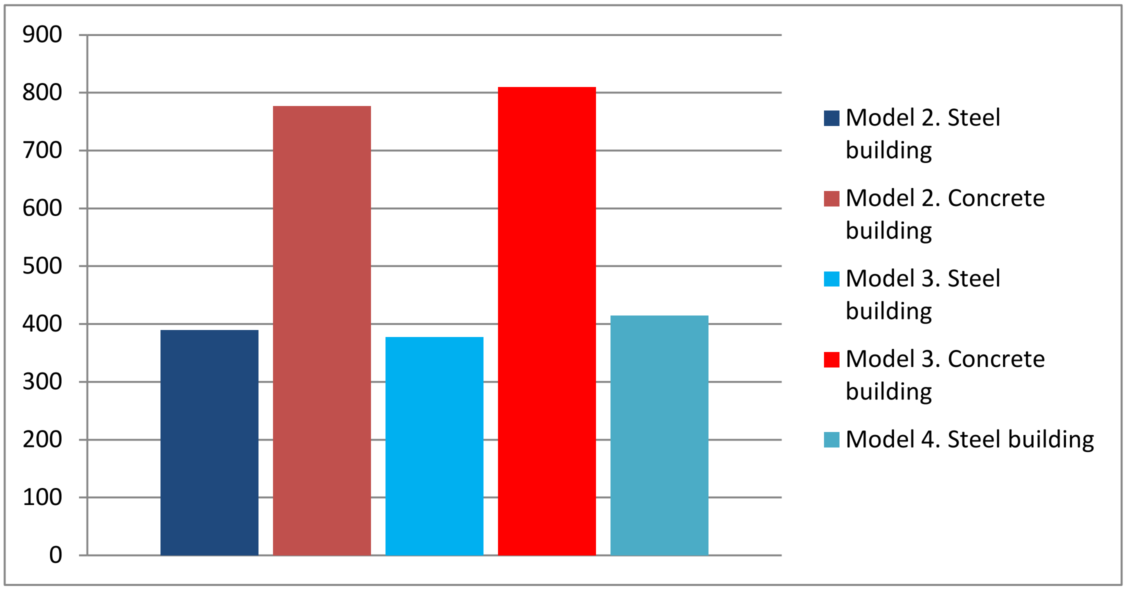


Figure 28 - Cradle-to-gate GWP (tonnes CO_2 eq) for structural floor of whole building models

6.4. Operational and recurring embodied impacts

The above analysis focuses only on embodied impacts and ignores the impacts from operating and maintaining the building during its in-use phase. To put the embodied component into context of its full life cycle impact, the building models were evaluated over a 60 years life span to include operational energy use and recurring embodied impacts. As mentioned previously, the operational energy use by fuel type was determined by typical office energy use data from National Resources Canada statistics (NRCan, 2010), which estimates the average energy intensity of office buildings in Toronto to be approximately 420ekWh/m^2. Recurring impacts are relative to interior finishing and envelope (see section 5.3).

Observing the operational and recurring embodied environmental impacts such as PEC and GWP, it is possible to identify that the embodied impacts presented in Tables 21 to 25 are small compared to operational impacts. It was observed that the total embodied PEC (which includes initial embodied and recurring embodied impacts) is on average 2.1% of the total lifetime PEC including operational energy for the EIE whole building models. If we consider the embodied impact of the structure, it is found to be only 1.1% on average when compared to total lifetime PEC (which includes total embodied and operational impacts). For the total embodied GWP the proportion is on average 3.5% and 1.8% respectively compared to total life-cycle GWP. It was also detected that the recurring PEC due to maintenance is on average 20.9% for EIE whole building models. Similarly for recurring GWP this proportion is on average 26.4%. When only the structural components are considered, the recurring PEC is 2.9% and GWP is 1.2%. The recurring impacts are low for the structure since the software assumes that, unlike other components, the materials in the structure require little refurbishment during the life of the building.

Table 33 - Initial embodied primary energy consumption (PEC) VS operational PEC impacts comparison

Case / Model Evaluated over 60-year life span	Initial Embodied PEC	Total Lifetime PEC	Initial Embodied / Total PEC
Units	GJ/m²	GJ/m²	GJ/m²
Eco-Calculator - concrete - whole building (Model 1)	2.98	n/a	n/a
Eco-Calculator - steel - whole building (Model 1)	2.34	n/a	n/a
EIE by assemblies - concrete - whole building (Model 2)	2.54	138.69	1.83%
EIE by assemblies - steel - whole building (Model 2)	2.77	138.88	2.00%
EIE by quantities - concrete - whole building (Model 3)	2.50	138.57	1.80%
EIE by quantities - steel - whole building (Model 3)	2.53	138.62	1.83%
EIE + GaBi - steel - whole building (Model 4)	2.07	138.06	1.50%
Data collected from literature review case studies (see section 3 for details)			
1a - concrete – Vancouver – no life-span	1.57	not provided	not provided
1b - tilt-up wall - Vancouver – no life-span	1.65		
1c - prefabricated steel - Vancouver – no life-span	1.10		
1d - timber - Vancouver – no life-span	1.17		
2a - timber – Vancouver – 50 years life-span	10.58	58.54	18.07%
2b - steel - Vancouver – 50 years life-span	11.46	59.40	19.29%
2c - concrete - Vancouver – 50 years life-span	10.94	58.89	18.58%
2d - timber - Toronto – 50 years life-span	10.58	92.39	11.45%
2e - steel - Toronto – 50 years life-span	11.46	93.25	12.29%
2f - concrete - Toronto – 50 years life-span	10.94	92.74	11.80%
3a - steel frame/precast slabs – UK – 60 years life-span	2.60	38.50	6.75%
3b - steel frame/composite slabs - UK – 60 years life-span	2.60	38.60	6.74%
3c - in-situ reinforced concrete - UK – 60 years life-span	2.50	38.40	6.51%
3d - steel frame/cellular beams - UK – 60 years life-span	2.90	38.90	7.46%
3e - concrete frame/precast hollow - UK – 60 years life-span	2.70	38.50	7.01%
4a - in-situ cast concrete - Sweden – no life-span	1.20	not provided	not provided
4b - precast concrete - Sweden – no life-span	1.05		
4c - steel frame/concrete slabs - Sweden – no life-span	0.95		
5a - concrete - Midwestern US – 50 years life-span	8.30	81.82	10.14%
5b - steel - Midwestern US – 50 years life-span	9.50	81.82	11.61%

Tables 31 and 32 present a summary of operational and embodied PEC and GWP impacts for the LCA models developed. For comparison data from 20 case studies identified from literature reporting LCA studies of building that used steel, concrete and timber structural systems is also listed. These case studies were presented on Section 3. Embodied PEC and embodied GWP columns present values for only initial embodied impacts (cradle-to-gate without maintenance), therefore do not include recurring impacts. The other two columns (Total PEC and Total GWP) include the total impacts from cradle-to-grave.

Table 34 - Initial embodied global warming potential (GWP) VS operational GWP impacts comparison

Case / Model	Initial Embodied GWP	Total Lifetime GWP Emissions	Initial Embodied / Total GWP
Units	kg eCO_2/m^2	kg eCO_2/m^2	kg eCO_2/m^2
Eco-Calculator - concrete - whole building (Model 1)	278.95	n/a	n/a
Eco-Calculator - steel - whole building (Model 1)	178.03	n/a	n/a
EIE by assemblies - concrete - whole building (Model 2)	196.84	5,519.00	3.57%
EIE by assemblies - steel - whole building (Model 2)	149.38	5,468.28	2.73%
EIE by quantities - concrete - whole building (Model 3)	194.17	5,511.52	3.52%
EIE by quantities - steel - whole building (Model 3)	144.65	5,462.19	2.65%
EIE + GaBi - steel - whole building (Model 4)	157.96	5,479.24	2.88%
Data collected from literature review case studies (see section 3 for details)			
1a - concrete - Vancouver – no life-span	103.80	not provided	not provided
1b - tilt-up wall - Vancouver – no life-span	108.60		
1c - prefabricated steel - Vancouver – no life-span	66.50		
1d - timber - Vancouver – no life-span	51.10		
2a - timber - Vancouver – 50 years life-span	not provided	not provided	not provided
2b - steel - Vancouver – 50 years life-span			
2c - concrete - Vancouver – 50 years life-span			
2d - timber - Toronto – 50 years life-span			
2e - steel - Toronto – 50 years life-span			
2f - concrete - Toronto – 50 years life-span			
3a - steel frame/precast slabs – UK – 60 years life-span	251.00	2,484.00	10.10%
3b - steel frame/composite slabs – UK – 60 years life-span	241.00	2,480.00	9.72%
3c - in-situ reinforced concrete – UK – 60 years life-span	286.00	2,520.00	11.35%
3d - steel frame/cellular beams – UK – 60 years life-span	259.00	2,499.00	10.36%
3e - concrete frame/precast hollow – UK – 60 years life-span	333.00	2,565.00	12.98%
4a - in-situ cast concrete – Sweden – no life-span	125.00	not provided	not provided
4b - precast concrete – Sweden – no life-span	110.00		
4c - steel frame/concrete slabs – Sweden – no life-span	90.00		
5a - concrete - Midwestern US – 50 years life-span	550.00	5,909.09	9.31%
5b - steel - Midwestern US – 50 years life-span	620.00	5,909.09	10.49%

The results show a large variation and some inconsistencies with some examples being more than 10 times larger than others. Some of this can be explained by variations in building design, region, lifetime, modeling assumptions, etc. Nevertheless the scale of variations suggests that there are some basic inconsistencies in methodology between the case studies.

These results suggest that to reach a reasonable consistency on LCA studies for comparison, buildings should be evaluated under the same LCA tool, including the same LCI data, assumptions and functional unit. Many different LCA tools and LCI data were used for the various studies presented here. This imposes challenges when comparing results from different impact indicators as shown in Tables 31 and 32.

6.4.1. Operational VS Embodied Impacts – Sensitivity Analysis

In order to develop a better understanding of the relation between the embodied impacts to the operational impacts, the Model 3 (EIE by weight) steel building was calculated through a 50-year life span. The average energy consumption for office building in Toronto as reported by National Resources Canada (NRCan, 2010) or 425kWh/m^2 is very high when considering new buildings. Therefore the sensitivity analysis consists of analysing the steel building with the average, and compare to an improved performance by decreasing the total consumption by 30% (297.5kWh/m^2) and by 50% (212.5kWh/m^2). However, it is expected that to considerably increase the operational performance of a building, significant changes to the envelope must be made, which therefore might increase the embodied impacts of the building. And so, the embodied impacts were increased by 5% with 30% less energy and 10% for 50% less energy.

Table 35 - PEC and GWP for steel building (EIE by weight) over 50-years life span

Steel building by weight 100% energy consumption	**Manufact.**	**Const.**	**Maint.**	**End - Of - Life**	**Operating Energy**	**Total Effects**
	Total	**Total**	**Total**	**Total**	**Total**	
Primary Energy Consumption MJ	**21,149,775**	**574,811**	**2,171,271**	**389,725**	**1,063,021,245**	**1,087,306,827**
Global Warming Potential (kg CO2 eq)	**1,197,125**	**40,585**	**115,095**	**26,563**	**46,340,129**	**47,719,497**
Steel building by weight 30% less energy and 5% more embodied	**Manufact.**	**Const.**	**Maint.**	**End - Of - Life**	**Operating Energy**	**Total Effects**
	Total	**Total**	**Total**	**Total**	**Total**	
Primary Energy Consumption MJ	**22,207,264**	**603,552**	**2,279,834**	**409,212**	**744,094,120**	**769,593,981**
Global Warming Potential (kg CO2 eq)	**1,256,981**	**42,615**	**120,850**	**27,891**	**32,438,813**	**33,887,149**
Steel building by weight 50% less energy and 10% more embodied	**Manufact.**	**Const.**	**Maint.**	**End - Of - Life**	**Operating Energy**	**Total Effects**
	Total	**Total**	**Total**	**Total**	**Total**	
Primary Energy Consumption MJ	**23,264,753**	**632,292**	**2,388,398**	**428,698**	**531,495,797**	**558,209,938**
Global Warming Potential (kg CO2 eq)	**1,316,838**	**44,644**	**126,604**	**29,219**	**23,170,581**	**24,687,885**

Table 35 suggests that the operational impacts outweigh the embodied impacts by over 90% for all three analyses. The highest embodied impact compared to operational is the global warming potential, as shown on figures 29 and 30 below.

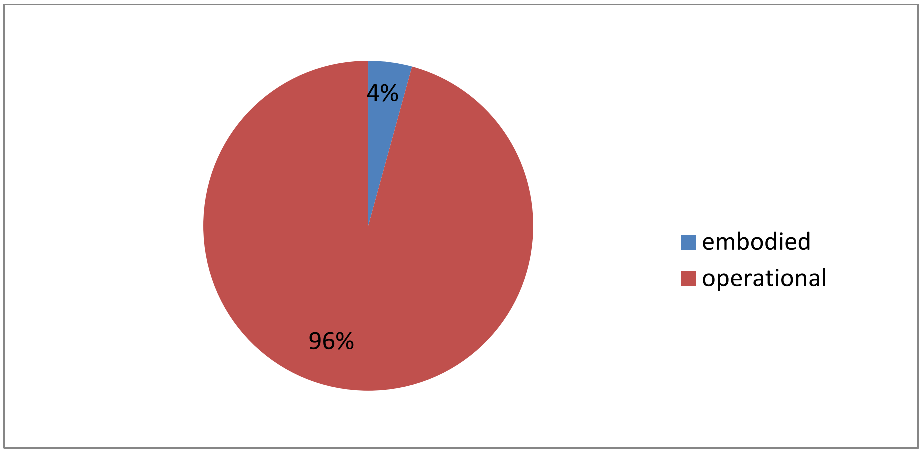


Figure 29 - GWP Embodied VS Operational for steel building by weight with 70% energy use

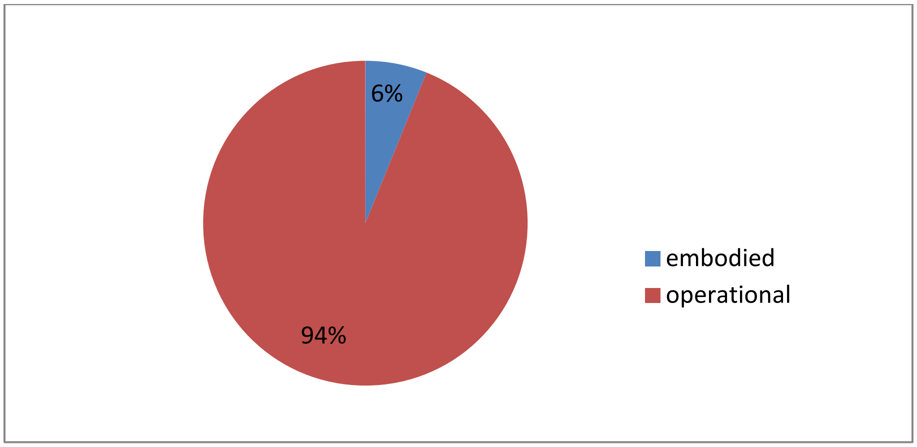


Figure 30 - GWP Embodied VS Operational for steel building by weight with 50% energy use

Figure 30 indicates that even decreasing the operational energy consumption of the building by 50%, the embodied impact is still a very small portion of the total impacts during the whole life-cycle of the building. However, Athena Environmental Impact Estimator does not include the embodied impacts for mechanical systems, which would increase the impacts. Nonetheless, the difference is very high between embodied and operational and no considerable change is expected.

7. Conclusions

This project study provided a thorough overview of LCA and demonstrated its use with the comparison of steel and concrete structural options for a commercial building located in Toronto. This research has shown the most important criteria to be considered when developing an LCA study of whole buildings. The main objective was to provide a fair comparison between steel and concrete. This study has allowed answering the following questions:

- How to provide a fair comparison between steel and concrete structural systems using LCA? – main topic of the study

Starting from the literature reviewed including various LCA methodologies and tools and some similar LCA studies, to a complete building analysis provided in this research, it is possible to note that the consistency is the key word to provide a fair comparison between the evaluated structural systems. This is also true to any LCA study focused in comparing the environmental performance of different processes or components. Consistency on an LCA study relates to a coherent functional unit applied using one single LCA tool and methodology. These issues become even more relevant when analysing whole buildings due to their complexity and because their LCA studies often requires more assumptions that might invalidate the study.

Nonetheless, the results of the analyses indicate that the steel building design seems to perform better with the least environmental impacts compared to the concrete building in most of the categories evaluated. When focusing on global warming potential (GWP) results by developing a more in-depth comparison, the research has detected that the use of concrete topping for the steel building flooring assembly is what significantly increased this impact indicator for the steel building.

- Which LCA tools are the most relevant in North America and internationally?

The most relevant LCA tools in North America for the construction industry are BEES and Athena EIE. The EIE software is the most important as it can provide an analysis for the major assemblies and components to whole buildings. However, BEES can provide assessments at a product level, therefore is able to complement the studies from EIE such as including impacts for finishing materials and other products that are missing from EIE software. It is important to note that open based LCA tools are also important because they allow users to develop LCA studies of anything, but it is considerably complex and time consuming, which impose great problems if being used for decision making during a design process.

- How these LCA tools perform regarding their Life Cycle Inventory (LCI) database and methodologies?

The LCI databases used by these LCA software are the most recognized and complete in North America. They were developed by the U.S. Environmental Protection Agency (EPA) and the Athena Institute and includes close to 100% of the assemblies and components in the construction industry. Nevertheless, some material database are older and requires update in order to keep up with the constant upgrades in the industry. As pointed previously, Athena Institute is a non for profit company, and even with little resources is leading the LCI databases development in Canada.

- What are the implications in comparing results from various LCA studies?

The research has pointed the complexity of comparing results from different LCA studies. Each LCA study presents their own specific characteristics, from the goal and scope to methodologies and tools used to reach the results for evaluation. This study has shown that it is impossible to reach any conclusive understanding of such comparison due to the varying methodologies, assumptions, life-span and region presented in each study. Nonetheless, the literature review has pointed to many important aspects and topics also included in this research, such as the importance of analysing embodied and operational impacts, broadening the LCA study to include more impact indicators than just energy consumption and global warming, and other aspects specific to the comparison of steel and concrete. It is a consensus between the analysed studies that steel structural system has higher energy consumption and lower global warming potential when compared to concrete structural systems.

- How accurately Athena Environmental Impact Estimator (EIE) evaluates impacts for steel and concrete structural systems?

The use of 4 different LCA methodologies allowed the comparison of results for the same building and provided a better understanding of their full life cycle impacts. The methodology applied to develop the LCA models for the steel and concrete office buildings using Athena EIE has shown that the software dialogs do not represent steel structural system of the modelled building as accurately as for concrete structure. Table 18 indicates an average inaccuracy in material volume of 6% for the concrete building models and Table 14 has shown an average inaccuracy of 28% for the steel building models. A possible reason for this difference may be the assumptions related to span and bay of steel beam assemblies. Moreover, this study has identified that Athena EIE software does is inaccurate when modeling buildings using its predefined assembly dialogs as shown on tables 15 & 19, which may difficult a proper LCA comparison between different building. The research has shown that the major difference in results is regarding the assumptions used by Athena EIE software about columns & beams. Therefore, a review on the modeling framework for steel structural systems might be required, and possibly allowing the software to incorporate shared beams and columns between adjacent slab plates. This would also facilitate the interpretation and understanding of how the software is evaluating users input. It should be noted that these conclusions are based on the assessment of only one building so further investigation is required.

- How does compare results from different LCA tools evaluating the same building?

The research has also shown that results can vary significantly by modeling the same building with different LCA tools. Each LCA tool has a set of inherent methodologies, LCI datasets and assumptions that imposes challenges when comparing impact indicator results. In order to enable a fair comparison between various studies, they should be developed using the same LCA tool, including same LCI dataset, methodologies and assumptions. Another approach to this problem would be the use of an international benchmark rating system for whole building and building components LCA studies. It would allow LCA practitioners to keep using a diverse source of LCA tools and data that best suits their LCA study objectives, scope and boundaries, but at the same time, providing a way to compare different buildings around the world. Likewise, enable to track sustainable development initiatives applied to building designs that were assessed through a scientific framework as LCA.

- What are the major considerations in the comparison between embodied and operational environmental impacts?

In order to achieve a better understanding of the comparison between operational and total embodied impacts (initial and recurring embodied impacts) further energy use sensitivity analysis should be developed. This research used average energy and fuel consumption values for a typical office building in Toronto from the National Resources Canada statistics and it showed high energy intensity of 420ekWh/m^2. If further analysis is developed comparing operational and embodied impacts, energy performance modeling should be used. The various approaches to decrease the base energy performance (420ekWh/m^2) focused on the physical building (e.g. exterior walls, roof, etc.) must be reflected in new LCA modeling. Such as by improving the envelope to higher thermal resistance, all new materials must be modeled in LCA reaching new results. By decreasing the operational impacts, the total embodied impacts become more significant portion of the total impact of the building during its full life cycle.

Concluding remark:

Although this research has shown some limitations and uncertainties regarding the Athena EIE tool, the software maintains its credibility as a useful design tool to help with understanding the life cycle environmental burdens of design decisions. The software has a significant applicability for the construction industry as a design tool and this study presented one of many. However, this project highlights that without careful consideration it is dangerous to compare results of LCA analyses using different tools, and rather that these tools are perhaps more powerful as aids to design improvement of a particular building, rather than as a way of comparing a variety of buildings.

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Appendix A – Life cycle inventory and methodologies for integration of recycling aspects in LCA tools

1. Life Cycle Inventory phase

The life cycle inventory (LCI) phase is the most work intensive and time consuming of all phases. This is due to the difficult task of compiling all physical flows (inputs and outputs) for every process within the system boundaries. The preferred data collection is as a primary source (such as information collected from site/plant visits), but it is also accepted scientific proven secondary sources from literature and/or available databases. Although LCA studies are being developed for over 30 years, there is still great data scarcity, especially for the building industry in North America (EPA, 2006; Finnveden, et al., 2009; Malin, 2005). Another complex task during the LCI phase is the correct allocation of the physical flows to each finished part/component of all processes involved within the system boundaries. Furthermore, the allocation of physical flows for recyclable content, recyclability potential and reuse aspects of products within same life cycle stage or between different stages. Figure 5 is an example for reuse and recycling aspects of a system boundary. Many methodologies were developed to address this complex task of properly allocating physical flows. Although these methodologies can provide different results for a same product, they are accepted by ISO standards if they are applied consistently and transparently throughout an LCA study.

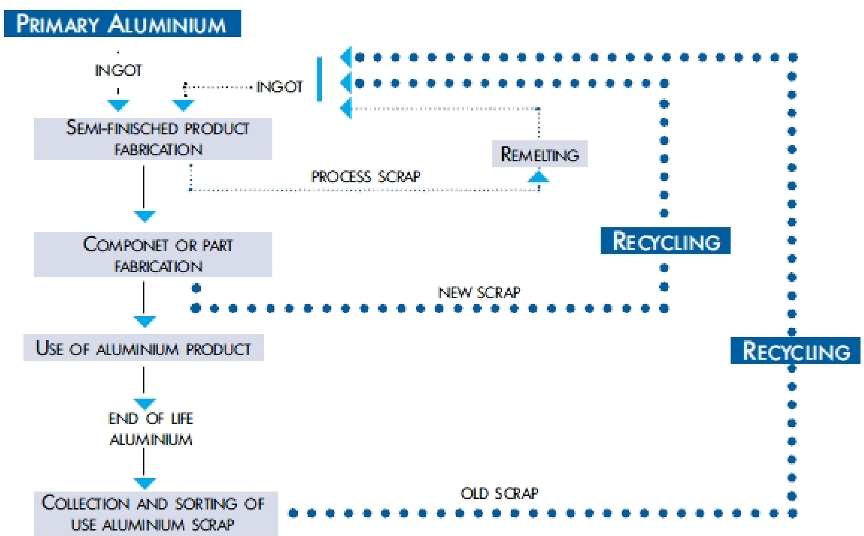

Figure 5 - Example of system boundaries for aluminum products life cycle (EAA, n.d.)

The ISO 14041 standards, section 6.5.3, describe allocation procedures, and ISO 14049, section 7.2, exemplify the three-step hierarchy, and that must be also applied for recycling considerations under the LCI phase (Athena, 2004; EPA, 2006; Finnveden, et al., 2009; Howard, N., Edwards, S., & Anderson, J., n.d.; Pears, A., & Grant, T., n.d.; Peuportier, B., and Putzeys, k., 2005; Trusty, W., 2002):

- First, the practitioner must avoid the allocation process:

This can be achieved by either increasing the modeling detail, i.e. further developing the studied process into all its subprocesses and accounting all inputs and outputs within the subprocesses; or by system expansion, which therefore consider a system boundary expansion, incorporating the new function (product) in the study.

- Second, when allocation cannot be avoided, the partition must reflect the physical relation between products, co-products and by-products:

The practitioner must develop sensitivity analyses within the system processes in order to identify how the additional products are changed considering the elementary flows, and then divide the inputs and outputs to their physical relevance. In this step, ISO states that "the allocation will not be in proportion to any simple measurement such as mass or molar flows of co-products".

- Third, when the physical relationship study alone cannot be used for the allocation, the partitioned inputs and outputs should reflect more simpler physical relationships:

Because of the complexity of allocation in LCI, practitioners often fall into this third step due to lack of information for the other steps or even time and resources available for the study. It is common practices to use mass as the physical relationship to allocate inputs and outputs, but another important relation is the economic value of the output products.

In regarding allocation for reuse and recycling, ISO standards 14041, outlined in section 6.5.4, defines the closed- or open-loop recycling in full attributional LCA studies. ISO states that the closed-loop recycling can be considered as the waste allocation method in which the materials wasted will not carry any environmental burdens, and in the case of being recycled, it must account the "full system of processes required for recovery and recycling", such as collection of material, transportation, reprocessing, etc., until the product is ready to be used in the main studied process production. Waste allocation method is the opposite of the co-product allocation method, where the output co-product must carry part of the environmental burdens generated from the process.

The open-loop recycling allocation is more complex, and ISO specifies that the total life cycles of the studied object must be estimated, from its primary production and use till the incorporation of the object in the studied process. An example model for open-loop recycling is provided by the US LCI guidelines in accordance to ISO standards:

- The first step is to develop the original production of the recovered product using LCI data for the representative typical product that is entering the material recovery stream of the studied system

- Secondly, the allocation must reflect the previous recycled content of the recovered product to the current studied object

- Thirdly, if there is not enough data to track the life cycles of the recovered product entering the studied system, it must be assumed that there was no previous recycling and half of the burdens of the primary production must be allocated to the study

- In addition, all operational burdens are not accounted to reclaimed materials, but similarly to the closed-loop recycling, all systems and processes required to collect, and reprocess the material must be accounted

The four attributes considered by ISO to calculate the net LCI considering production of primary and recycled materials are (FWI, 2007):

- The primary LCI which consists of the cradle-to-gate LCI to produce virgin material
- The recycled LCI which consists of the LCI for recycling the material grave-to-gate
- Recovery Rate which consists of the fraction of material that is recovered over one life cycle
- Yield aspect which consists of the secondary process's efficiency in converting the reclaimed material into primary product

2. Methodologies for integration of recycling aspects in LCA tools

The "home-scrap" is an important consideration as a recycling potential material, but its environmental burdens must be accounted to the main product and co-products output stream of a process. Therefore, when home-scrap is added in the input stream as a source of material, it is actually decreasing the embodied impacts of the process. However, recycling potential from materials reclaimed at operational and end-of-life stages have inherent environmental impacts, and the process of reclaiming and preparing for reprocessing must be also accounted before integrating them into the input stream of the studied process. There are many methodologies developed to account these materials with potential to recycling and recycling content of products, and in this section some of them are presented. The major issues related to recycling and reuse allocation integrated in an LCA tool is (Athena, 2004; Gorgolewski, n.d.; Howard, et al., n.d.; FWI, 2007; Pears, et al., n.d.; Peuportier, B., & Putzeys, K., 2005):

- To avoid counting more than once or undercounting the benefits and/or demerits
- Distinguish and allocate impacts between recycled, reused and primary materials from by-products, co-products or end-of-use scrap
- Timeframe scale of building's life span and the recyclability potential of materials in a distant future

2.1. Methodologies for integration of recycling aspects in LCA tools

In general, this is the most common method used on LCI in order to incorporate recycling into studied processes. The studied "building part" produced in the studied process is accounted with a fixed ratio of recycled content and primary material as per regional or global averages. When this part leaves the system, at the end-of-life, its environmental burdens is not considered for forthcoming generations, i.e. cut-off process as shown in Figure 6.

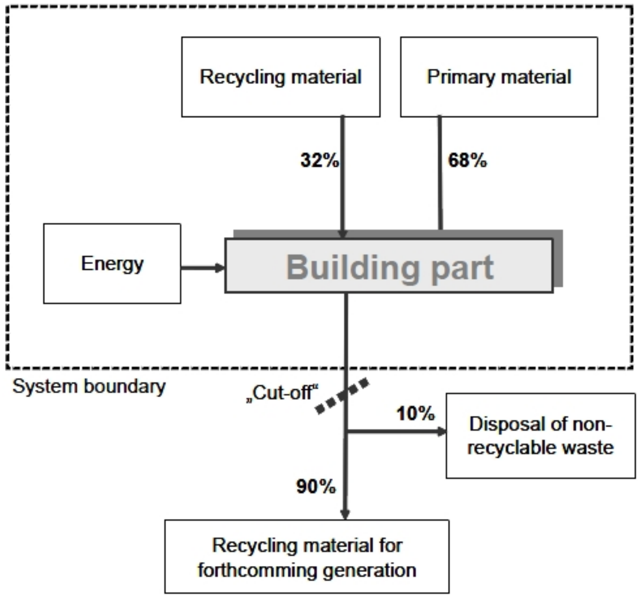

Figure 6 - Cut-off methodology example (Peuportier, et al., 2005)

The major implication of this methodology is that this system does not take into consideration the potential of future recycling of the material, so it does not portray the real aspects of recycling in materials such as steel with high recycled content and high recyclability. Furthermore, there is no distinction between home-scrap recycling and post-consumer recycling, in other words, the waste leaving the system is considered as home-scrap, as described before, with no environmental burdens.

2.2. The "bonus" methodology

The bonus is the difference between the impact of fabrication [I_n] of the main product and the impact of recycling [I_r] the product:

$I_n - I_r$ = bonus (>0 means lower impact; <0 means higher impact)

When the material is not 100% recycled, but has a recycling rate [r] lower than 1 (100%), than the bonus is:

$r \times (I_n - I_r)$

If the recycled material is used in the construction, the bonus accounted in the system is half of the total bonus. In order to reach the total bonus, the material must be considered to be reclaimed and recycled from the demolition, and the other half bonus is accounted. The non-recycled material impact [I_t] corresponding to landfilling or any other practice must be accounted:

$(1 - r) \times I_t$

The impact of the whole life cycle of the studied product is:

$(1 - r)\,(I_n + I_t) + r\,I_r$

Although this method rewards use and production of recycled materials and the collection and reprocessing, it is still a very simplistic method that does not take into consideration variation in ratios of recycling content and recyclability, accounting for fixed values in using or reclaiming the mix of recycled and primary material. Once again, this is not a fair method when considering open-loop recycling or even complex recycling situations such as with steel products.

2.3. The "value corrected" substitution methodology

This methodology is similar to the previous method, however, there is no distinction between recyclability potential at the beginning or at the end of the life cycle, and in this method it is considered a down-cycle rate [p] which consists of a simpler calculation for the ISO term yield of a scrap potential to become a primary product again.

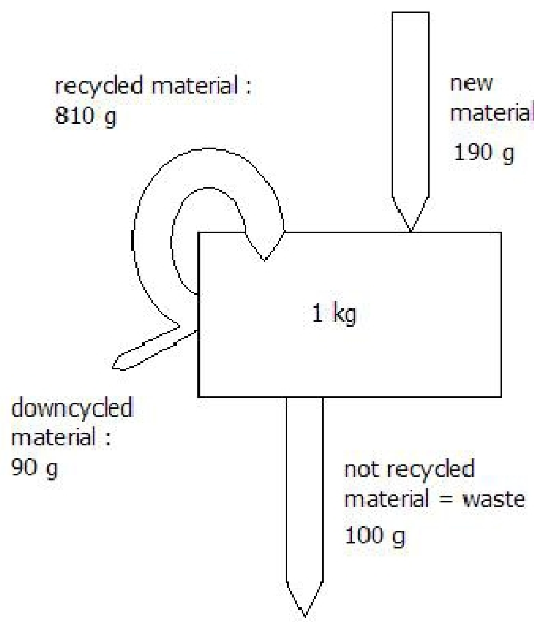

Figure 7 - "Value corrected" methodology for allocation (Peuportier, et al., 2005)

Considering the whole life-cycle of a product, using the corrected value methodology, the formula from the previous method becomes:

$(1 – r \times p)\ I_n + (1 – r)\ I_t + r \times I_r$

In this method, the impact for down-cycling is neglected assuming that is considered the same as the recycling impact, and the recycling rate is considered the same at the beginning and at the end-of-life stages, which results in a less realistic allocation since the method considers that the recycling rate of a material will produce the same recyclability rate. As shown in Figure 7, by not considering the impact of down-cycling, almost 50% of the waste treatment impact is not being considered, and if considering this method for steel, which is primarily produced with a range of 15 to 35% recyclable and secondarily with 85 to 95% recyclability, this method become invalid.

2.4. The “value corrected” substitution methodology

The UK Building Research Establishment (BRE) developed a more complex methodology to develop environmental profiles of materials which was integrated to the Envest 2 LCA software tool. This methodology takes into consideration two important physical relationships of the products, value [v] and mass [t], applying them interconnected (each product has v.t) to previous discussed ISO standards for allocation. The first key point to address the BRE methodology is that it is applied to attributional LCA, therefore, the method considers current practices and values for recycling content and recyclability in order to create a current realistic “playing field” for decision makers.

- Closed-loop recycling

By applying system expansion, the BRE methodology is able to consider recycling into same processes as follows:

From a studied process, the process P is produced as $t_p.v_p$ and used. In the end-of-life, the product reclaimed has $t_r.v_r$ as recyclability potential. Hence, the primary production is:

$P [1 – y (v_r/v_p)] + y (v_r/v_p)$, where y is the yield ratio between t_r/t_p

- Open-loop recycling

For a production of a material that will be recycled into a different process for another use, the final recycled production is:

$R + P (y . v_r/v_p)$

When separate recycling processes are integrated to n number of recycles [R] the final recycled production must be allocated as:

$R [1 – (y . v_r/v_p)^n] + P [(y . v_r/v_p)^n – (y . v_r/v_p)^{(n+1)}]$

In this case, the BRE methodology explicit considers waste scrap with value and environmental burdens to be carried from the primary production, in other words, “burdens will be allocated based on the residual value of the waste stream compared to the value of the process product (and waste) streams”.

As per ISO specifications, when a material is recycled into the same process, it is assumed that its inherent properties did not change in the recycling process, therefore closed-loop. In this situation, if the material to be recycled came from the same process, “home-scrap” it should not bring any environmental burden, while if it is reclaimed, all processes to prepare it for reprocessing must be accounted. Whereas the BRE methodology seems plausible and coherent with the ISO standards, and BRE mention that home-scrap has no environmental burdens accounted, by using relation weight x value, the methodology is computing environmental burdens to every waste produced, home-scrap or post-consumer scrap. Furthermore, the use of monetary value for the products is subjective, because value is subjected to changes according to market trends, while the environmental impacts of the same production would still the same, i.e. if the price of a product grows or diminishes, the environmental impact of that production will keep the same.

In general terms, the final formula for considering allocation in the BRE method via the primary production route is:

$X = X_{primary} – X_{primary}\ y\ (v_r/v_p)$ where X is LCI values for whole production, $X_{primary}$ LCI value for primary production.

Another critique possible regarding the BRE method is the ratio t_r/t_p considered between the amount of produced recycled product over the total production of the product, which invalidate the realistic recycling rate, that should be between the total recycled material over the total scrap produced from the same product, in other words, if the material has a recycling rate of 90%, meaning that 90% of all scrap produced is being recycled, in the BRE method this value is not considered and poses unsatisfactory comparison between products that are not sensitively modified by the method.

2.5. The IISI methodology – for allocation of metallic production

The steel industry often critique the method that general LCA methodologies portray their products into studies comparing different material and products, because other methodologies does not “accurately reflects the environmental benefits of using material that is 100% and infinitely recyclable, capable of yielding recycled products with little or no change in inherent properties, and [that are] currently being recycled” at high percentage rates 70 – 90%. This methodology is globally considered by many LCI datasets that includes steel, and it is also considered the most realistic for any material, while it was originated to calculate LCI data for stainless-steel production. In its first consideration, the International Iron and Steel Institute (IISI) developed a method for closed-loop recycling since steel has negligible inherent properties loss in recycling processes:

$X = X_{primary} + (X_{recycled} – X_{primary}) \times RR \times Y$

Where,

X = LCI data with recycling credit

$X_{primary}$ = X in the case of production on 100% virgin material use

$X_{recycled}$ = X in the case of production on 100% recycled material use

RR = recovery rate, i.e. total weight of recovered scrap over weight delivered (< 1)

Y = yield, which represents the useful recycled product over the input of scrap as raw material (< 1)

This methodology is able to consider all specifications required from ISO as shown before, and was considered to be universally applicable to other products also. This statement can be proven by the following open-loop recycling formula derived from the previous formula:

$X = (X_{primary} - X_{recycled})\ [(1 - r) / (1 - r.n)] + X_{recycled}$

Where r is the yield of useful recycled product over the weight delivered or RR x Y, and n is the number of life cycle stages. In this formula, when n becomes infinite number, both formulas becomes identical:

$X = X_{primary} + r\ (X_{recycled} - X_{primary})$

The relationship r = RR x Y was also developed in additional studies, such as in Young, et al. (2006), with the following depicted method, where W is the same as RR and Y is the same:

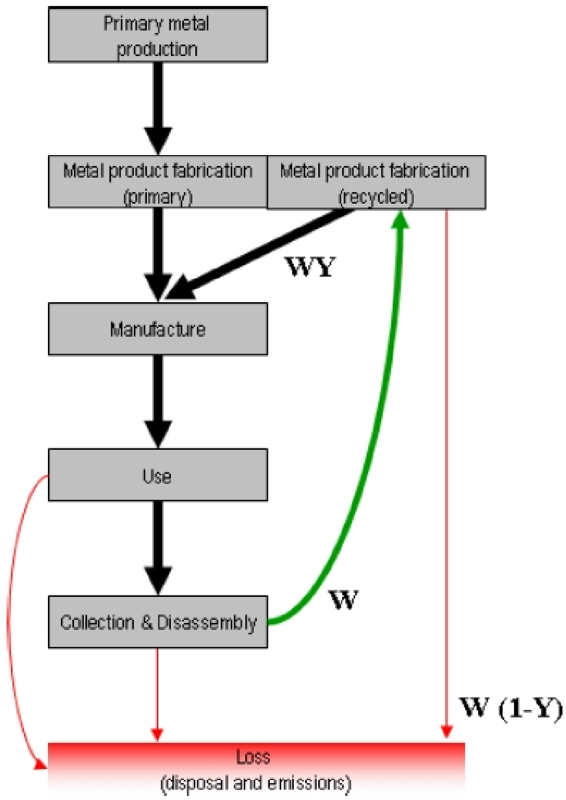

Figure 8 - Depiction of W and Y values from Young, et al. (2006) method (FWI, 2007)

As further considerations for this method, including all other methods, as LCI requires consistency of data, the methodology chosen for the data input in LCI phase on an LCA must be coherent for all products studied and compared. Specifically for this method, Peuportier, et al. (2005) considers that the method cannot be used to LCA focused in describing real impacts for a certain area and time, but is not correct. The IISC methodology was developed considering attributional LCA application, and most comprehensive method. The method is able to calculate regionalized data if the values for RR and Y are referenced for the specific area, but the limitation for comparison to additional products that are not steel or other metallic products is to acquire relevant rates such as RR and Y for the additional materials to be compared. This limitation can impose low credibility for an LCA study, because it will be shifting between different LCI methodologies.

Appendix B – Steel Building Details

The following is a detailed description of the steel building as modelled.

1. Foundation

The characteristics to model the foundation design are:

- Concrete slab on grade = 1426m^2 x 100mm thick
- Grade beams = 145.2m x 400mm x 500mm deep
- Concrete footings = 3.2m x 3.2m x 600mm deed (inner columns, total of 6) and 2.4m x 2.4m x 500mm deep (outer columns, total of 18)
- Footing cap = 2.6m x 2.6m x 500mm deep (inner columns) and 1.6m x 1.6m x 500mm deep (outer columns)

Regarding the Athena Environmental Impact Estimator (EIE) model, the concrete option was 20MPa with 9% flyash (or average) for slab on grade and grade beams and 30MPa with 9% flyash (average) for footings. In order to achieve same functional unit between the EIE model and the Athena Eco-Calculator (EC) mode, extruded polystyrene insulation was added to the grade beams. In the EC model, the assembly group for grade beams consists of poured concrete with extruded polystyrene insulation. Table 1 shows the total materials that represent the foundation design.

Table 1 - Foundation materials quantity

TOTAL FOUNDATION (EIE by assemblies – Model 2)		
Material	Quantity	Unit
Concrete 20 MPa (flyash av)	180.2089	m^3
Concrete 30 MPa (flyash av)	138.6252	m^3
Extruded Polystyrene	118.9928	m^2 (25mm)
Nails	0.0036	Tonnes
Rebar, Rod, Light Sections	2.6126	Tonnes
Welded Wire Mesh / Ladder Wire	1.2886	Tonnes

2. Envelope (walls)

The curtain wall design can be referenced to the Kawneer 7525 series that consists of double pane glazing, 25mm sealed units, with 100mm insulated metal spandrel and thermal break. The glazing area was estimated to be 70% of the total curtain wall area. The penthouse envelope selected was the Vicwest insulated metal panels. The curtain wall design per floor consists of:

- Ground floor = 143m length x 4.48m height = 640.64m^2, therefore 192.192m^2 (spandrel panel) and 448.448m^2 (double pane glazing)

- 2nd to 5th floor = 143m length x 3.7m height = 529.1m^2, therefore 158.73m^2 (spandrel panel) and 370.37m^2 (double pane glazing)

- 6th floor = 143m length x 3.42m height = 489.06m^2, therefore 146.718m^2 (spandrel panel) and 342.342m^2 (double pane glazing)

- Penthouse = 57.2m length x 3.5m height = 200.2m^2 (no glazing area)

The EIE software does not allow choosing a specific manufacturer's product. The EIE model simplifies the design of the curtain wall allowing choosing the size of the wall, its glazing and insulated area. And so, the penthouse EIE model is a curtain wall made of only insulated spandrel panels. Table 2 shows the total materials that represent the curtain wall design.

Table 2 - Envelope walls materials quantity

TOTAL CURTAIN WALL (EIE by assemblies – Model 2)		
Material	Quantity	Unit
Aluminum	47.328	Tonnes
Batt. Fiberglass	9706.547	m^2 (25mm)
EPDM membrane (black, 60 mil)	567.9504	kg
Galvanized Sheet	7.9909	Tonnes
Glazing Panel	83.1649	Tonnes

3. Envelope (roofing)

The roofing assembly specifications for the EIE model are:

- Standard modified bitumen, 2 ply over 1224m^2 (lower roof) and 162m^2 (upper roof)

- Expanded polystyrene insulation 200mm thick

Table 3 shows the total materials that represent the roofing assembly.

Table 3 - Roofing envelope materials quantity

TOTAL ROOFING (EIE by assemblies – Model 2)		
Material	Quantity	Unit
Expanded Polystyrene	11318.966	m^2 (25mm)
Modified Bitumen membrane	12248.636	kg

4. Interior walls and finishes

The interior walls and finishes were designed to represent part of the recurring embodied impacts throughout the building's life span. This consists of partition walls and fire rated protection. According to CISC (2009), the ceiling fire rating should be a sprayed-on protection, and for columns can be sprayed or gypsum boards. In both cases, the protection should withstand at least 1 hour of fire. Since EIE software has no sprayed-on fire rate protection option, all assemblies requiring protection were represented by type-X gypsum boards.

The interior walls and finishing consists of:

- 150m partition walls per floor, with gypsum board and painted on both sides
- Fire-rated walls on central core service
- Fire-rated ceiling
- Fire-rated columns

Table 4 shows the total materials that represent the interior walls and finishing.

Table 4 - Interior walls and finishing materials quantity

TOTAL WALLS & FINISHING (EIE by assemblies – Model 2)		
Material	Quantity	Unit
1/2" Fire-Rated Type X Gypsum Board	11705.62	m^2
1/2" Regular Gypsum Board	5709	m^2
Galvanized Studs	11.6861	Tonnes
Joint Compound	17.3821	Tonnes
Nails	0.2488	Tonnes
Paper Tape	0.1994	Tonnes
Water Based Latex Paint	1873.18	L

5. Above grade structural systems

The structural steel design was take from CISC (2009), the steel deck used in the floor system is the Canam P2432 composite steel deck (76mm deep and 0.91mm gauge) with 65mm concrete (25MPa) topping. In order to model the steel structural system design in EIE by assemblies (Model 2), the typical floor level was divided in 4 plate types (see Figure 1):

- Plate 01 = 12m x 12m (corresponding to grids AC-13, EG-13, AC-46 and EG-46)
- Plate 02 = 12m x 9m (corresponding to grids CD-13, DE-13, CD-46 and DE-46)
- Plate 03 = 9m x 9m (corresponding to grids CD-34 and DE-34)
- Plate 04 = 12m x 9m (corresponding to grids AC-34 and EG-34)

The framing members are (see Figure 1):

- Beams (B) & Spandrel Beams (SB) = W410x46 X 9m length and W410x46 X 4.25m length on corners)
- Core Beams (CB) = W360x45 X 9m length from 1st to 4th floor, and W360x33 X 9m length from 5th to penthouse
- Spandrel Girders (SG) = W610x113 X 9m length
- Girders (G1) = W760x147 X 9m length
- Girders (G2) = W760x173 x 12m length
- Floor open-web steel Joists (FJ) = 750mm depth X 12m long, 25.3kg/m

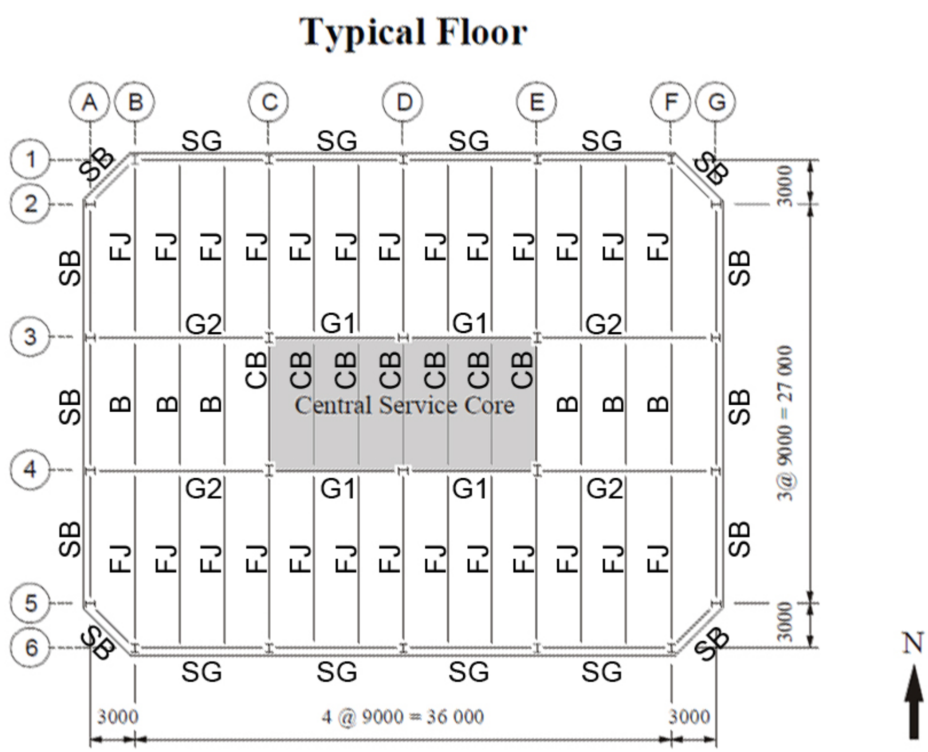

Figure 1 - Typical steel building floor plan framing specification

There are two sets of columns specification for the steel building design, the inner columns (total of 6) and outer columns (total of 18), hence a total of 24 columns. These columns vary per floor level. The inner columns specifications are:

- W310x179 from 1st to 3rd floor
- W310x86 from 4th to 6th floor
- W250x49 at the penthouse

The outer columns specifications are:

- W310x129 from 1st to 3rd floor
- W310x74 from 4th to 6th floor

Additionally to these structural specifications, the building was designed to withstand earthquakes and wind loads. Therefore, the building was designed with hollow core steel bracing in the central core service of the building. These braces also vary per floor level as described below:

- 1st floor = HSS203x203x6.4 X 6.16m length
- 2nd floor = HSS203x203x6.4 X 5.86m length
- 3rd and 4th floors = HSS152x152x6.4 X 5.86m length
- 5th and 6th floors = HSS152x152x4.8 X 5.86m length
- Penthouse = HSS102x102x3.2 X 5.7m length

The design for the roof structural system did not require concrete topping. Lower and upper roof steel decks are supported mainly by open-web steel joists. To withstand snow-load, the design has various distances of the joists (o/c.). In order to model the roof structural system, these distances were averaged while keeping the same amount of joists. The roof steel deck is a Canam with 38mm depth and 0.91mm gauge. In order to model the roof structural system in EIE by assemblies (Model 2), the roof plan was divided in 3 plate types (see Figure 2):

- Plate 01 (upper roof) = 9m x 9m (corresponding to grids CD-34 and DE-34)
- Plate 02 (lower roof) = 12m x 9m (corresponding to grids BC-13, CD-13, DE-13, EF-13, AC-34, EG-34, BC-46, CD-46, DE-46 and EF-46)
- Plate 03 (lower roof) = 12m x 3m (corresponding to grids AB-13, FG-13, AB-46 and FG-46)

The upper roof framing consists of:

- Upper Roof open-web steel Joists (URJ) = 700mm depth X 9m long @ 1.8m o/c, 14.7kg/m
- Upper Roof Beams (URB) = W360x33 X 9m long
- Upper Roof Girders (URG) = W530x74 X 9m long

The lower roof framing consists of:

- Lower Roof open-web steel Joists (LRJ) = 700mm depth X 9m long @ 1.3m o/c (averaged) & 700mm depth X 10.5m long @ 1.5m o/c, 14.7kg/m

- Perimeter Beams (PB) = W360x33 X 9m length & W360x33 X 4.25m length (corners)
- Lower Roof Girders (LRG) = W760x147 X 12m length

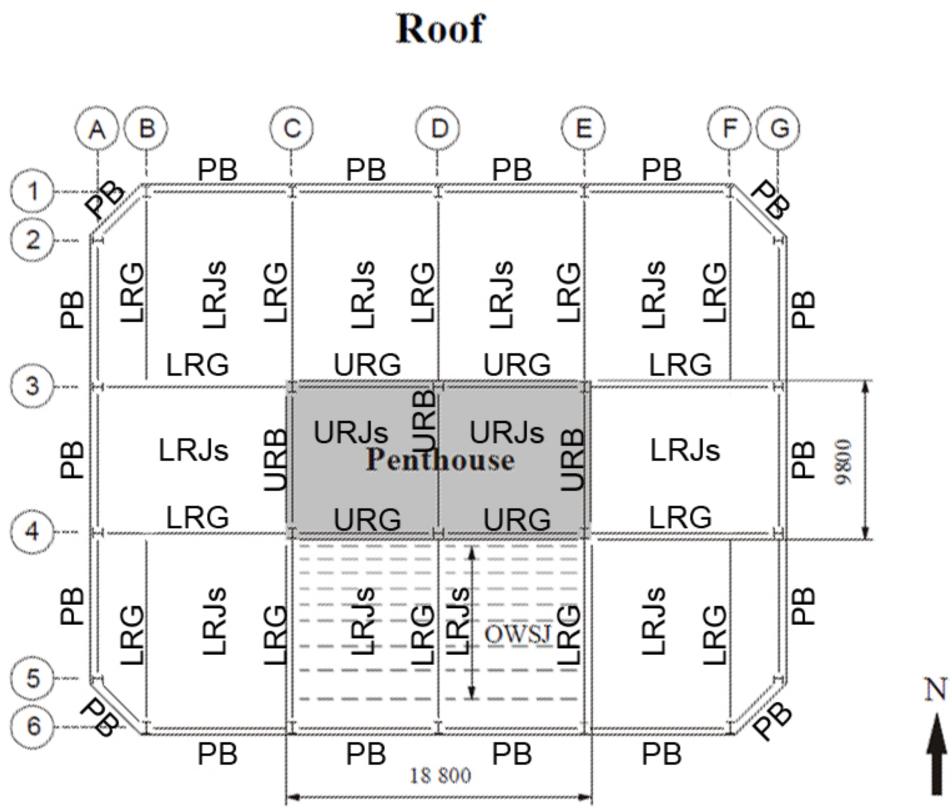

Figure 2 - Typical steel building roof plan framing specification

Table 6 shows the total materials that represent the above grade structural materials.

Table 6 - Total structural materials quantity

Material	EIE by assemblies (Model 2) material list for above grade structural materials (provided by EIE) Quantity	Unit	EIE by quantities (Model 3) take-off list (hand calculated)		TOTAL	Ratio of EIE by assemblies over EIE by quantities
Concrete 20 MPa (flyash av 9%)	655.30	m^3	103 mm	$7092m^2$	730.48	90%
Galvanized Decking (floor)	70.20	Tonnes	15 kg/m^2	$7092m^2$	81.56	86%
Galvanized Decking (roof)	13.72	Tonnes	10 kg/m^2	$1386m^2$	13.86	99%
OWSJ (130 x 12m x 750mm)	44.32	Tonnes	25.3 kg/m	1560m	39.47	112%
OWSJ (+-103 x 9m x 700mm)	18.45	Tonnes	14.7kg/m	(+-990m)	13.58	136%
Rebar, Rod, Light Sections	6.41	Tonnes	1.26 kg/m^2	$8046m^2$	10.15	63%
Screws Nuts & Bolts	21.82	Tonnes	n/a	n/a	21.82	100%
W360x33 (+-33 x 9m)	n/a	kg	33kg/m	296m	9,768.00	n/a
W360x45 (28 x 9m)	n/a	kg	45kg/m	252m	11,340.00	n/a
W410x46 (+-73 x 9m)	n/a	kg	46kg/m	661m	30,406.00	n/a
W530x74 (4 x 9m)	n/a	kg	74kg/m	36m	2,664.00	n/a
W610x113 (40 x 9m)	n/a	kg	113kg/m	360m	40,680.00	n/a
W760x147 (20 x 9m)	n/a	kg	147kg/m	180m	26,460.00	n/a
W760x173 (20 x 12m)	n/a	kg	173kg/m	240m	41,520.00	n/a
W760x147 (14 x 12m)	n/a	kg	147kg/m	168m	24,696.00	n/a
W310x86 (18 x 3.7m)	n/a	kg	86kg/m	66.6m	5,727.60	n/a
W250x49 (penthouse) (6 x 3.5m)	n/a	kg	49kg/m	21m	1,029.00	n/a
W310x129 (36 x 3.7m + 18 x 4.2)	n/a	kg	129kg/m	208.8m	26,935.20	n/a
W310x179 (12 x 3.7m + 6 x 4.2)	n/a	kg	179kg/m	69.6m	12,458.40	n/a
W310x74 (54 x 3.7m)	n/a	kg	74kg/m	199.8m	14,785.20	n/a
Wide Flange Sections	385.39	Tonnes	n/a		248.47	155%
HSS102x102x3.2 (8 x 5.7m)	n/a	Tonnes	9.62kg/m	45.6m	0.44	n/a
HSS203x203x6.4 (8 x 5.86m + 8 x 6.16m)	n/a	Tonnes	38.4kg/m	96.16m	3.69	n/a
HSS152x152x6.4 (16 x 5.86m)	n/a	Tonnes	28.3kg/m	93.76m	2.65	n/a
HSS152x152x4.8 (16 x 5.86m)	n/a	Tonnes	21.7kg/m	93.76m	2.03	n/a
TOTAL STEEL	560.31	Tonnes	n/a	n/a	437.73	128%

5.1. Steel building with composite floor system for sensitivity analysis

The structural steel design from CISC (2009) was adapted with composite floor system. The framing members are (see Figure 1):

- Beams (B) & Spandrel Beams (SB) = W360x33 X 9m length and W360x33 X 4.25m length on corners)
- Core Beams (CB) = W360x45 X 9m length from 1st to 4th floor, and W360x33 X 9m length from 5th to penthouse
- Spandrel Girders (SG) = W410x46 X 9m length
- Girders (G1) = W610x101 X 9m length
- Girders (G2) = W690x125 x 12m length
- Floor open-web steel Joists (FJ) = 750mm depth X 12m long, 25.3kg/m

Table 7 shows the total materials that represent the above grade structural materials.

Table 7 - Total structural materials quantity

		EIE by quantities (Model 3) take-off list for composite floor system			Ratio of composite floor system material quantities over non-composite floor system material quantities
Material	Unit			TOTAL	
Concrete 20 MPa (flyash av 9%)	m^3	103 mm	$7092m^2$	730.476	100%
Galvanized Decking (floor)	Tonnes	$11.5\ kg/m^2$	$7092m^2$	81.558	100%
Galvanized Decking (roof)	Tonnes	$10\ kg/m^2$	$1386m^2$	13.86	100%
OWSJ (130 x 12m x 750mm)	Tonnes	25.3 kg/m	1560m	39.468	100%
OWSJ (+-103 x 9m x 700mm)	Tonnes	14.7kg/m	924m	13.5828	100%
Rebar, Rod, Light Sections	Tonnes	$1.13\ kg/m^2$	$14042\ m^2$	15.86746	64%
Screws Nuts & Bolts	Tonnes	n/a	n/a	21.8245	100%
W360x33 (+-112 x 9m)	kg	33kg/m	1011m	33363	29%
W360x45 (28 x 9m)	kg	45kg/m	252m	11340	100%
W410x46 (44 x 9m)	kg	46kg/m	396m	18216	167%
W530x74 (4 x 9m)	kg	74kg/m	36m	2664	100%

		EIE by quantities (Model 3) take-off list for composite floor system			Ratio of composite floor system material quantities over non-composite floor system material quantities
Material	Unit			TOTAL	
W610x101 (20 x 9m)	kg	101kg/m	180m	18180	146%
W690x125 (20 x 12m)	kg	125kg/m	240m	30000	138%
W760x147 (14 x 12m)	kg	147kg/m	168m	24696	100%
W310x86 (18 x 3.7m)	kg	86kg/m	66.6m	5727.6	100%
W250x49 (penthouse) (6 x 3.5m)	kg	49kg/m	21m	1029	100%
W310x129 (36 x 3.7m + 18 x 4.2)	kg	129kg/m	208.8m	26935.2	100%
W310x179 (12 x 3.7m + 6 x 4.2)	kg	179kg/m	69.6m	12458.4	100%
W310x74 (54 x 3.7m)	kg	74kg/m	199.8m	14785.2	100%
Wide Flange Sections	Tonnes	n/a		199.3944	125%
HSS102x102x3.2 (8 x 5.7m)	Tonnes	9.62kg/m	45.6m	0.438672	100%
HSS203x203x6.4 (8 x 5.86m + 8 x 6.16m)	Tonnes	38.4kg/m	96.16m	3.692544	100%
HSS152x152x6.4 (16 x 5.86m)	Tonnes	28.3kg/m	93.76m	2.653408	100%
HSS152x152x4.8 (16 x 5.86m)	Tonnes	21.7kg/m	93.76m	2.034592	100%
TOTAL STEEL	Tonnes	n/a	n/a	394.3744	111%

6. Final materials take-off list

Table 8 shows the final take-off materials list used to develop the EIE models by quantities (Model 3) for the steel building: values on the left for the whole building model and values on the right for the structure only. Note that the boxes highlighted relate to structure and so were hand-calculated, others were taken from EIE. The values on the structural model column that are 0 or less than the value for the whole building model refers to non-structural materials. The only non-structural materials included on structural model are those included in fire rated protection walls for columns, beams, steel decks and central core services.

Table 8 - Final materials take-off list for steel building models by quantities (Model 3)

Materials	Unit	Non-composite floor system Whole building	Non-composite floor system Structural building	Composite floor system Structural building (10% less steel)	Composite floor system Structural building (20% less steel)
Concrete 20 MPa (flyash av)	m^3	902.12	902.12	902.12	902.12
Concrete 30 MPa (flyash av)	m^3	132.02	132.02	132.02	132.02
Galvanized Decking	Tonnes	95.42	95.42	95.42	95.42
Galvanized Sheet	Tonnes	7.91	0.00	0.00	0.00
Galvanized Studs	Tonnes	11.57	3.74	3.74	3.74
Hollow Structural Steel	Tonnes	8.82	8.82	8.82	8.82
Nails	Tonnes	0.24	0.11	0.11	0.11
Open Web Joists	Tonnes	53.05	53.05	53.05	44.31
Rebar, Rod, Light Sections	Tonnes	12.76	12.76	18.48	20.12
Screws Nuts & Bolts	Tonnes	21.19	21.19	21.19	21.19
Welded Wire Mesh / Ladder Wire	Tonnes	1.26	1.26	1.26	1.26
Wide Flange Sections	Tonnes	248.47	248.47	199.39	166.55
1/2" Fire-Rated Type X Gypsum Board	m^2	10641.47	10641.47	10641.47	10641.47
1/2" Regular Gypsum Board	m^2	5190.00	0.00	0.00	0.00
Joint Compound	Tonnes	16.24	10.92	10.92	10.92
Paper Tape	Tonnes	0.19	0.13	0.13	0.13
Batt. Fiberglass	m^2 (25mm)	9244.33	0.00	0.00	0.00
Expanded Polystyrene	m^2 (25mm)	10779.97	0.00	0.00	0.00
Extruded Polystyrene	m^2 (25mm)	113.33	0.00	0.00	0.00
EPDM membrane (black, 60 mil)	kg	551.41	0.00	0.00	0.00
Modified Bitumen membrane	kg	11891.88	0.00	0.00	0.00
Aluminum	Tonnes	47.33	0.00	0.00	0.00
Glazing Panel	Tonnes	83.16	0.00	0.00	0.00
Water Based Latex Paint	L	1836.45	1234.41	1234.41	1234.41

Note: Values for concrete volume and rebar differ from Table 7 because in this table it includes foundation materials. Table 10 refers to above grade structural materials.

Appendix C – Concrete Building Details

This appendix provides additional details of the concrete building.

1. Foundation

The characteristics to model the foundation design for the concrete building are:

- Concrete slab on grade = 1426m^2 x 100mm thick (same for steel building)
- Grade beams = 145.2m x 400mm x 500mm deep (same for steel building)
- Concrete footings = 3.36m x 3.36m x 600mm deed (inner columns, total of 12) and 2.52m x 2.52m x 500mm deep (outer columns, total of 18)
- Footing cap = 2.73m x 2.73m x 500mm deep (inner columns) and 1.7m x 1.7m x 500mm deep (outer columns)

Table 1 shows the total materials that represent the foundation design. As with the steel building, 20MPa concrete was used for slab on grade and grade beams, and 30MPa concrete for all footings. The total concrete volume for the concrete building foundation is approximately 25% more than the foundation for the steel building on Table 2.

Table 1 - Total foundation materials quantity

TOTAL FOUNDATION (EIE by components)		
Material	Quantity	Unit
Concrete 20 MPa (flyash av)	180.2089	m^3
Concrete 30 MPa (flyash av)	218.7373	m^3
Extruded Polystyrene	118.9928	m^2 (25mm)
Nails	0.0036	Tonnes
Rebar, Rod, Light Sections	1.6681	Tonnes
Welded Wire Mesh / Ladder Wire	1.2886	Tonnes

2. Interior walls and finishes

Regarding the functional unit of both building designs, the concrete building does not require fire rated protection on its structure, but similarly to the steel building, the ceiling was designed to withstand at least one hour fire with the use of type-X gypsum boards. The interior walls and finishes consist of:

- 150m partition walls per floor, with gypsum board, painted on both sides

Table 2 shows the total materials that represent the interior walls and finishing.

Table 2 - Interior walls and finishing materials quantity

TOTAL WALLS & FINISHING (by components)		
Material	Quantity	Unit
1/2" Fire-Rated Type X Gypsum Board	9345.897	m^2
1/2" Regular Gypsum Board	5709	m^2
Galvanized Studs	7.908	Tonnes
Joint Compound	19.4519	Tonnes
Nails	0.2266	Tonnes
Paper Tape	0.1722	Tonnes
Water Based Latex Paint	1619.359	L

3. Above grade structural systems

The structural system is mainly suspended concrete slabs, supported by drop panels above columns. The typical floor level was divided in 3 plate types:

- Plate 01 = 7.5m x 7.5m (corresponding to grids AB-12, EF-12, AB-45 and EF-45)
- Plate 02 = 7.5m x 9m (corresponding to grids BC-12, CD-12, DE-12, AB-23, EF-23, AB-34, EF-34, BC-45, CD-45 and DE-45)
- Plate 03 = 9m x 9m (corresponding to grids BC-23, CD-23, DE-23, BC-34, CD-34, DE-34, with the central core services represented by CD-23 and CD-34)

The typical floor area is 1426m^2, the same for the steel building. Since the drop panel is integrated to the slab (considering its volume of concrete and reinforcement), its area was included on the floor slab to provide the values for the model by quantities (Model 3). The drop panels are 4.5m x 4.5m area, and both slab and panels are 220mm thick. The total slab area is (33m x 42m) slab + (20.25m x 20m) drop-down panels = 1791m^2. The concrete design therefore has only two components to be considered structurally, the slabs and columns. As the building has bigger grid, it also accounts for more columns. The concrete design has 18 outer columns and 12 inner columns, with total of 30 columns.

4. Envelope (walls)

The curtain wall design for the concrete building was the same as for the steel building.

5. Envelope (roof)

The roof finish for the concrete building was the same as for the steel building.

6. Final materials take-off list

Table 3 represents the total materials that consists the concrete building design that was used to develop the model by unit. It is divided by material category and includes values for each respective waste ratio, as well the reference values (hand calculated and extracted from EIE model by component). The right column represents values used for an only structural concrete building model. Please note that the values used in the green boxes were hand calculated, therefore the waste ratio was not applied.

Table 3 - Materials take-off list for concrete building model by quantities (Model 3)

MATERIALS	Unit	EIE model by quantities Whole building	EIE model by quantities Structural
Concrete 20 MPa (flyash av)	m^3	565.66	565.66
Concrete 30 MPa (flyash av)	m^3	2,422.22	2,422.22
Galvanized Sheet	Tonnes	7.91	0
Galvanized Studs	Tonnes	7.83	0
Nails	Tonnes	0.22	0
Rebar, Rod, Light Sections	Tonnes	305.83	305.83
Screws Nuts & Bolts	Tonnes	1.90	1.90
Welded Wire Mesh / Ladder Wire	Tonnes	1.26	1.26
1/2" Fire-Rated Type X Gypsum Board	m^2	8,496.27	0
1/2" Regular Gypsum Board	m^2	5,190	0
Joint Compound	Tonnes	18.18	0
Paper Tape	Tonnes	0.16	0
Batt. Fiberglass	m^2 (25mm)	9,244.33	0
Expanded Polystyrene	m^2 (25mm)	10,779.97	0
Extruded Polystyrene	m^2 (25mm)	113.33	0
EPDM membrane (black, 60 mil)	kg	551.41	0
Modified Bitumen membrane	kg	11,891.88	0
Aluminum	Tonnes	47.33	0
Glazing Panel	Tonnes	83.16	0
Water Based Latex Paint	L	1,587.61	0
Note: Values for concrete volume and rebar differ from Table 10 because in this table it includes foundation materials. Table 11 refers to above grade structural materials.			

Appendix D – Detailed Results

This section presents the summary of results for all models prepared for the steel and concrete buildings. All results presented here are the embodied impacts of the buildings. A series of models were developed to reach these results, including sensitivity analysis testing. The details will be discussed specifically to each case.

1. Steel building results

Table 1 - Eco-calculator results – Model 1 whole building (Steel Building)

ASSEMBLY	Total area (sq ft)	Fossil Fuel Consumption (MJ) TOTAL	Weighted Resource Use (tonnes) TOTAL	GWP (tonnes CO_2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	HH Respiratory Effects Potential (kg PM2.5 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
Foundations & Footings	16,124	713,752	803	93	27,574	233	25,161	208	306
Columns & Beams	94,042	3,785,312	327	158	65,570	316	289,213	1	321
Intermediate Floors	78,699	5,606,477	2,370	413	129,550	1,102	183,186	389	905
Exterior Walls	12,633	1,754,795	128	131	212,413	1,586	50,315	425	967
Windows	24,450	3,910,508	667	610	533,181	8,172	199,414	753	3,911
Interior Walls	41,149	1,327,914	172	62	24,609	400	18,600	14	167
Roof	15,344	3,345,025	175	89	44,448	257	32,031	4	695
TOTALS	**3,824**	20,443,783	4,642	1,556	1,037,345	12,066	797,920	1,794	7,272

Table 2 - EIE by assemblies – Model 2 whole building (Steel Building per life cycle phase)

Steel Building by assemblies	Manufacturing			Construction			End - Of - Life			Total Effects
Whole building	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	22,990,144	272,466	**23,262,610**	181,778	389,578	**571,356**	291,097	117,643	**408,739**	**24,242,706**
Weighted Resource Use kg	4,315,807	7,311	**4,323,118**	3,956	9,160	**13,116**	6,842	2,766	**9,608**	**4,345,841**
Global Warming Potential (kg CO_2 eq)	1,217,216	20,273	**1,237,489**	11,241	29,100	**40,341**	18,942	8,788	**27,730**	**1,305,560**
Acidification Potential (moles of H+ eq)	864,994	7,036	**872,030**	5,623	9,178	**14,802**	1,050	2,772	**3,822**	**890,653**
HH Respiratory Effects Potential (kg PM2.5 eq)	7,572	8	**7,581**	8	11	**19**	1	3	**4**	**7,604**
Eutrophication Potential (kg N eq)	902	7	**910**	4	10	**14**	1	3	**3**	**927**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-03	8.E-07	**2.E-03**	4.E-10	1.E-06	**1.E-06**	9.E-07	4.E-07	**1.E-06**	**2.E-03**
Smog Potential (kg NOx eq)	4,929	159	**5,088**	111	205	**316**	13	62	**75**	**5,479**

Table 3 - EIE by assemblies – Model 2 whole building (Steel building per assembly groups)

Steel Building by assemblies (whole building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	721,946	7,289,683	8,936,978	992,257	6,301,843	**24,242,706**
Weighted Resource Use kg	848,493	545,503	624,167	24,395	2,303,283	**4,345,841**
Global Warming Potential (kg CO_2 eq)	90,488	472,686	303,086	28,550	410,750	**1,305,560**
Acidification Potential (moles of H+ eq)	26,144	598,307	126,134	14,976	125,092	**890,653**
HH Respiratory Effects Potential (kg PM2.5 eq)	232	5,855	606	57	855	**7,604**
Eutrophication Potential (kg N eq)	16	171	552	7	181	**927**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-04	1.E-03	2.E-06	6.E-07	4.E-04	**2.E-03**
Smog Potential (kg NOx eq)	298	3,234	617	506	823	**5,479**

Table 4 - EIE by assemblies – Model 2 structural building (Steel building per life cycle phase)

Steel Building by assemblies	Manufacturing			Construction			End - Of - Life			Total Effects
(structural building)	Material	Transportation	Total	Material	Transportation	Total	Material	Transportation	Total	
Primary Energy Consumption MJ	15,135,663	238,113	**15,373,776**	173,665	256,323	**429,987**	285,334	100,449	**385,783**	**16,189,546**
Weighted Resource Use kg	3,785,564	6,430	**3,791,994**	3,807	6,027	**9,833**	6,706	2,362	**9,068**	**3,810,896**
Global Warming Potential (kg CO_2 eq)	743,150	18,137	**761,286**	10,814	19,147	**29,961**	18,567	7,503	**26,070**	**817,317**
Acidification Potential (moles of H+ eq)	261,165	6,198	**267,363**	5,444	6,039	**11,483**	1,029	2,366	**3,396**	**282,242**
HH Respiratory Effects Potential (kg PM2.5 eq)	1,703	7	**1,710**	8	7	**15**	1	3	**4**	**1,729**
Eutrophication Potential (kg N eq)	735	6	**742**	4	6	**11**	1	2	**3**	**755**
Ozone Depletion Potential (kg CFC-11 eq)	6.E-04	7.E-07	**6.E-04**	4.E-10	8.E-07	**8.E-07**	8.E-07	3.E-07	**1.E-06**	**6.E-04**
Smog Potential (kg NOx eq)	1,302	140	**1,441**	110	135	**245**	13	53	**66**	**1,753**

Table 5 - EIE by assemblies – Model 2 structural building (Steel building per assembly groups)

Steel Building by assemblies (structural building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	713,174	237,553	8,936,978	n/a	6,301,843	**16,189,546**
Weighted Resource Use kg	848,299	35,146	624,167	n/a	2,303,283	**3,810,896**
Global Warming Potential (kg CO_2 eq)	90,043	13,438	303,086	n/a	410,750	**817,317**
Acidification Potential (moles of H+ eq)	25,951	5,064	126,134	n/a	125,092	**282,242**
HH Respiratory Effects Potential (kg PM2.5 eq)	231	37	606	n/a	855	**1,729**
Eutrophication Potential (kg N eq)	16	5	552	n/a	181	**755**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-04	3.E-07	2.E-06	n/a	4.E-04	**6.E-04**
Smog Potential (kg NOx eq)	290	22	617	n/a	823	**1,753**

Table 6 - EIE by quantities – Model 3 whole building (Steel building per life cycle phase)

Steel Building by quantities	Manufacturing			Construction			End - Of - Life			Total Effects
(whole building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	20,893,647	256,128	**21,149,775**	182,877	391,934	**574,811**	264,783	124,942	**389,725**	**22,114,312**
Weighted Resource Use kg	4,474,411	7,020	**4,481,430**	3,980	9,215	**13,195**	6,223	2,938	**9,161**	**4,503,786**
Global Warming Potential (kg CO_2 eq)	1,178,015	19,110	**1,197,125**	11,309	29,276	**40,585**	17,230	9,333	**26,563**	**1,264,273**
Acidification Potential (moles of H+ eq)	840,297	6,718	**847,015**	5,657	9,234	**14,891**	955	2,944	**3,899**	**865,805**
HH Respiratory Effects Potential (kg PM2.5 eq)	7,488	8	**7,497**	8	11	**19**	1	4	**4**	**7,520**
Eutrophication Potential (kg N eq)	738	7	**745**	4	10	**14**	1	3	**3**	**763**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-03	8.E-07	**2.E-03**	4.E-10	1.E-06	**1.E-06**	8.E-07	4.E-07	**1.E-06**	**2.E-03**
Smog Potential (kg NOx eq)	4,837	152	**4,989**	112	206	**318**	12	66	**78**	**5,384**

Table 7 - EIE by quantities – Model 3 whole building (Steel building per assembly groups)

Steel Building by quantities (whole building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	726,523	7,940,725	5,949,177	1,026,087	6,471,799	**22,114,312**
Weighted Resource Use kg	1,036,723	771,346	501,646	29,553	2,164,518	**4,503,786**
Global Warming Potential (kg CO_2 eq)	94,615	531,695	208,732	30,499	398,732	**1,264,273**
Acidification Potential (moles of H+ eq)	25,800	629,830	83,913	15,412	110,850	**865,805**
HH Respiratory Effects Potential (kg PM2.5 eq)	238	6,138	404	58	682	**7,520**
Eutrophication Potential (kg N eq)	17	175	358	6	207	**763**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-04	1.E-03	2.E-06	7.E-07	3.E-04	**2.E-03**
Smog Potential (kg NOx eq)	283	3,505	418	539	639	**5,384**

Table 8 - EIE by quantities – Model 3 structural building (Steel building per life cycle phase)

Steel Building by quantities	Manufacturing			Construction			End - Of - Life			Total Effects
(structural building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	13,091,782	222,266	**13,314,048**	175,409	258,897	**434,306**	259,125	107,605	**366,730**	**14,115,084**
Weighted Resource Use kg	3,949,215	6,153	**3,955,368**	3,845	6,087	**9,932**	6,102	2,535	**8,638**	**3,973,938**
Global Warming Potential (kg CO_2 eq)	705,886	17,012	**722,898**	10,923	19,339	**30,262**	16,895	8,055	**24,950**	**778,110**
Acidification Potential (moles of H+ eq)	237,241	5,894	**243,135**	5,499	6,099	**11,598**	937	2,541	**3,477**	**258,210**
HH Respiratory Effects Potential (kg PM2.5 eq)	1,623	7	**1,630**	8	7	**15**	1	3	**4**	**1,649**
Eutrophication Potential (kg N eq)	574	6	**580**	4	6	**11**	1	2	**3**	**594**
Ozone Depletion Potential (kg CFC-11 eq)	6.E-04	7.E-07	**6.E-04**	4.E-10	8.E-07	**8.E-07**	8.E-07	3.E-07	**1.E-06**	**6.E-04**
Smog Potential (kg NOx eq)	1,212	133	**1,345**	112	136	**248**	12	57	**69**	**1,661**

Table 9 - EIE by quantities – Model 3 structural building (Steel building per assembly groups)

Steel Building by quantities (structural building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	827,430	866,678	5,949,177	n/a	6,471,799	**14,115,084**
Weighted Resource Use kg	1,136,567	171,206	501,646	n/a	2,164,518	**3,973,938**
Global Warming Potential (kg CO_2 eq)	116,794	53,851	208,732	n/a	398,732	**778,110**
Acidification Potential (moles of H+ eq)	35,959	27,487	83,913	n/a	110,850	**258,210**
HH Respiratory Effects Potential (kg PM2.5 eq)	333	229	404	n/a	682	**1,649**
Eutrophication Potential (kg N eq)	19	9	358	n/a	207	**594**
Ozone Depletion Potential (kg CFC-11 eq)	4.E-04	2.E-06	2.E-06	n/a	3.E-04	**6.E-04**
Smog Potential (kg NOx eq)	454	150	418	n/a	639	**1,661**
Note: Foundation values are higher in this model because of the proportion of material impacts under construction phase cannot be included to envelope roof.						

Table 10 - EIE+GaBi by quantities – Model 4 whole building (Steel Building per life cycle phase)

Steel Building by quantities	**Manufacturing**				**Construction**			**End - Of - Life**			**Total Effects**
(EIE + GaBi - whole building)	Material (GaBi)	Material (EIE)	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	7,541,349	9,348,472	249,776	**17,139,597**	181,702	389,417	**571,120**	259,060	125,301	**384,360**	**18,095,077**
Weighted Resource Use kg	2,831,071	3,392,226	6,984	**6,230,282**	3,954	9,156	**13,110**	6,089	2,946	**9,035**	**6,252,427**
Global Warming Potential (kg CO_2 eq)	594,399	699,907	18,702	**1,313,008**	11,236	29,088	**40,325**	16,857	9,360	**26,217**	**1,379,549**
Acidification Potential (moles of H+ eq)	97,045	676,958	6,650	**780,653**	5,621	9,174	**14,795**	935	2,952	**3,887**	**799,335**
HH Respiratory Effects Potential (kg PM2.5 eq)	614	6,680	8	**7,303**	8	11	**19**	1	4	**4**	**7,326**
Eutrophication Potential (kg N eq)	55	176	7	**238**	4	10	**14**	1	3	**3**	**255**
Ozone Depletion Potential (kg CFC-11 eq)	0.E+00	2.E-03	8.E-07	**2.E-03**	4.E-10	1.E-06	**1.E-06**	8.E-07	4.E-07	**1.E-06**	**2.E-03**
Smog Potential (kg NOx eq)	0	4,225	151	**4,376**	111	205	**316**	12	66	**78**	**4,769**

Table 11 - EIE+GaBi by quantities - Model 4 structural building (Steel Building per life cycle phase)

Steel Building by quantities	**Manufacturing**				**Construction**			**End - Of - Life**			**Total Effects**
(EIE + GaBi - structural building)	Material (GaBi)	Material (EIE)	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	6,805,093	1,991,142	215,914	**9,012,150**	173,704	256,380	**430,084**	253,915	108,195	**362,110**	**9,804,343**
Weighted Resource Use kg	2,264,612	2,915,012	6,118	**5,185,742**	3,808	6,028	**9,836**	5,968	2,544	**8,512**	**5,204,089**
Global Warming Potential (kg CO_2 eq)	533,507	254,696	16,603	**804,807**	10,817	19,151	**29,967**	16,523	8,082	**24,605**	**859,379**
Acidification Potential (moles of H+ eq)	85,977	79,334	5,826	**171,137**	5,445	6,040	**11,485**	916	2,549	**3,465**	**186,087**
HH Respiratory Effects Potential (kg PM2.5 eq)	546	839	7	**1,391**	8	7	**15**	1	3	**4**	**1,410**
Eutrophication Potential (kg N eq)	49	29	6	**84**	4	6	**11**	1	2	**3**	**97**
Ozone Depletion Potential (kg CFC-11 eq)	0.E+00	6.E-04	7.E-07	**6.E-04**	4.E-10	8.E-07	**8.E-07**	7.E-07	3.E-07	**1.E-06**	**6.E-04**
Smog Potential (kg NOx eq)	0	621	132	**753**	110	135	**245**	12	57	**69**	**1,067**

1.1. Steel structural building sensitivity analysis

Table 12 - EIE by quantities – Model 3 structural building composite floor system 10% less steel (Steel building per life cycle phase)

Steel Building by quantities	**Manufacturing**			**Construction**			**End - Of - Life**			**Total Effects**
(composite structural building) -10% steel	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	12,165,541	212,034	**12,377,575**	171,101	252,538	**423,639**	244,435	107,153	**351,588**	**13,152,803**
Weighted Resource Use kg	3,884,609	5,910	**3,890,519**	3,750	5,938	**9,688**	5,745	2,519	**8,264**	**3,908,471**
Global Warming Potential (kg CO_2 eq)	676,020	16,251	**692,270**	10,654	18,864	**29,518**	15,906	8,004	**23,910**	**745,699**
Acidification Potential (moles of H+ eq)	224,336	5,651	**229,987**	5,364	5,950	**11,313**	882	2,524	**3,406**	**244,706**
HH Respiratory Effects Potential (kg PM2.5 eq)	1,559	7	**1,566**	7	7	**15**	1	3	**4**	**1,584**
Eutrophication Potential (kg N eq)	514	6	**520**	4	6	**11**	1	2	**3**	**534**
Ozone Depletion Potential (kg CFC-11 eq)	6.E-04	7.E-07	**6.E-04**	4.E-10	8.E-07	**8.E-07**	7.E-07	3.E-07	**1.E-06**	**6.E-04**
Smog Potential (kg NOx eq)	1,156	128	**1,283**	109	133	**242**	11	56	**68**	**1,593**

Table 13 - EIE by quantities – Model 3 structural building composite floor system 10% less steel (Steel building per assembly groups)

Steel Building by quantities (composite structural building) -10% steel	**Foundations**	**Walls**	**Columns and Beams**	**Roofs (envelope)**	**Floors (structural)**	**Total**
Primary Energy Consumption MJ	827,430	866,678	4,623,306	n/a	6,835,389	**13,152,803**
Weighted Resource Use kg	1,136,567	171,206	299,621	n/a	2,301,076	**3,908,471**
Global Warming Potential (kg CO_2 eq)	116,794	53,851	150,394	n/a	424,660	**745,699**
Acidification Potential (moles of H+ eq)	35,959	27,487	61,479	n/a	119,780	**244,706**
HH Respiratory Effects Potential (kg PM2.5 eq)	333	229	276	n/a	746	**1,584**
Eutrophication Potential (kg N eq)	19	9	284	n/a	221	**534**
Ozone Depletion Potential (kg CFC-11 eq)	4.E-04	2.E-06	8.E-07	n/a	3.E-04	**6.E-04**
Smog Potential (kg NOx eq)	454	150	276	n/a	714	**1,593**

Table 14 - EIE by quantities – Model 3 structural building composite floor system 20% less steel (Steel building per life cycle phase)

Steel Building by quantities sensitivity	**Manufacturing**			**Construction**			**End - Of - Life**			**Total Effects**
(structural building) - 20% steel	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	11,185,295	201,487	**11,386,782**	167,479	247,192	**414,671**	230,625	106,281	**336,906**	**12,138,359**
Weighted Resource Use kg	3,806,926	5,641	**3,812,566**	3,671	5,812	**9,483**	5,420	2,499	**7,919**	**3,829,969**
Global Warming Potential (kg CO_2 eq)	643,301	15,455	**658,757**	10,429	18,465	**28,894**	15,007	7,939	**22,946**	**710,596**
Acidification Potential (moles of H+ eq)	210,194	5,388	**215,581**	5,250	5,824	**11,074**	832	2,504	**3,336**	**229,991**
HH Respiratory Effects Potential (kg PM2.5 eq)	1,489	7	**1,495**	7	7	**14**	1	3	**4**	**1,513**
Eutrophication Potential (kg N eq)	455	6	**461**	4	6	**10**	1	2	**3**	**474**
Ozone Depletion Potential (kg CFC-11 eq)	6.E-04	6.E-07	**6.E-04**	4.E-10	8.E-07	**8.E-07**	7.E-07	3.E-07	**1.E-06**	**6.E-04**
Smog Potential (kg NOx eq)	1,097	122	**1,219**	106	130	**236**	11	56	**67**	**1,522**

2. Concrete building results

The same methodology described for the steel building modeling was applied to the concrete models by quantities – Model 3.

Table 15 - Eco-calculator results – Model 1 whole building (Concrete building)

ASSEMBLY	**Total area (sq ft)**	Fossil Fuel Consumption (MJ) TOTAL	Weighted Resource Use (tonnes) TOTAL	GWP (tonnes CO2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	HH Respiratory Effects Potential (kg PM2.5 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
Foundations & Footings	16,124	917,722	1,011	117	34,869	294	34,086	261	378
Columns & Beams	94,042	7,089,932	3,312	539	180,539	1,290	468,274	852	1,410
Intermediate Floors	78,699	7,509,882	6,416	800	249,679	2,237	283,279	1,621	2,627
Exterior Walls	12,633	1,754,795	128	131	212,413	1,586	50,315	425	967
Windows	24,450	3,910,508	667	610	533,181	8,172	199,414	753	3,911
Interior Walls	27,922	901,071	116	42	16,699	272	12,621	9	113
Roof	15,344	3,980,269	1,336	199	77,153	559	62,761	326	1,131
TOTALS	**2,595**	26,064,179	12,986	2,438	1,304,533	14,410	1,110,750	4,247	10,537

Table 16 - EIE by assemblies – Model 2 whole building (Concrete Building per life cycle phase)

Concrete Building by assemblies	Manufacturing			Construction			End - Of - Life			Total Effects
(wholde building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	19,733,380	498,565	**20,231,946**	582,775	691,924	**1,274,699**	389,721	290,878	**680,599**	**22,187,244**
Weighted Resource Use kg	9,625,906	12,873	**9,638,779**	13,469	16,268	**29,737**	9,160	6,839	**15,999**	**9,684,516**
Global Warming Potential (kg CO_2 eq)	1,545,346	37,144	**1,582,490**	39,129	51,685	**90,814**	25,360	21,728	**47,088**	**1,720,392**
Acidification Potential (moles of H+ eq)	941,448	12,531	**953,979**	18,539	16,301	**34,840**	1,406	6,853	**8,259**	**997,078**
HH Respiratory Effects Potential (kg PM2.5 eq)	8,891	15	**8,906**	21	20	**41**	1	8	**10**	**8,956**
Eutrophication Potential (kg N eq)	708	13	**721**	18	17	**35**	1	6	**7**	**764**
Ozone Depletion Potential (kg CFC-11 eq)	4.E-03	2.E-06	**4.E-03**	6.E-11	2.E-06	**2.E-06**	1.E-06	9.E-07	**2.E-06**	**4.E-03**
Smog Potential (kg NOx eq)	6,214	282	**6,496**	454	364	**817**	18	153	**171**	**7,484**

Table 17 - EIE by assemblies – Model 2 whole building (Concrete Building per assembly groups)

Concrete Building by assemblies (whole building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	904,430	7,052,130	4,902,910	1,073,573	8,254,202	**22,187,244**
Weighted Resource Use kg	1,068,003	510,357	1,430,978	39,662	6,635,516	**9,684,516**
Global Warming Potential (kg CO_2 eq)	116,020	459,248	267,276	33,044	844,804	**1,720,392**
Acidification Potential (moles of H+ eq)	33,339	593,243	94,160	17,279	259,058	**997,078**
HH Respiratory Effects Potential (kg PM2.5 eq)	298	5,818	621	77	2,143	**8,956**
Eutrophication Potential (kg N eq)	20	166	292	6	280	**764**
Ozone Depletion Potential (kg CFC-11 eq)	3.E-04	1.E-03	3.E-04	8.E-07	2.E-03	**4.E-03**
Smog Potential (kg NOx eq)	375	3,211	674	516	2,707	**7,484**

Table 18 - EIE by assemblies – Model 2 structural building (Concrete Building per life cycle phase)

Concrete Building by assemblies	Manufacturing			Construction			End - Of - Life			Total Effects
(structural building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	11,416,816	457,978	**11,874,793**	574,662	536,789	**1,111,451**	383,921	266,521	**650,441**	**13,636,686**
Weighted Resource Use kg	9,003,108	11,846	**9,014,954**	13,320	12,621	**25,941**	9,023	6,266	**15,290**	**9,056,184**
Global Warming Potential (kg CO_2 eq)	1,046,429	34,543	**1,080,972**	38,703	40,097	**78,799**	24,982	19,908	**44,891**	**1,204,662**
Acidification Potential (moles of H+ eq)	324,365	11,546	**335,912**	18,359	12,646	**31,006**	1,385	6,279	**7,664**	**374,581**
HH Respiratory Effects Potential (kg PM2.5 eq)	2,900	14	**2,914**	21	15	**36**	1	8	**9**	**2,959**
Eutrophication Potential (kg N eq)	539	12	**551**	18	13	**31**	1	6	**7**	**589**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-03	1.E-06	**2.E-03**	0.E+00	2.E-06	**2.E-06**	1.E-06	8.E-07	**2.E-06**	**2.E-03**
Smog Potential (kg NOx eq)	2,542	260	**2,802**	453	282	**735**	18	140	**158**	**3,695**

Table 19 - EIE by assemblies – Model 2 structural building (Concrete building per assembly groups)

Concrete Building by assemblies (structural building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	895,657	n/a	4,902,910	n/a	7,838,119	**13,636,686**
Weighted Resource Use kg	1,067,809	n/a	1,430,978	n/a	6,557,397	**9,056,184**
Global Warming Potential (kg CO_2 eq)	115,575	n/a	267,276	n/a	821,811	**1,204,662**
Acidification Potential (moles of H+ eq)	33,146	n/a	94,160	n/a	247,275	**374,581**
HH Respiratory Effects Potential (kg PM2.5 eq)	297	n/a	621	n/a	2,040	**2,959**
Eutrophication Potential (kg N eq)	20	n/a	292	n/a	277	**589**
Ozone Depletion Potential (kg CFC-11 eq)	3.E-04	n/a	3.E-04	n/a	2.E-03	**2.E-03**
Smog Potential (kg NOx eq)	366	n/a	674	n/a	2,655	**3,695**

Table 20 - EIE by quantities – Model 3 whole building (Concrete Building per life cycle phase)

Concrete Building by quantities	Manufacturing			Construction			End - Of - Life			Total Effects
(whole building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	19,388,618	490,479	**19,879,096**	578,909	687,333	**1,266,241**	384,313	287,950	**672,263**	**21,817,601**
Weighted Resource Use kg	9,507,685	12,666	**9,520,351**	13,380	16,116	**29,496**	9,033	6,770	**15,803**	**9,565,650**
Global Warming Potential (kg CO_2 eq)	1,523,899	36,536	**1,560,435**	38,870	51,202	**90,071**	25,008	21,509	**46,517**	**1,697,023**
Acidification Potential (moles of H+ eq)	934,107	12,329	**946,436**	18,416	16,149	**34,565**	1,386	6,784	**8,170**	**989,171**
HH Respiratory Effects Potential (kg PM2.5 eq)	8,840	15	**8,855**	21	19	**40**	1	8	**9**	**8,905**
Eutrophication Potential (kg N eq)	688	13	**701**	18	17	**35**	1	6	**7**	**743**
Ozone Depletion Potential (kg CFC-11 eq)	3.E-03	2.E-06	**3.E-03**	6.E-11	2.E-06	**2.E-06**	1.E-06	9.E-07	**2.E-06**	**3.E-03**
Smog Potential (kg NOx eq)	6,164	278	**6,441**	451	360	**811**	18	151	**169**	**7,422**

Table 21 - EIE by quantites – Model 3 whole building (Concrete Building per assembly groups)

Concrete Building by quantities (whole building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	876,813	7,698,627	3,688,543	1,016,981	8,536,636	**21,817,601**
Weighted Resource Use kg	1,068,294	601,822	797,109	24,242	7,074,183	**9,565,650**
Global Warming Potential (kg CO_2 eq)	115,279	495,992	176,387	29,118	880,246	**1,697,023**
Acidification Potential (moles of H+ eq)	32,287	617,959	64,713	15,225	258,986	**989,171**
HH Respiratory Effects Potential (kg PM2.5 eq)	297	5,953	390	57	2,208	**8,905**
Eutrophication Potential (kg N eq)	19	171	229	6	318	**743**
Ozone Depletion Potential (kg CFC-11 eq)	3.E-04	1.E-03	2.E-04	6.E-07	2.E-03	**3.E-03**
Smog Potential (kg NOx eq)	359	3,483	447	539	2,595	**7,422**

Table 22 - EIE by quantities – Model 3 structural building (Concrete Building per life cycle phase)

Concrete Building by quantities	Manufacturing			Construction			End - Of - Life			Total Effects
(structural building)	Material	Transportation	**Total**	Material	Transportation	**Total**	Material	Transportation	**Total**	
Primary Energy Consumption MJ	11,123,101	450,335	**11,573,436**	567,727	530,310	**1,098,037**	379,128	263,302	**642,430**	**13,313,903**
Weighted Resource Use kg	8,887,872	11,652	**8,899,524**	13,159	12,469	**25,628**	8,911	6,191	**15,101**	**8,940,253**
Global Warming Potential (kg CO_2 eq)	1,026,837	33,969	**1,060,806**	38,235	39,613	**77,848**	24,670	19,668	**44,338**	**1,182,993**
Acidification Potential (moles of H+ eq)	317,767	11,357	**329,124**	18,138	12,494	**30,632**	1,368	6,203	**7,571**	**367,326**
HH Respiratory Effects Potential (kg PM2.5 eq)	2,850	14	**2,864**	20	15	**35**	1	7	**9**	**2,908**
Eutrophication Potential (kg N eq)	521	12	**532**	18	13	**31**	1	6	**7**	**570**
Ozone Depletion Potential (kg CFC-11 eq)	2.E-03	1.E-06	**2.E-03**	0.E+00	2.E-06	**2.E-06**	1.E-06	8.E-07	**2.E-06**	**2.E-03**
Smog Potential (kg NOx eq)	2,495	255	**2,750**	448	279	**726**	18	138	**156**	**3,633**

Table 23 - EIE by quantities – Model 3 structural building (Concrete Building per assembly groups)

Concrete Building by quantities (structural building)	Foundations	Walls	Columns and Beams	Roofs (envelope)	Floors (structural)	Total
Primary Energy Consumption MJ	882,547	n/a	3,750,812	n/a	8,680,544	**13,313,903**
Weighted Resource Use kg	1,068,245	n/a	797,212	n/a	7,074,796	**8,940,253**
Global Warming Potential (kg CO_2 eq)	115,961	n/a	178,128	n/a	888,904	**1,182,993**
Acidification Potential (moles of H+ eq)	33,133	n/a	66,812	n/a	267,381	**367,326**
HH Respiratory Effects Potential (kg PM2.5 eq)	298	n/a	392	n/a	2,218	**2,908**
Eutrophication Potential (kg N eq)	19	n/a	231	n/a	320	**570**
Ozone Depletion Potential (kg CFC-11 eq)	3.E-04	n/a	2.E-04	n/a	2.E-03	**2.E-03**
Smog Potential (kg NOx eq)	374	n/a	479	n/a	2,780	**3,633**
Note: By adding the material impacts during construction phase and proportionated to each assembly category, the values for columns, beams and floors became higher than the values for whole building model. Therefore, there is a margin of 2% accuracy between the results presented here.						