A LIFE CYCLE ASSESSMENT COMPARISON OF EMBODIED EMISSIONS FOR MASS TIMBER, REINFORCED CONCRETE AND STEEL BUILDING STRUCTURES

By

DAVID MOORE

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McMaster University

ABSTRACT

As society becomes more focused on addressing climate change, building stakeholders are increasingly concerned with identifying and communicating the environmental impact of their construction. While much of this impact comes through life cycle operating emissions, the embodied impacts of construction are both non-negligible and increasing in importance. In an effort to add to the database of reference structures, this thesis compares the embodied environmental impacts of a five-storey building in Toronto if it were designed with reinforced concrete, steel, or mass timber. A cradle-to-grave life cycle analysis (LCA) was done in Athena's Impact Estimator for Buildings for each scenario and results were organized by phase in product life as well as structural assembly. Wood performed better than steel in four out of seven categories, including the potential for global warming, acidification, human health (HH) particulate and total primary energy. The structural system posts negative global warming potential results due to the inclusion of the end-of-life phase which gives credit for carbon sequestration. Although designing with wood leads to a decrease in greenhouse gas emissions, the LCA shows that it leads to an increased potential for eutrophication, ozone depletion and smog in comparison to a steel structure. The reinforced concrete design had the highest embodied impacts for all seven categories except for HH particulate where the steel structure was the greatest. Relative and absolute comparisons of environmental metrics highlight the importance in both architectural and structural design decisions.

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Chapter 1: Introduction

1.1 A Canadian Perspective

The global community has become more cognizant of human-induced impacts on the environment, especially as it relates to the anthropogenic greenhouse effect. In June 2019, Canada joined the UK, France and Ireland in declaring a climate emergency which recognizes the need to act against greenhouse gas emissions (GHG) (Green Party, 2020). The International Energy Agency reported that as of 2019, the buildings and building construction sector is responsible for 40% of total global CO2 emissions (IEA, 2019) and in Canada this sector is responsible for 17% of the country's total emissions or in absolute terms about 111 million tonnes of GHG (Standing Senate Committee, 2018). In order for Canada to meet its Paris Agreement target of reduced emissions for 2030, the Pan-Canadian Framework for Clean Growth and Climate Change was established and it has issued changes to the National Building Code (NBC) starting in 2020, to begin adopting "net zero energy ready" building codes (Government of Canada, 2018a). With increasing environmental concern and carbon taxes being implemented across Canada, those in the buildings and construction sector have been looking at ways to decrease the operational energy of buildings. Thus, as the operational emissions (amount of CO2 eq released in use of building) decrease through cleaner energy and more energy efficient buildings, the embodied emissions (amount of CO2 eq required to produce the building) of the materials become relatively more significant to the total environmental impact of construction. At the same time, in the pursuit of decreasing the global warming potential (GWP) of buildings it is important not to neglect other environmental metrics which could also lead to increased GHG in the long run.

1.2 Barriers to Sustainable Development

There are many barriers in implementing sustainable design that a structural engineer may face. A previous survey of green building professionals consisting of architects, engineers and contractors in North America stated that obstacles to implementing green building practices include actual or perceived cost, ensuring building code is met for new systems and low availability of green structure materials (Griffin et al. 2010). The authors also note that gaps in environmental comprehension between different parties was also an obstacle in implementing sustainable design. Rodriguez-Niki et al. (2014) conducted a survey of structural engineers in Oregon, USA, which saw many structural engineers believing that they do have a responsibility in considering sustainability in structural engineering through using more sustainable material. Despite recognizing the embodied impacts of structural material, many structural engineers felt that other parties such as the client or architect were more responsible. Many respondents cited cost, lack of knowledge in contractors, clients, and structural engineers and also lack of information as barriers for sustainable development. Rodriguez-Niki et al. (2014) concluded that structural engineers need to be more informed about sustainability and as an industry, need to advise clients and other stakeholders on implementing sustainable design. In keeping with this recommendation, this thesis aims to provide information to better educate structural engineers and others who are involved with building development about the impacts different structural material may have on the environment.

1.3 Objective

The objective of this thesis is to aid decision makers in building development to make informed environmental decisions through a comprehensive understanding of material impacts organized by phase, practice and building assembly. After establishing an understanding of relevant past work, this thesis investigates the environmental impact of three materials in the structural system of buildings through conducting life cycle assessments (LCAs). For this study, a five-storey office building is designed using reinforced concrete, steel and wood and environmental impacts are compared. By designing structural components to be used as inputs in the program, a more detailed understanding of where most of the material is coming from can be obtained. Despite the focus of the thesis on structural systems, architectural assemblies are also included in the LCA to estimate the rough comparison of impacts from the two practices and to arrive at total results that will be closer to the actual absolute impact of these buildings. Results are organized by product life phases and building assemblies to allow a comprehensive analysis.

Chapter 2: Literature Review

2.1 Review of Studies on Operational and Embodied Emissions

There have been varying results in the relative percentage of embodied emissions relative to the full amount of emissions that a building accrues over time. Reported emissions within studies vary due to the many factors responsible for operational and embodied emissions. Operational emissions depend upon the fuel mix, energy efficiency of appliances, building envelope efficiency, building size, building use, building life, and climate, among many other variables. Embodied emissions vary due to regional energy mix used in production, production standards, type of material used, and type of structural and architectural systems, among many other variables.

Ibn-Mohammed et al. (2013) conducted a literature review of many existing papers and the varying results among them. Among the work reviewed in this thesis are Yohanis and Norton (2002) who report that for a single storey office building in the UK, for a 25 year life cycle, embodied energy was 67% of its operating energy. This value is relatively large compared to others but they took the percent in comparison to OE as opposed to the total energy and it is reported for a 25 year life cycle as opposed to 50 years which many previous studies use as a base line. Yohanis and Norton (2002) also note that the structure and substructure account for a total of 48% of the embodied emissions based on their case study. This value is in line with a previous study from Cole and Kernan (1996) which found that the structure accounts for 20% to 65% of the total embodied energy. Similar findings were reported by Ajayi et al. (2019) which concluded that embodied emissions could vary between 8.4% and 22.3% but rose to contribute 60% of the total building emissions in energy efficient buildings.

Sartori and Hestnes (2007) conducted a review of 60 case studies of life cycle building emissions in various countries and reported that in conventional buildings, embodied energy was responsible for 2% to 38% of emissions and for low-energy buildings, this value increased to between 9% and 46%. The authors note that the differences from case to case are too great to draw any general conclusion. Another large study of

73 cases across 13 countries was conducted by Ramesh et al. (2010), and noted that embodied energy of a building generally varies between 10% and 20% . Unfortunately, many of these numbers lose their significance without the context behind each of the cases or a discussion as to what is the main cause behind the variable results. These studies do generally show however, that embodied emissions for buildings are not negligible and should be considered when looking at the life cycle emissions of a building and even more so when analyzing other environmental impacts.

It is also important to remember that regardless of the relative amount of emissions, the absolute value does not change. Webster (2004) estimated that when looking at this topic in absolute terms, the US industry's embodied emissions is equivalent to 22 million new cars driving 19,000 km per year. With the growing relative importance of embodied greenhouse gas emissions and the absolute values of embodied energies not decreasing over time, this thesis investigates whether changing structural material makes a significant difference in emissions.

2.2 Review of Studies on LCAs for Structural Material

Studies which have surveyed multiple buildings can offer great insight into what to expect when using certain structural materials. A baseline expectation of the contribution of the structural components and architectural components for RC buildings can be found in a study by Kaethner and Burridge (2012) where concrete office buildings were surveyed. Through the study it was found that the superstructure accounted for 42% of total embodied carbon, construction 16%, substructure 13%, external cladding 13%, floor finishes 7%, partitions 4%, roof 4% and other finishes 2%. From these findings, the authors make a case that the focus on reduction of embodied carbon should start with the structure as it makes up on average 71% of the embodied carbon if construction is included.

There have been many papers which compare the embodied carbon of structural frames, but many choose to only compare two out of the three materials put forward in this thesis. A review of currently published papers (Saade et al. 2020) comparing GWP of structural frames has showed that in 5 out of 6 papers wood frames had lower embodied carbon than steel, in 14 out of 22 papers concrete frames had lower embodied carbon than steel, and in 8 out of 8 papers wood structures had lower embodied carbon than concrete structures. It is helpful to look into past studies closer in order to get an idea of the scope and mode of analysis.

The changing scope between life cycle assessments (LCAs) is one of the main reasons why results between case studies vary. Pomponi and Moncaster (2016) conducted a meta-analysis on LCA papers and found that out of the 77 studies considered, 90% of them only conducted a cradle-to-gate analysis which does not take into consideration the use phase, end-of-life phase or beyond end-of-life phase. Not considering the other phases is shortsighted and does not allow decision makers to understand future impacts of the materials used. Not taking into account the beyond end-of-life phase is especially concerning since this is often the phase in which LCA software like Athena account for material recycling or carbon sequestration.

One of the first studies that compared all three structural materials was done by Cole and Kernan (1996) in which wood outperformed steel by 38% and concrete outperformed steel by 21% in terms of embodied energy. A more recent and comprehensive study found that the concrete frame was the least desirable in terms of GWP and when designed with steel or timber, the GWP was found to be 11% and 41% lower respectively (Buchanan et al. 2013). Another study comparing reinforced concrete, light-guage steel and wood buildings found that the RC and steel buildings had similar emissions while the wood building produced 30% less emissions than the other two buildings (Gong et al. 2012). It is important to note that the wood was assumed to be carbon neutral due to the sequestration of carbon of the beginning of use and the emission of it by the end of the life of the wood.

One paper by Caruso et al. (2017) looked at RC, steel and timber as a structural material of a three-storey building in Italy but found very different results than many previous papers. The RC structure performed the worst in GWP, where it was 15 to 20% higher than steel and wood, but outperformed steel and timber construction in the other impact categories which consist of ozone depletion potential, photochemical oxidation, acidification, eutrophication and non-renewable fossil fuels. These results may have been produced due to the methodology used in IMPACT2002+, an LCA software not commonly used in other papers. There were also changes that were made to the life cycle inventory data for the RC material using more refined Environmental Product Declarations (EPDs) instead of the data provided by the commonly used Ecoinvent data which the program typically would assume. The unprecedented results from the paper show how LCA results can change dramatically depending on the assumptions made.

Most other studies compared the embodied carbon of a timber structure to that of concrete rather than all three. Froese and Tehrani (2017) found a 24% decrease in carbon emissions when timber is used over RC in the comparison of two similar existing buildings in British Columbia; however, the scope was only until the building’s end-of-life, implying that credits for material reuse or bio-carbon sequestration were not applied. A similar study also analyzed an existing reinforced concrete building in British Columbia and designed a mass timber equivalent of the same building so an LCA comparison can be done. This study concluded that the timber building performed 70% better in terms of emissions within the scope of a cradle-to-gate analysis (Robertson et al. 2012). It is important to note that although phases from use to beyond end-of-life were not considered, the study still accounted for the carbon storage in wood without having to consider the beyond end-of-life emissions. Despite analyzing similar structures in the same region, both papers produced different results due to the scope used and the life cycle phase within which carbon sequestration was accounted for.

Li and Altan (2011) showed through their study that regional considerations have a direct role in influencing embodied emissions as they performed a comprehensive emissions analysis on structures in Taiwan. Looking at RC, steel and wood projects in Taiwan, the authors found that the RC structure produced the most emissions with an average of 325 kg CO2/m^2 and steel and wood buildings producing 30% and 63% less CO2. Despite wood products being shipped from the US to Taiwan and the ore for steel being mined and shipped from Australia, both buildings produced significantly less GHG than RC buildings did. Another study (Hassan and al Wahid Jassim 2019) looked at 5-storey buildings in Iraq and concluded that using steel over concrete resulted in 68% more emissions. This large discrepancy between steel and RC buildings are most likely due to different assumptions, one of which would be the different material environmental data that would be used in Iraq.

Other studies have looked at variation in emissions based on building height. One study (Skullestad et al. 2016), saw a decrease of 34% to 84% depending on the building height, when timber was used instead of RC. A similar study (Li et al. 2019) looked at a hypothetical high rise building and found GWP to be decreased by -160% when mass timber was used over RC; however, the study's scope was cradle-to-gate and was not calculated under a certain standard. Another study which looked at the influence of building height for an RC building and a mass timber building found that the kg/m^2 of CO2 emissions decreased with increased building height and the wood building saw increases in kg/m^2 of negative CO2 emissions (Guo et al. 2017). For the four-storey building, using RC resulted in 308 kg/m^2 while the timber building had -84 kg/m^2 in CO2 emissions for the construction phase. The study accounted for the sequestering of carbon during the first phase of the life cycle instead of during the end-of-life phase.

Within all these studies and almost every other life cycle study, a breakdown of the structural system into structural assemblies is not shown. This information would be valuable for a structural engineer trying to reduce the amount of embodied carbon as they could focus their efforts towards assemblies that are the greatest contributors. Most LCAs follow international standards and present the data by Phase A-C (raw material extraction to demolition) or Phase A-D (raw material extraction to beyond-building-life); however, there is no establishment of a deeper understanding of what aspects of production cause the resulting high impacts by looking at EPDs. Discussion on temporal carbon accounting as it relates to the building(s) in the study and what is represented through phases is typically not addressed either.

Chapter 3: Life Cycle Assessment

3.1 LCA Goal and Scope

LCAs reveal the environmental impacts of a product from extraction of the raw material to treatment of waste. The International Standards Organisation (ISO 2006) outlines four steps for a successful LCA: goal and scope definition, life cycle inventory, an impact assessment, and interpreting the results. With so many variables in the definition of the LCA, it becomes extremely difficult to compare results between different assessments and thus it is often seen as a tool when looking at project alternatives to understand relative impacts.

The LCA in this study was defined in order to see the relative and absolute environmental performance of a five-storey office building if the structural system were to be designed with one of three materials. Another goal of this study is to compare the embodied carbon of the structural system with that of primary architectural assemblies by observing the GWP.

The scope of this LCA will be from cradle-to-grave and will consist of all structural assemblies and the most environmentally influential architectural components. Many previous LCA studies looking at material impact of buildings have done cradle-to-gate LCAs, typically noting that it is uncertain where the industry will be in terms of disposal practices after the building’s life. Although the concerns of uncertainty are valid, this may also lead to bias due to differences in how easily each material can be recycled and other credits such as carbon sequestration that are accounted for only in Phase D. These aspects are important when comparing environmental impacts of materials and thus it will be considered for this study. The building is based in Toronto, Canada which is important when considering the energy mix and transportation required to and from production facilities.

3.2 Relation Between Energy and Emissions

A primary focus of this study will be on the embodied emissions of buildings and potential tradeoffs required to pursue low emissions. Many previous studies have looked at embodied energy of materials and compared it with operational energy, however, increased embodied energy is not directly related to increased emissions as is the case with operational energy. Operational energy relates to the energy required for heating, cooling, lighting, ventilation, operating appliances and other building related energy uses. The relation to operational energy to operational emissions depends on the fuel mix. If the fuel mix is primarily dependent on renewable energy, then the carbon emissions from energy production will be low. Conversely, if fossil fuels are used as the primary energy source then there will be a higher release of carbon content per unit of energy produced. Despite this, given a steady energy mix, operational energy and emissions are directly related and are often interchanged in papers.

Conversely, embodied energy is not directly related to the amount of carbon released due to the nature of various building materials. Concrete, for instance, consists of cement which releases carbon through a chemical process when it is created. In contrast, timber sequesters carbon and acts as a carbon sink until it is burned or it decomposes. To avoid confusion between embodied emissions and energy, this study will instead use global warming potential (GWP) and total primary energy, respectively. Although GWP is the main focus of this study, an LCA will be conducted covering other metrics as outlined by the US Environmental Protection Agency's Impact Assessment methodology called TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts), which works alongside LCA as a tool to measure other environmental metrics such as: ozone depletion, smog formation, acidification, eutrophication, human health pollutants and total primary energy (Bare et al., 2003).

3.3 Athena Software

The Athena Impact Estimator for Buildings (IE4B) tool (Athena, 2019) was used to conduct the LCA due to its focus on buildings developed in North America, its free license, and its transparency. The data used for the LCA is Athena's life cycle inventory (LCI) and is regionally sensitive based on the location of the building, which is important when considering the energy mix required to produce materials. Data within this database is updated frequently and major LCI components were most recently updated in 2018, according to the user manual and transparency document IE4B database table (Athena, 2019).

With multiple transformations during a product's life, it is important to understand which actions are included within the assessment. Typical processes which are expected of all LCA software are included such as raw material supply, transport, manufacturing, construction, deconstruction/demolition and disposal. It is not expected for there to be as much GHG produced during the in-use phase (Phase B), as the only actions taken into account during this phase are partial maintenance (only painting) and replacement of materials. Other Phase B actions such as repair and refurbishment are not taken into account. It is also noted that the software, like many other LCA software, does not account for site development issues such as nature disturbance or eco-system alteration as this is site-specific.

The office building analysed for this study was assumed to be a rental or leased property which has less aggressive maintenance than an owner-occupied building. For simplicity, replacement of materials throughout the life span are also assumed to be the same as that used in the original construction.

Athena's user manual and transparency documents recognize that aluminum curtain wall framing and aluminum window frames may not accurately reflect the actual current impact that these systems have in the industry. Currently Athena uses LCI profiles from steel tubes, hollow structural steel, galvanized studs, wide flange sections, among other assemblies to estimate the cradle-to-grave impacts of curtain wall and window framing. Current LCI aluminum profiles are being reviewed by the Athena Institute to be implemented within future versions.

Athena assumes the same end-of-life conditions exist when the buildings service life has finished. This would not be the case realistically as technology and mitigation techniques would have most likely evolved within the building life but it is impossible to predict to what extent and thus the current state of disposal is used as a baseline. It is noted that besides metals, any product that is recycled, reused or incinerated for energy are considered to have left the boundaries of the LCA and credits should be applied to the next product or use to avoid counting the credits for materials twice. It is also noted that all environmental burdens associated with products leaving the boundaries should also be applied to the next usage. Athena does take into account the net amount of scrap by using the avoided burden methodology which essentially gives credit for recyclable content of the material which allowed for an avoidable burden in production.

In terms of biogenic carbon sequestration, Athena is intended to be conservative when accounting for the favourable effects of having wood as a carbon sink. The most significant assumption that Athena makes is that it ignores the temporary storage of biogenic carbon during the building's life (Athena, 2019). The IE4B still accounts for sequestration but only for Phase D, which is the beyond end-of-life phase and then it subtracts the estimated emissions that occur for wood at the end of its life. Athena applies a 100-year cut off for emission accounting which takes place after the end of the building's service life. At the end-of-life stage, wood currently either gets put into a landfill (80%), is combusted for energy (10%), or is recycled (10%). Within each of these processes, the wood is conservatively assumed to be converted 100% into carbon save for the portion that is sent to landfills with no gas capture where methane emission is also accounted for and decay models are used. All credits and beyond end-of-life emissions are added together to produce one Phase D value, meaning that the credits and emissions at this phase cannot be discerned.

3.4 LCA Metrics

A baseline understanding of the LCA metrics need to be established in order to interpret the tradeoffs between environmental impact metrics as described by Athena Sustainable Materials Institute (2019). GWP is measured in CO2 equivalence and its calculation is the most well-known out of the impact categories. The calculation, as seen below in Equation 1, uses CO2 as a base and applies a multiple to emissions of CH4 and N2O based on their relative heat trapping capability to CO2. It is noted that Athena takes into consideration other GWP contributors such as HFCs and CFCs but CO2, CH4 and N2O are the most prevalent gasses.

$$\text{CO2 Equivalent kg} = \text{CO2 kg} + (\text{CH4 kg} \times 28) + (\text{N2O kg} \times 265) \qquad (1)$$

In contrast to the scale of impact that GWP has, acidification potential has a more local or regional effect. Acidification potential is a metric which accounts for emissions which increase the acidity of water and soils which is calculated based off of SO2 equivalence. Acidification of soil and waterways usually occur due to the precipitation of acid rain which can eventually end up in plants or animals and can also contribute to damaging infrastructure. Major sources of these emissions include fuel combustion for energy and also agriculture (Myhre et al., 2013).

Human health (HH) particulates also have a regional effect and can greatly impact the health of those within the area as it is linked to many human respiratory problems. Particulate matter (PM) is often cited as either PM_{10} or $PM_{2.5}$ which is PM smaller than 10μm or 2.5μm, respectively. The smaller the particulate matter, the more danger it poses as it is more likely to enter our lungs or bloodstream. Primary anthropogenic sources of PM include combustion engines, energy production and industrial activity. Although HH particulates are a concern worldwide, this metric may be weighted more in areas where it is a daily problem such as in India, where Delhi has the greatest concentration of PM_{10} in the world (WHO, 2018).

Eutrophication potential measures the degree to which pollutants can contribute to the fertilization of surface waters. The result is expressed as an equivalent mass of Nitrogen (N) which takes into account other chemicals such as phosphorus (P) and nitrate ($NO3^-$) which are common elements responsible for aquatic plant growth. Anthropogenic causes of eutrophication primarily include fertilizers, aquaculture and to a lesser degree building material through biodeterioration and weather (Kobetičová and Čern, 2019).

Ozone depletion accounts for degradation of the ozone layer by substances such as CFCs, HFCs and halons. The amounts of ozone depleting substances are taken relative to CFC-11 due to its previous wide-use as a refrigerant and for insulation.

Smog potential arises when emissions get trapped close to the ground and are heated by sunlight. Ground level ozone is produced through photochemical reactions with volatile organic compounds (VOCs) and nitrogen oxides (NOx) (Ontario Ministry of the Environment, 2010). Smog and air pollution have a direct correlation and as such the sources of smog come primarily from industrial and vehicle emissions, road dust, agriculture and construction (Government of Canada, 2018b).

Total primary energy includes all direct and indirect sources of embodied energy. For a building this would include energy required for material production, transportation, construction, demolition and even inherent energy within the material such as feedstock energy within wood. Previous LCAs have reported high total primary energy results due to wood being considered as an inherent energy source (Froese and Tehrani, 2017). It is important to have an underlying comprehension of these metrics and where these may be originating from in terms of a building's life cycle in order to obtain a greater appreciation for the results.

Chapter 4: Case Study

4.1 Project Definition

A five-storey rental office building in Toronto with a footprint of 42 m x 30 m was used as the basis for three separate structural models designed with reinforced concrete, steel and wood. A service life of 60 years was assumed based on previous case studies done to facilitate comparison. The storey heights remained the same between each building, with a first floor height of 4.2 m and a typical floor height of 3.7 m for other floors. The architectural components stayed the same for each building and consisted of built-up roofing with insulation, an external façade and partition walls. Although choosing the roofing insulation based on a similar R-value between all roof assemblies is ideal, changing insulation thickness within Athena was seen to change overall emissions in buildings by less than 1% and thus was assumed to be negligible.

4.2 Architectural Assumptions

The goal of the architectural makeup of the building was to be representative of a typical office building, and thus, the data was based on FEMA's Normative Quantity Estimation Tool which surveyed over 3000 buildings to characterize typical building components based on occupancy type (FEMA, 2012). FEMA's estimation tool calculates total partition walls in linear metres by multiplying the floor area by 0.1, which results in 126 m for the case study model. The partition walls were assumed to be on every floor except for the bottom floor for a total height of 14.8 m. Partition walls were also assumed to be non-load bearing light (25 Ga) steel stud with 39x152 stud thickness at 400 mm spacing and having oriented strand board sheathing. The external façade curtain wall system from the FEMA's estimation tool was assumed for the case study building. This curtain wall is assumed to be 70% glazing and 30% metal spandrel panels. The built-up roofing is composed of #30 organic felt, bitumen which was assumed to have a total thickness of 0.5", fine aggregate crushed stone at a thickness of 0.5", oriented strand board, polyisocyanurate foam board and a structural deck, slab or panel which was specific to the building being analyzed. Exact thicknesses for the bitumen and fine aggregate crushed stone were difficult to ascertain but the difference is negligible considering that the built-up roofing, without the structural panel, contributes to 1% of the total GWP in the RC building. Screenshots of Athena inputs can be seen in Appendix B.

4.3 Structural Assumptions

All loads were kept the same between each model with the exception of self-weight of the structural assembly. Wood and steel structural framing was assumed to be within 0.5 kPa, while the self-weight of the RC system was calculated as it was heavily dependent on member sizes. Curtain wall systems were assumed to be bottom supported and within the partition allowance to facilitate calculations. With this assumption, spandrel beams were made the same size as interior beams and spandrel joists were made the same as interior joists. Wind loads were assumed to govern over earthquake loads for lateral force resisting system (LFRS) design. Roof deflection limits were L/240 while floor deflection limits were L/360. Loads were specified given information from the National Building Code (NBC) and design was carried out within CSA requirements (CCBFC, 2015). RC material was designed with CSA A23.3-14 (CSA, 2014a), wood was designed with CSA O86-14 (CSA, 2014b) andsteel material was designed with CSA S16-14 (CSA, 2014c).

The changes between each model are in the design of the structural system only. The reinforced concrete and steel models had bay dimensions of 8.4 m by 7.5 m between columns while the mass timber building had bay dimensions of 7 m x 6 m. The smaller bay lengths for the wood building is typical of mass timber design for office spaces as steel and concrete beams can typically span longer distances. The beams and columns in the steel building were designed with W Shapes while the mass timber building had glulam columns and beams. Floor systems for the RC, steel, and wood buildings are one-way reinforced concrete slabs, composite steel decks, and one-way CLT panels, respectively. Design resulted in thicknesses of 200 mm RC slabs, 100 mm composite decking and 87 mm CLT panels. All concrete was designed with

CAN 35 MPa including all building foundations. Structural steel was assumed to have a strength of 345 MPa for design purposes. Structural floor plans for the three buildings depicting the beam and joist sizes and details are available in Appendix A.

The lateral force resisting system for reinforced concrete is a RC shear wall and for mass timber CLT panels acted as shear walls while for the steel building chevron bracing with steel angles were used. Columns for the RC building were designed with square RC cross section, wide flange columns were used for the steel building and glulam columns were used for the timber building. Sizes of the columns are detailed in Table 1 below.

Table 1: Lateral Force Resisting System and Column Summary

Level	Lateral Force Resisting System (LFRS)				Columns		
	RC Wall*	Steel E-W	Steel N-S	Timber Panel	RC**	Steel	Timber
5	200 mm	L76x76x4.8	L64x64x4.8	87 mm CLT	300x300	W200x59	265x342
4	200 mm	L76x76x6.4	L76x76x4.8	87 mm CLT	300x300	W200x59	265x342
3	200 mm	L76x76x13	L76x76x7.9	87 mm CLT	300x300	W200x59	265x342
2	200 mm	L89x89x13	L76x76x13	87 mm CLT	400x400	W250x80	315x456
1	200 mm	L102x102x16	L89x89x13	105 mm CLT	400x400	W250x80	315x456

*RC Wall has longitudinal and transverse reinforcement of 15M @ 500 mm

**300x300 columns have 10M ties @ 300 mm with 6-30M longitudinal reinforcement and 400x400 columns have 10M ties @ 400 mm with 6-30M longitudinal reinforcement

Reinforced concrete pad footings were used for each building and differed in size due to self-weight of the structural material and also due to strip footings required under the load bearing shear walls. The largest first-storey column load was used to design pad footings for that building. For the RC building, pad footings were 3.25 m x 3.25 m x 0.8 m with reinforcement of 20M @ 180 mm each way. For strip footing in the RC building the dimensions were 9 m x 3.4 m x 0.9 m with 25M @ 170 mm each way. The steel building consisted of only pad footing which had dimensions of 2.55 m x 2.55 m x 0.6 m and reinforcement of 20M

@ 230 mm each way. The wood building had pad footing dimensions of 2 m x 2 m x 0.48 m with 20M @ 290 mm each way. The strip footings for the CLT shear walls were 9.1 m x 3.4 m x 0.9 m with reinforcement of 25M @ 170 mm each way. The ULS of the soil was assumed to be 500 kPa and overbearing soil weight was assumed to be negligible for conservative design.

4.4 Scope Limitations

The scope of the models focused on primary structural load resisting members that would change between each structure as well as primary architectural finishes for a comparison between structural and architectural systems. A component that was kept out of scope was the inclusion of a concrete core for stairs or elevators, which can be required by code for emergency or fire safety. These walls would be the same size for each type of building following regulation and thus, would not have an effect when comparing the relative environmental burdens of the structural system. If a concrete core were to be included, it could possibly decrease the sizes of the lateral load resisting system as the core walls would also act as shear walls to resist lateral forces. Other components left out of scope include stairs, structural connections, floor finishes, ceiling finishes, and mechanical and electrical equipment. These assemblies were assumed to have negligible differences between buildings relative to the total LCA results.

Chapter 5: Results

5.1 Normalized Environmental Impacts by Phase

In this section, results are presented by phases to allow a better understanding of the influence of processes throughout the building's life. Phase A consists of the raw material extraction, transport, production and construction of the product. Phase B consists of impacts made during the building's service life such as maintenance, repair and refurbishment. Phase C is known as the end-of-life stage and encapsulates the demolition, transport and disposal of the product. Phase D is representative of the benefits and loads beyond the building life cycle such as reuse and recycling.

The results seen in Figure 1 are normalized based on the greatest impact between the three buildings which was the summation of each component's contribution from Phase A to C. Figure 1 breaks each metric down by the phase and the summations of the results from Phase A to D are summarized in Table 2. The results reveal that the reinforced concrete building performs the worst in all categories except for human health (HH) particulate, where the steel building performs worse than the concrete building by 4%. Wood outperforms the other materials when looking at GWP, acidification potential, HH particulate and total primary energy. The most notable difference is in GWP where the net GWP for the wood building was only 12% whereas the net GWP of the RC and steel buildings were 96% and 53%, respectively. Steel outperforms the other materials in the context of eutrophication, ozone depletion and smog.

All reinforced concrete impact categories pointed to it being the worst or close to worst (for HH particulate) material. The extraction and supply of materials are cited as the major source of environmental effects and this is specifically due to cement production (ASTM, 2015). Energy demand is also great in the manufacturing stages which contributes to the GWP and to the total primary energy used. Increasing supplementary cementitious material (Smith and Durham 2016) and improving energy use efficiency in the pre-production phase can help mitigate the environmental effects.

Looking to past studies as a reference point of expected results it was not surprising to see reinforced concrete perform worse than mass timber; however, it was surprising to see the steel building outperform the wood building in three environmental metrics (eutrophication, ozone depletion and smog). When observing the normalized environmental impacts by phase, it is evident that the main difference between the net result is due to Phase A. Although Phase A encompasses raw material extraction to construction, the extraction and refinement of raw materials are where most impacts occur. EPD's give greater insight into the higher than expected results for these metrics. The results from eutrophication potential are mainly due to the glulam column and beams which make up 41% of the total category, which are a result of the heat needed to dry glulam wood as well as the heat treatment for wood residues on site (Thünen, 2018). The ozone depletion results are also primarily due to the glulam columns and beams (57%) which are a consequence of substances in the adhesive used (Thünen, 2018). The CLT floors are the main influence on smog potential in the wood building (37%) and reports point to the supply of raw material as the largest contributor (Thünen, 2019). This level of analysis is necessary to address the root cause of negative environmental impacts.

Phase D is not always included in LCAs, but it can be seen in Figure 1 that Phase D can play a large impact on total impact results, especially as it pertains to GWP. It is within Phase D where the "avoided burden" methodology is used to give a product credit for re-used or recycled material and for carbon sequestration. Athena partially adopts an approach defined by British Standards Institution (BSI) Group under Public Available Specification (PAS) 2050, which prescribes a 100-year cut off for carbon sequestration or emissions by a material (Athena, 2018). It is modified in Athena by moving this 100-year cut off to the end of Phase C and thus effects of sequestration and subsequent emissions of the stored carbon are accounted for only after the product's life. This is important given the immediacy of the climate crisis and the temporal nature implied by phases in LCAs. Assuming sustainable forestry practices, carbon sequestration realistically occurs within Phase A as there is an immediate storage of carbon for a long period of time and emission occurs in the years after the building's end-of-life depending on if it is recycled, combusted or sent to a landfill. Given the urgency in decreasing GHG emissions, this timeline of carbon accounting should be considered.

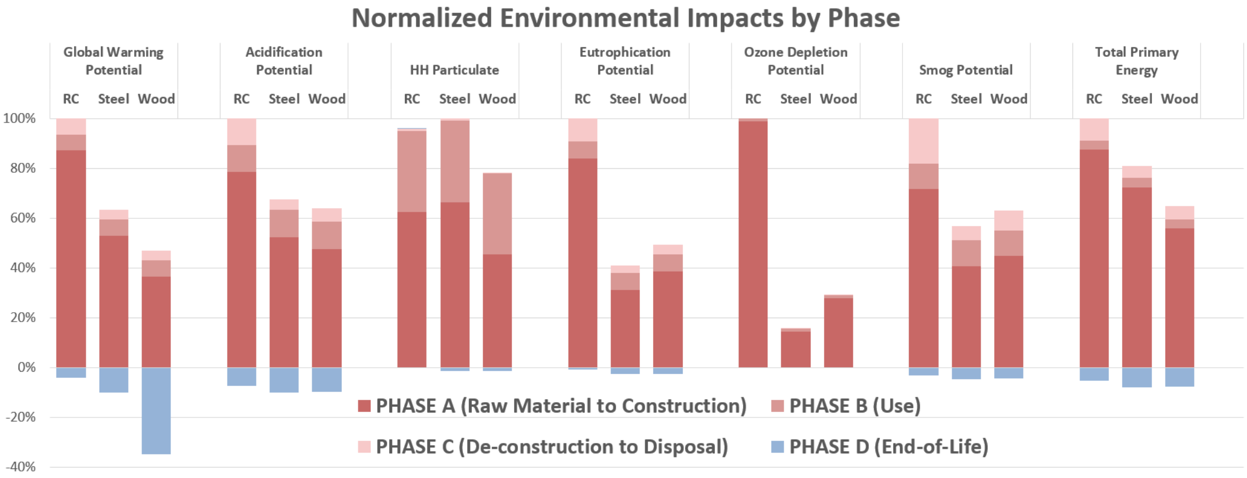

Figure 1: Normalized LCA Results Organized by Phase

Table 2: Normalized LCA Totals from Phase A to D

Type	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy
RC	96%	93%	96%	99%	99%	97%	95%
Steel	53%	58%	99%	38%	16%	52%	73%
Wood	12%	54%	77%	47%	29%	58%	57%

5.2 Structural and Architectural Environmental Impact Comparison

Comparing the structural and architectural environmental impacts of the system allows decision makers to obtain a better understanding of how significant of a role their decisions may play. Table 3 below summarizes what percentage of the total metric is due to the structural system according to the LCA. It is clear from these results that when designing with reinforced concrete that generally the structural system will play a bigger role in environmental metrics. Overall, the structural contribution for all three materials is significant with it being greater than 60% in most categories. It is also interesting to note that when designing with wood, the wood acts to reduce the GWP of the project. Despite the positive influences of wood in terms of GWP, there are other metrics which show that the use of wood is still harmful to the environment in other ways.

With the structural systems contributing over 60% of the impact in most categories, results were found to align with Kaethner and Burridge's study (2012) which found the structural system to be the main source of embodied emissions. The RC results for GWP in Table 3 found that the structural system contributed 76% to the total emissions which is similar to the 71% calculated by Kaethner and Burridge (2012). This study adds to those previous findings showing that the structural system is the main source of embodied impacts for most LCA categories. Although embodied emissions are smaller than operational emissions, the timeline for embodied emissions is much shorter and occurs primarily within the raw material extraction to construction period which is unfavourable considering CO2 positive feedback loops and the potential development of mitigation strategies over the building's life.

There is a noticeable disparity between the GWP for wood with regards to the structural and architectural system. If building stakeholders choose to put a great emphasis on GWP then based on the results, wood should be chosen as the structural material. The results also highlight that within this scenario, the architectural system which is primarily composed of the curtain wall, would be responsible for 189% of the GHG emissions, due to the negative emissions from wood sequestering carbon. The absolute impact of the curtain wall is 402000 kg CO2 eq which is equivalent to an average of 86 vehicles on the road for one year (EPA, 2019). The majority of the emissions due to the production of a curtain wall system are because of the aluminum framing system typically supporting the panels. A lot of energy is required in converting alumina to aluminium and in a previous LCA study it was reported that on a tonne CO2 eq per unit weight basis aluminum is 136 times greater than concrete (Biswas, 2014). As an architect or engineer it is important to be cognizant of the potential environmental impacts that can be caused by design decisions and the weight of these decisions.

Table 3: Percent of Impact Category Due to Structural System

Type	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy
RC	76%	65%	23%	80%	95%	70%	80%
Steel	57%	45%	25%	48%	72%	44%	74%
Wood	-89%	41%	5%	58%	84%	50%	67%

5.3 Environmental Impacts by Structural Assembly

When attempting to reduce the negative impact of the structural system it is helpful to understand what assembly contributes most to the category of interest. Figure 2 below summarizes the results for each impact category and categorizes these normalized outputs by structural assemblies. Unlike Figure 1, architectural assemblies are not included as this graph is meant to allow structural engineers to see an expected breakdown of the impact categories by the systems they are designing with. The curtain wall and partition wall category were not included within this analysis as the focus is on the structural assemblies; however, if they were included they would be the most prominent assembly for most metrics due to the negative impacts of glass and aluminum production.

Analysing a building by structural assemblies allow engineers to distinguish where exactly the impacts are coming from. From Figure 2, one can see that for GWP, RC slabs contribute much more to the overall structural system when compared to floor systems within the steel and wood building, which have composite decking and CLT panels, respectively. The 200 mm RC slabs are responsible for 45% of the GWP in the RC structural system whereas the 100 mm composite decking is responsible for 20% in the steel system. The wood structural system produces negative GWP results and the 87 mm CLT panels contribute to 47% of the negative GHG emissions. RC slabs along with columns and beams contribute significantly within each impact category. Hollow core slabs are an alternative that could potentially be used to decrease the environmental impact of an RC structural system. Within steel systems, columns and beams require the most attention especially when looking at HH particulate as it is responsible for 91% of particulates. Looking at the wood, the amount of CLT to glulam is similar with CLT consisting of 56% of the wood in the structure by weight and glulam consisting of the other 44%. Thus, Figure 2 suggests that CLT performs better than glulam in HH particulate and ozone depletion while glulam is better suited if total primary energy is a concern. The other metrics have a roughly equal contribution by CLT or glulam or one that is representative of the wood assemblies in the total structural system. The differences that arise between glulam and CLT within the mentioned metrics hint at discrepancies in the manufacturing process of the materials as the type of wood is the same. After understanding which components contribute the most to the environmental categories of interest, engineers can then begin to find solutions to decrease the building's impact.

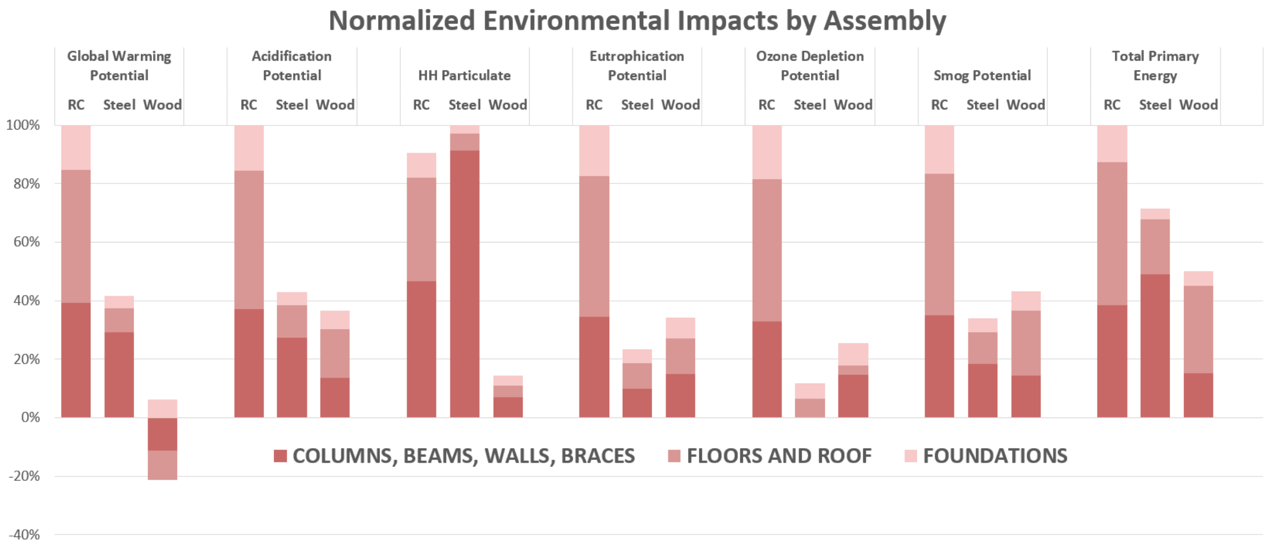

Figure 2: Normalized LCA Results Organized by Structural Assemblies

5.4 Absolute Impacts

Previous findings emphasized relative results, which is typically highlighted within LCA studies; however, noting absolute impacts while keeping in mind the scope of the study is valuable as well and is summarized in Table 3 below. The decision to use timber as a structural material as opposed to RC results in a net decrease in GWP of 1.46 million kg CO2 eq which is equivalent to 311 passenger vehicles removed from the roads for a year according to EPA's GHG Equivalency Calculator (EPA, 2019). Unfortunately, there are not common standard equivalencies for other LCA metrics which would help make these units less abstract for decision makers. Figure 1 and 2 show that the use of wood assists in decreasing the GWP of the project and the Canadian Wood Council (CWC) has a carbon calculator which allows users to understand this impact (CWC, 2020). The CWC calculation for the wood building reports that the carbon stored in the wood is equivalent to 241 cars off the road for a year and the timber that would be used in the project could be regrown from Canadian and US forests within 3 minutes.

Table 3: Summary of Absolute Impacts by LCA Metric*

Type	Global Warming Potential (Mg CO2 eq)	Acidification Potential (Mg SO2 eq)	HH Particulate (Mg PM2.5 eq)	Eutrophication Potential (kg N eq)	Ozone Depletion Potential (g CFC-11 eq)	Smog Potential (Mg O3 eq)	Total Primary Energy (TJ)
RC	1680	9.30	6.96	630	10.2	163	17.0
Steel	933	5.80	7.16	244	1.59	87.5	13.1
Wood	214	5.46	5.60	298	2.95	98.2	10.3

*Data includes both structural and architectural components

A further breakdown of the absolute impacts can be achieved through categorizing results by structural assembly. Looking at absolute results by structural assembly can help designers determine actual impacts specific changes to an assembly can make. Tables 4, 5 and 6 below summarize the absolute impacts of the RC, steel, wood structural systems by assembly, respectively. When comparing the three tables, one of the interesting comparisons to make is between the GWP values for the foundations as the same material is used for all three. The foundations for the RC building produce the most GHG, followed by the wood building and then the steel building. The RC foundations contributing more to GHG is not surprising as the self-weight of the system adds roughly another 1000kN to each pad foundation which results in larger foundations which are responsible for 139 Mg CO2 eq more in GWP than the steel system, which had the same bay sizes. It is important to note too that the RC and wood building had four shear walls which required strip footing which contributed to the RC building's large GWP and to the wood building's foundations producing more 24 Mg CO2 eq than the steel building. The wood building also had smaller bay sizes than the steel system and thus more pad footings were required as there were more columns. Overall, the wood structure has a lower GWP than the other buildings but if a designer were looking to decrease emissions even more, they should focus on the foundations. Looking at the total results help swhen deciding which primary structural material would be best for a building, but once a material is selected, analyzing the environmental impacts by component can help decrease emissions further.

Table 4: RC Building Absolute Impacts by Structural Assembly

LCA Measures	Unit	Col, Bm, Walls, Braces	Floor & Roof	Foundations
Global Warming Potential	Mg CO2 eq	499	577	195
Acidification Potential	Mg SO2 eq	2.25	2.87	0.94
HH Particulate	kg PM2.5 eq	836	638	149
Eutrophication Potential	kg N eq	174	243	87
Ozone Depletion Potential	g CFC-11 eq	3.20	4.72	1.79
Smog Potential	Mg O3 eq	39.9	55.0	18.9
Total Primary Energy	TJ	5.24	6.64	1.73

Table 5: Steel Building Absolute Impacts by Structural Assembly

LCA Measures	Unit	Col,Bm, Walls, Braces	Floor & Roof	Foundations
Global Warming Potential	Mg CO2 eq	370	104	56
Acidification Potential	Mg SO2 eq	1.67	0.67	0.26
HH Particulate	kg PM2.5 eq	1636	107	50
Eutrophication Potential	kg N eq	50	44	24
Ozone Depletion Potential	g CFC-11 eq	0.02	0.63	0.50
Smog Potential	Mg O3 eq	20.9	12.5	5.2
Total Primary Energy	TJ	6.67	2.58	0.50

Table 6: Wood Building Absolute Impacts by Structural Assembly

LCA Measures	Unit	Col,Bm, Walls, Braces	Floor & Roof	Foundations
Global Warming Potential	Mg CO2 eq	-144	-128	80
Acidification Potential	Mg SO2 eq	0.82	1.02	0.38
HH Particulate	kg PM2.5 eq	125	73	61
Eutrophication Potential	kg N eq	75	61	36
Ozone Depletion Potential	g CFC-11 eq	1.42	0.30	0.75
Smog Potential	Mg O3 eq	16.5	25.2	7.6
Total Primary Energy	TJ	2.09	4.04	0.70

Chapter 6: Mitigation Measures

Sustainable development for buildings is a comprehensive issue which involves communication and agreement among multiple parties in order to be done successfully. Results of this study and many others show that using wood instead of RC or steel is an effective way to decrease embodied emissions (Saade et al. 2020); however, if the architect or client is opposed to using wood within the project, other mitigation measures should be pursued. If designing with the more carbon intensive RC, Gan et al. (2019) outlined different ways structural engineers can mitigate embodied carbon. One way is to specify the minimum cement content that will still allow for the needed concrete compressive strength. Other methods include using supplementary cementitious material such as 35% fly ash or 75% ground granulated blast-furnace slag, using eco-cement which incorporates industrial waste products and requires less energy to produce, or specifying a 40 mm aggregate size.

Regardless of the building material being used there are various mitigation measures one can take to lower the embodied carbon of the building. De Wolf (2017) discusses two low carbon pathways designers should consider during the planning phase which are lowering the structural material quantity (SMQ) and also lowering the embodied carbon content. To reduce SMQ, it is suggested that designers consider adaptability of the building for multiple uses, minimize waste and preserving existing buildings and optimize the layout plan and structural system. The reduction of embodied carbon content of building materials can be achieved through reusing building components, using recycled material, using bio-based material, incorporating low carbon material into the design and using local material.

In their survey of 77 LCA papers, Pomponi and Moncaster (2016) outline 17 different common mitigation measures which not only emphasize mitigation measures from a material perspective but also in terms of policy and practices. Government policy and regulation could provide financial incentives to design more sustainably such as a carbon tax or through an emissions trading policy. Other papers suggest changing policy and regulation within the construction sector such as having material suppliers display the mass of CO2 eq per kg of construction material produced (Acquaye and Duffy, 2010). More efficient construction processes and techniques also lead to environmental benefits with less waste in the production of material or on a construction site. Use of embodied carbon assessment tools was one of the most mentioned mitigation strategies, such as coordinating BIM with LCA software (Ariyatne and Moncaster, 2014) such as Autodesk's Green Building Studio Revit plug-in for operating energy analysis and the Tally Revit plug-in for embodied impact analysis (Najjar et al. 2017).

Chapter 7: Conclusions

As the significance of decreasing anthropogenic environmental effects becomes increasingly important, it is crucial that stakeholders look at the embodied impacts of buildings in the planning and design phase. In this study, three LCAs were done for a five-storey office building in Toronto using wood, steel and RC. Wood was found to be the best structural system for GWP, acidification, HH particulate and total primary energy while steel performed the best in terms of eutrophication, ozone depletion and smog. It was seen that using RC resulted in a worse environmental performance than both wood and steel for 6 out of 7 of the environmental metrics. Previous studies put an emphasis on embodied carbon when comparing these structural systems and often did not recognize the tradeoffs in other environmental impact categories. The LCAs for this specific building show that wood contributes 77% less to GWP than steel; however, designing with wood instead of steel results in some other increased impacts. Environmental decisions are complex and are often interlinked and thus it is recommended that future studies consider the effects of these tradeoffs in detail. It is important to note that results from this study, as with most LCA studies, are regional, temporal, building-specific and software specific. Results of this LCA will change if done again at a future date as product data evolves, another location is used as the energy mix changes, and if the dimensions and loads of the building change.

This study is limited to the defined building and future research should look into expanding the LCA to more models with different variables. Previous papers have looked at how embodied impacts of buildings change with building height but little research has been done concerning the building footprint. Future studies could look to see if the ratio of the building footprint perimeter to area influences embodied carbon considering the significant contribution of the curtain wall. Since this study has outlined assemblies which contribute the most in each structure, the next step is to consider how structural material quantity mitigation can be achieved through optimizing the layout and the structural system. This study covers only three different structural systems; however, there are various other widely used assemblies which can be looked at within each material such as hollow precast concrete slabs, waffle slabs, composite joists, voided slabs and nail-laminated timber just to name a few. Keeping in mind that perceived costs was a major factor preventing sustainable design, future studies should look at conducting a life cycle costing analysis along with an environmental analysis to see when these two interests intersect. Future research should continue to dig deeper into the final results through looking at Environmental Product Declarations for the material used to diagnose why the material may perform worse than others in certain LCA categories. It is through detailed analysis and understanding of current practices that the building industry can improve in reducing its environmental impact.

This study provides insight into expected results for a five-storey office building and also shows the value of looking at building LCAs by structural assembly. The significance of including end-of-life material credits in LCAs was demonstrated, especially since environmental credits which occur during raw material production are not realized unless effects beyond the building life are included. When including end-of-life results, choosing to use a mass timber structural system instead of RC would potentially result in the equivalent of 311 passenger vehicles removed from roads for a year. The assembly which has the greatest potential for reducing emissions in the structure changes depending on which material is used in the design. For the RC building, the RC slabs (45%) are the greatest contributor to the building’s embodied emissions while for the steel and wood buildings, the columns, beams and braces (70%) and the foundations (100%) represent the greatest emissions impact, respectively. The results highlight the influence designers have across multiple environmental metrics and the importance of analyzing material impacts through a temporal perspective and by assembly. As the signs of global warming become more apparent with each passing year, it is imperative that designers seek a deeper understanding of how their decisions effect the natural environment and seek design alternatives to mitigate environmental impacts.

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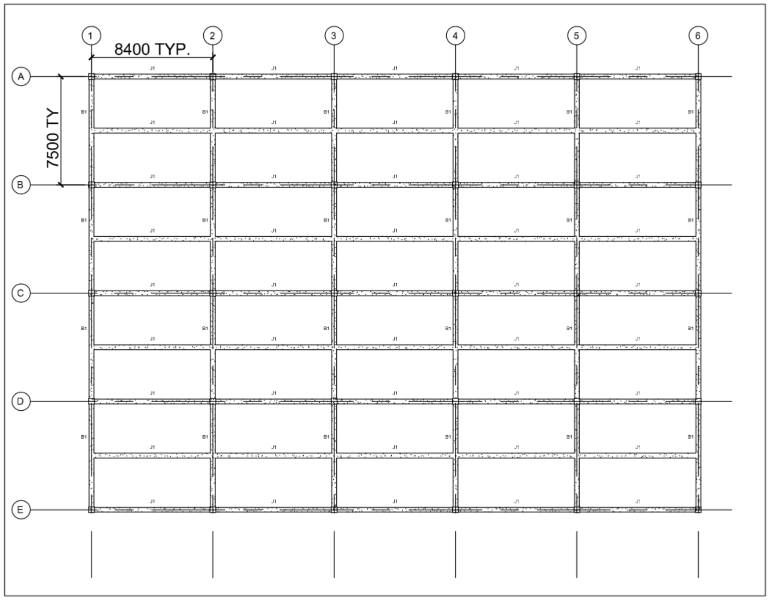
Appendix A: Case-Study Floor Plan Drawings

The following pages include the structural floor plans for the reinforced concrete, steel and wood building, respectively.



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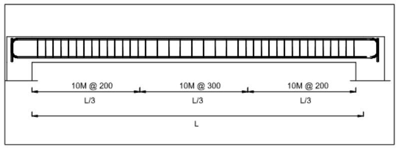
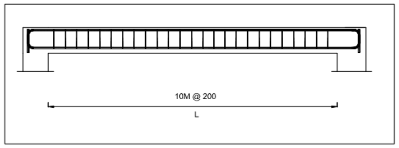
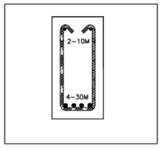


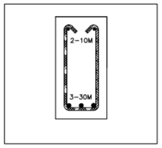
2 S1 JOIST (J1) TYP. PROFILE
1:150



3 S1 BEAM (B1) TYP. PROFILE
1:150



4 S1 FLR B1/J1 SECTION
1:35



5 S1 RF B1/J1 SECTION
1:35

NOTES

ROOF LOADS
- DEAD LOAD

DECK	0.10 kPa
INSULATION	0.10 kPa
FELT & GRAVEL	0.35 kPa
MECH. & SUSPENDED	0.40 kPa
TOTAL	0.95 kPa

- LIVE LOAD FOR ROOF IS 1.0 kPa
- SNOW LOAD
  - S(ULS)= 1.0 kPA
  - S(SLS)= 0.9 kPA

FLOOR LOADS
- DEAD LOAD

COMP. SLAB	2.5 kPa
PARTITION ALLOWANCE	1.0 kPa
FLR FIN & SUSPENDED	0.6 kPa
FRAMING	0.5 kPa
TOTAL	4.6 kPa

- LIVE LOAD FOR OFFICE IS 2.4 kPa

WIND LOAD
- q= 0.44 kPa

FOR ROOF
- J1 IS 310X620
- B1 IS 310X520
- SLAB IS 250 mm THICK W/ 10M @ 250 mm

FOR FLOORS
- J1 IS 335X670
- B1 IS 335X670
- SLAB IS 250 mm THICK W/ 10M @ 250 mm

No.	DATE	DESCRIPTION

LOCATION
TORONTO, ON

PROJECT
LCA
RC BUILDING

DRAWING TITLE
TYP. RC FRAMING PLAN

PROJECT No:
001

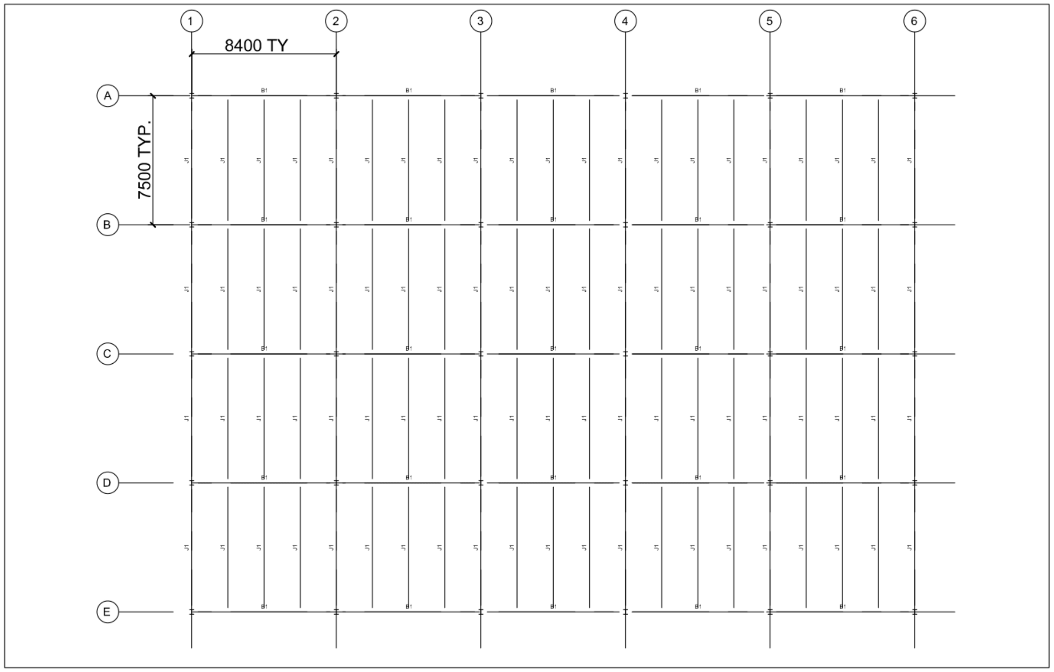
DATE:
1 APRIL 2020

SCALE:
–

DRAWING BY:
DM

APPROVED BY:
DM

DRAWING No
S1



1 / S2 TYPICAL FRAMING PLAN
1:350

NOTES

ROOF LOADS
- DEAD LOAD

DECK	0.10 kPa
INSULATION	0.10 kPa
FELT & GRAVEL	0.35 kPa
MECH. & SUSPENDED	0.40 kPa
FRAMING	0.50 kPa
TOTAL	1.45 kPa

- LIVE LOAD FOR ROOF IS 1.0 kPa
- SNOW LOAD
  S(ULS)= 1.0 kPA
  S(SLS)= 0.9 kPA

FLOOR LOADS
- DEAD LOAD

COMP. SLAB	2.5 kPa
PARTITION ALLOWANCE	1.0 kPa
FLR FIN & SUSPENDED	0.6 kPa
FRAMING	0.5 kPa
TOTAL	4.6 kPa

- LIVE LOAD FOR OFFICE IS 2.4 kPa

WIND LOAD
- q= 0.44 kPa

FOR ROOF
- J1 IS W200X27
- B1 IS W250X80
- ROOF IS CANAM P-3615 STEEL DECK TYPE 18

FOR FLOORS
- J1 IS W200X52
- B1 IS W360X134
- FLOOR IS CANAM P-3623 COMPOSITE SLAB WITH SLAB THICKNESS OF 100 mm AND DECK THICKNESS OF 0.76 mm

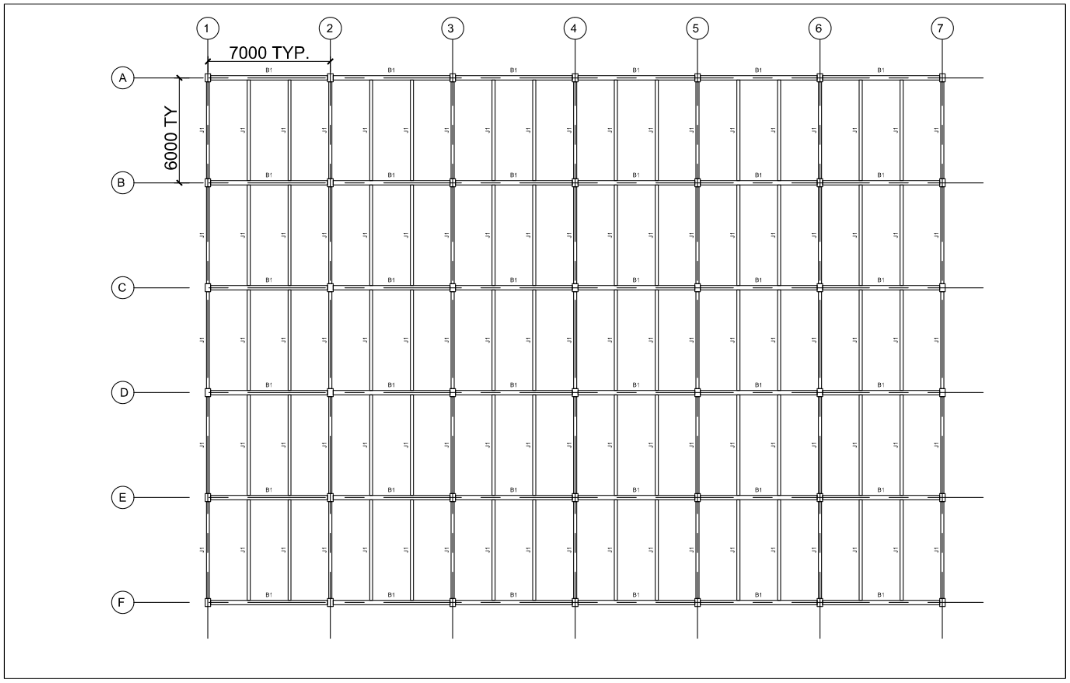
No.	DATE	DESCRIPTION

LOCATION
TORONTO, ON

PROJECT
LCA
STEEL BUILDING

DRAWING TITLE
TYP. STEEL FRAMING PLAN

PROJECT No: 001
DATE: 1 APRIL 2020
SCALE: –
DRAWING BY: DM
APPROVED BY: DM
DRAWING No S2



1 / S3 TYPICAL FRAMING PLAN
1:350

NOTES

ROOF LOADS
- DEAD LOAD

DECK	0.10 kPa
INSULATION	0.10 kPa
FELT & GRAVEL	0.35 kPa
MECH. & SUSPENDED	0.40 kPa
FRAMING	0.50 kPa
TOTAL	1.45 kPa

- LIVE LOAD FOR ROOF IS 1.0 kPa
- SNOW LOAD
  S(ULS)= 1.0 kPA
  S(SLS)= 0.9 kPA

FLOOR LOADS
- DEAD LOAD

COMP. SLAB	2.5 kPa
PARTITION ALLOWANCE	1.0 kPa
FLR FIN & SUSPENDED	0.6 kPa
FRAMING	0.5 kPa
TOTAL	4.6 kPa

- LIVE LOAD FOR OFFICE IS 2.4 kPa

WIND LOAD
- q= 0.44 kPa

FRAMING: B1 AND J1 ARE GLULAM SPF-20f-E
FOR ROOF
- J1 IS 130X342
- B1 IS 215X494
- ROOF IS 87V CROSSLAM CLT ROOF PANEL CLT, GRADE V2.1

FOR FLOORS
- J1 IS 175X418
- B1 IS 265X608
- FLOOR IS 87V CROSSLAM CLT FLOOR PANEL CLT, GRADE V2.1

No.	DATE	DESCRIPTION

LOCATION
TORONTO, ON

PROJECT
LCA
WOOD BUILDING

DRAWING TITLE
TYP. WOOD FRAMING PLAN

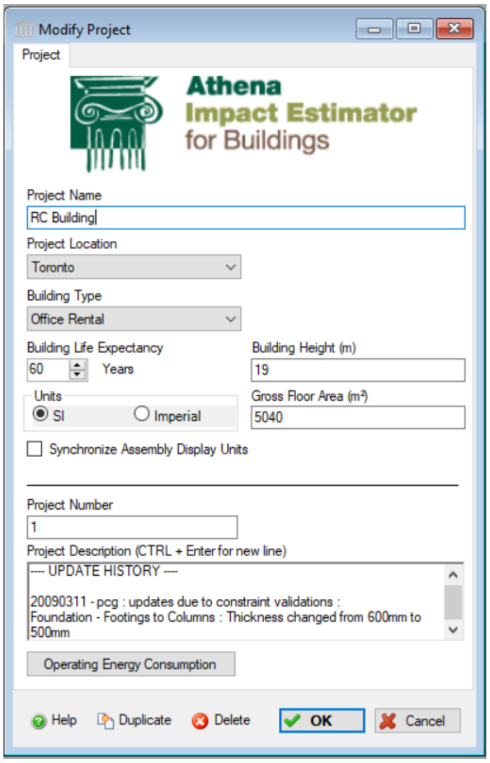
PROJECT No: 001
DATE: 1 APRIL 2020
SCALE: –
DRAWING BY: DM
APPROVED BY: DM

DRAWING No
S3

Appendix B: Athena Input Screenshots

The following pages include screenshots of inputs used in Athena.

General Inputs That Remained Similar Throughout All Projects

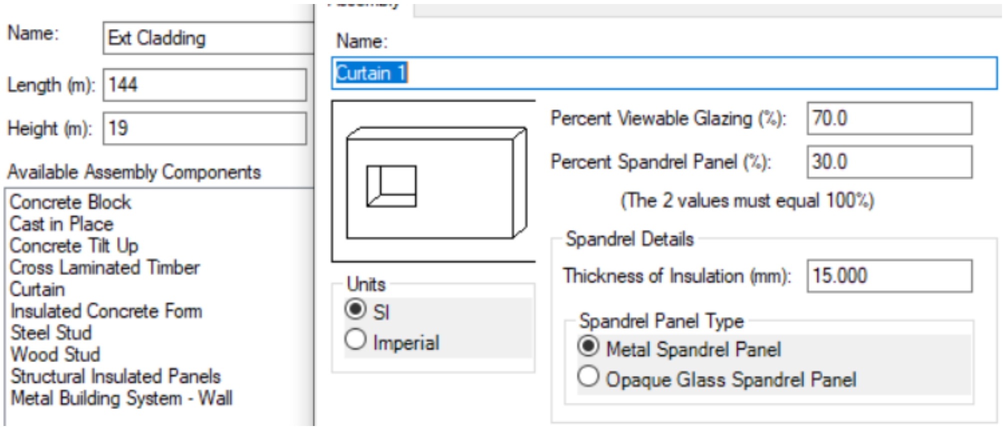


Project Name: RC Building
Project Location: Toronto
Building Type: Office Rental
Building Life Expectancy: 60 Years
Building Height (m): 19
Units: ● SI ○ Imperial
Gross Floor Area (m²): 5040
☐ Synchronize Assembly Display Units
Project Number: 1
Project Description (CTRL + Enter for new line):

---- UPDATE HISTORY ----

20090311 - pcg : updates due to constraint validations :
Foundation - Footings to Columns : Thickness changed from 600mm to 500mm

Figure B-1: General Project Information

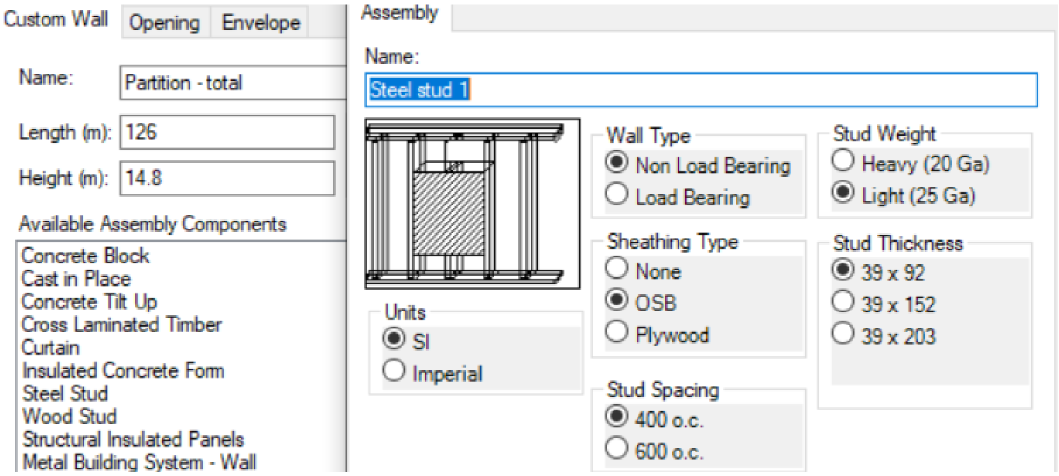


Name: Ext Cladding
Length (m): 144
Height (m): 19

Available Assembly Components
- Concrete Block
- Cast in Place
- Concrete Tilt Up
- Cross Laminated Timber
- Curtain
- Insulated Concrete Form
- Steel Stud
- Wood Stud
- Structural Insulated Panels
- Metal Building System - Wall

Name: Curtain 1
Percent Viewable Glazing (%): 70.0
Percent Spandrel Panel (%): 30.0
(The 2 values must equal 100%)
Units: ● SI ○ Imperial
Spandrel Details
Thickness of Insulation (mm): 15.000
Spandrel Panel Type
● Metal Spandrel Panel
○ Opaque Glass Spandrel Panel

Figure B-2: Typical Cladding Specifications



Name: Partition - total

Length (m): 126

Height (m): 14.8

Available Assembly Components

- Concrete Block
- Cast in Place
- Concrete Tilt Up
- Cross Laminated Timber
- Curtain
- Insulated Concrete Form
- Steel Stud
- Wood Stud
- Structural Insulated Panels
- Metal Building System - Wall

Name: Steel stud 1

Units
● SI
○ Imperial

Wall Type
● Non Load Bearing
○ Load Bearing

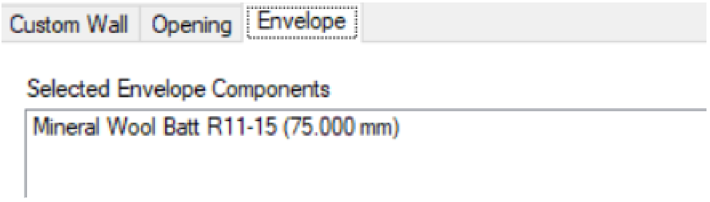
Sheathing Type
○ None
● OSB
○ Plywood

Stud Spacing
● 400 o.c.
○ 600 o.c.

Stud Weight
○ Heavy (20 Ga)
● Light (25 Ga)

Stud Thickness
● 39 x 92
○ 39 x 152
○ 39 x 203

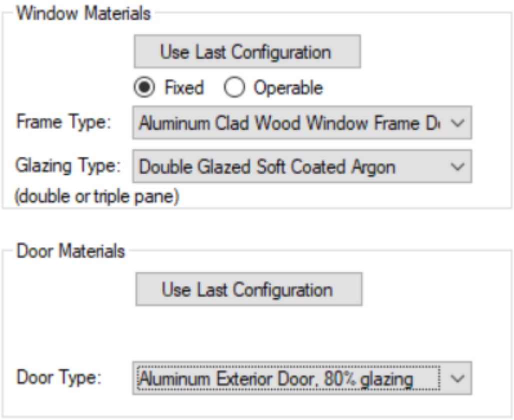
Figure B-3 Typical Partition Wall Specifications



Selected Envelope Components

Mineral Wool Batt R11-15 (75.000 mm)

Figure B-4: Typical Insulation for Partition Walls



Window Materials

● Fixed ○ Operable

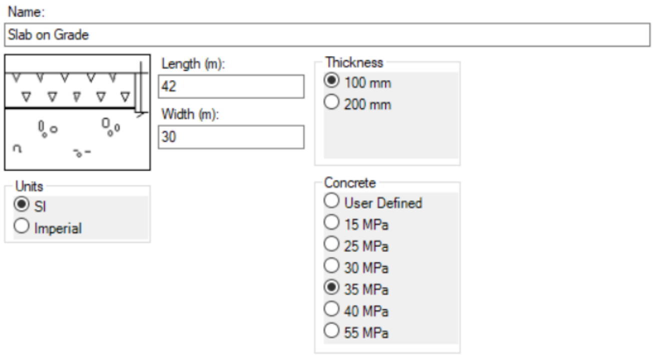
Frame Type: Aluminum Clad Wood Window Frame Di

Glazing Type: Double Glazed Soft Coated Argon
(double or triple pane)

Door Materials

Door Type: Aluminum Exterior Door, 80% glazing

Figure B-5 Typical Window and Door Inputs



Name: Slab on Grade

Length (m): 42

Width (m): 30

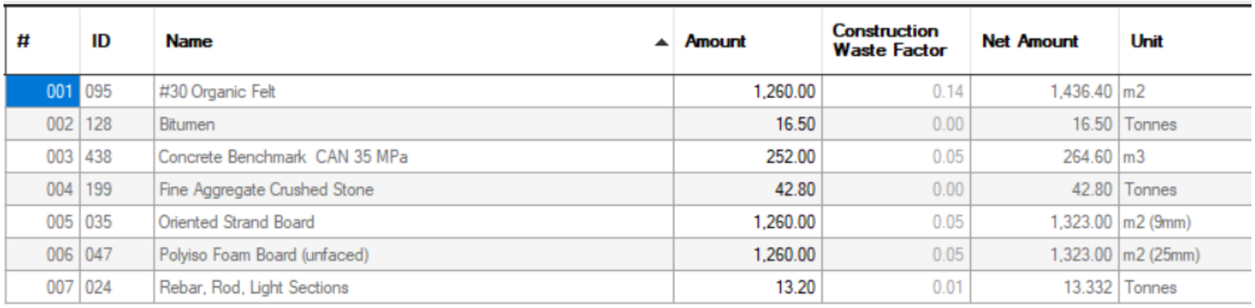
Thickness
● 100 mm
○ 200 mm

Units
● SI
○ Imperial

Concrete
○ User Defined
○ 15 MPa
○ 25 MPa
○ 30 MPa
● 35 MPa
○ 40 MPa
○ 55 MPa

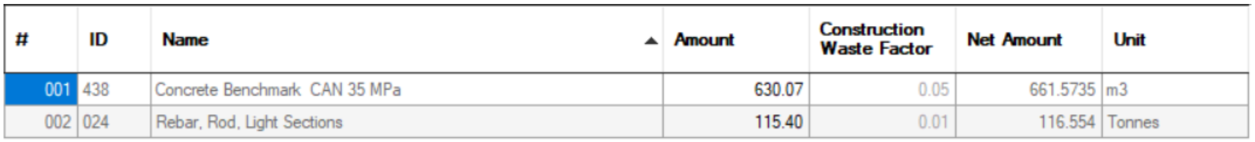
Figure B-6: Slab on Grade Input

Inputs for RC Building



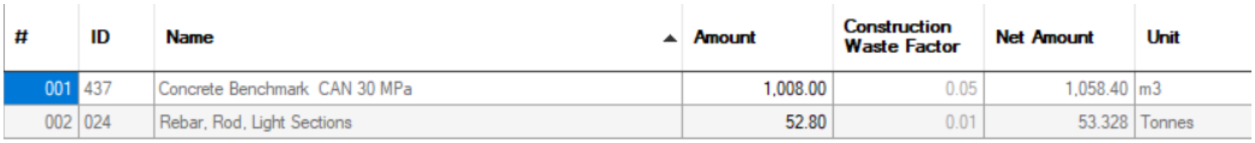
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	095	#30 Organic Felt	1,260.00	0.14	1,436.40	m2
002	128	Bitumen	16.50	0.00	16.50	Tonnes
003	438	Concrete Benchmark CAN 35 MPa	252.00	0.05	264.60	m3
004	199	Fine Aggregate Crushed Stone	42.80	0.00	42.80	Tonnes
005	035	Oriented Strand Board	1,260.00	0.05	1,323.00	m2 (9mm)
006	047	Polyiso Foam Board (unfaced)	1,260.00	0.05	1,323.00	m2 (25mm)
007	024	Rebar, Rod, Light Sections	13.20	0.01	13.332	Tonnes

Figure B-7: RC Roof Inputs



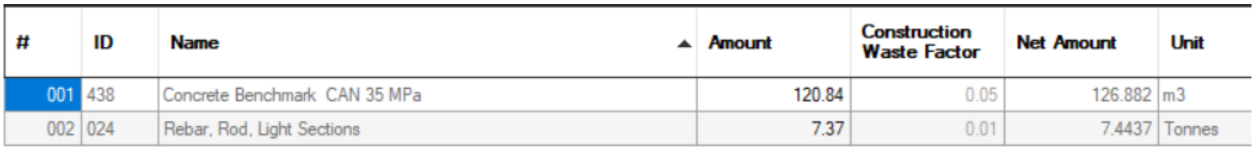
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	438	Concrete Benchmark CAN 35 MPa	630.07	0.05	661.5735	m3
002	024	Rebar, Rod, Light Sections	115.40	0.01	116.554	Tonnes

Figure B-8: RC Column and Beam Inputs



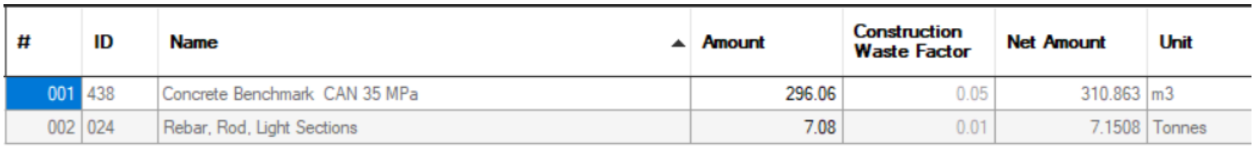
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	437	Concrete Benchmark CAN 30 MPa	1,008.00	0.05	1,058.40	m3
002	024	Rebar, Rod, Light Sections	52.80	0.01	53.328	Tonnes

Figure B-9: RC Floor Slab Inputs



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	438	Concrete Benchmark CAN 35 MPa	120.84	0.05	126.882	m3
002	024	Rebar, Rod, Light Sections	7.37	0.01	7.4437	Tonnes

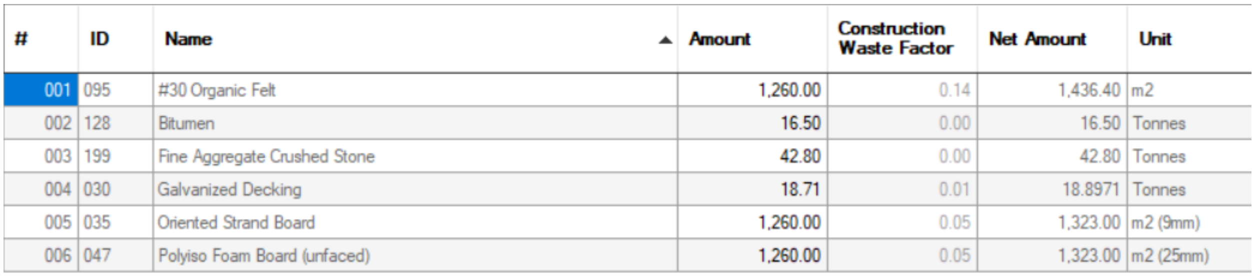
Figure B-10: RC Wall Inputs



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	438	Concrete Benchmark CAN 35 MPa	296.06	0.05	310.863	m3
002	024	Rebar, Rod, Light Sections	7.08	0.01	7.1508	Tonnes

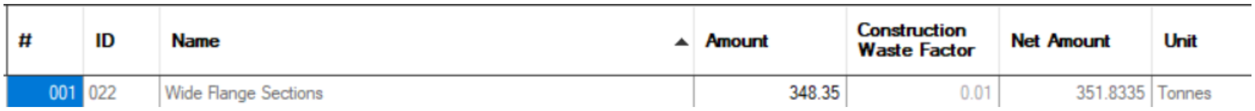
Figure B-11: RC Foundation Inputs

Steel Building Inputs



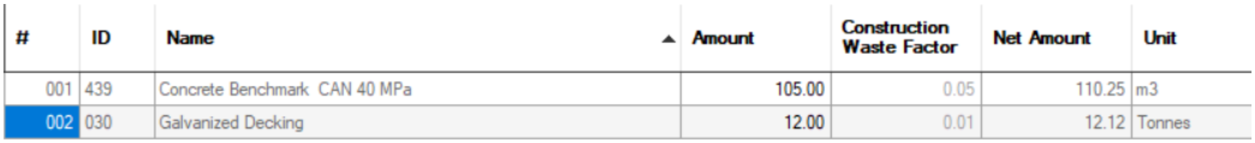
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	095	#30 Organic Felt	1,260.00	0.14	1,436.40	m2
002	128	Bitumen	16.50	0.00	16.50	Tonnes
003	199	Fine Aggregate Crushed Stone	42.80	0.00	42.80	Tonnes
004	030	Galvanized Decking	18.71	0.01	18.8971	Tonnes
005	035	Oriented Strand Board	1,260.00	0.05	1,323.00	m2 (9mm)
006	047	Polyiso Foam Board (unfaced)	1,260.00	0.05	1,323.00	m2 (25mm)

Figure B-12: Steel Building Roof Inputs



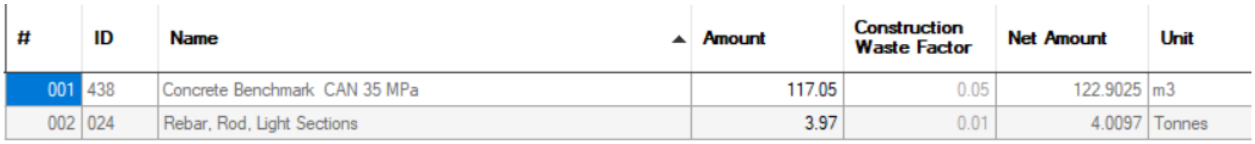
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	022	Wide Flange Sections	348.35	0.01	351.8335	Tonnes

Figure B-13: Steel Column and Beam Inputs



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	439	Concrete Benchmark CAN 40 MPa	105.00	0.05	110.25	m3
002	030	Galvanized Decking	12.00	0.01	12.12	Tonnes

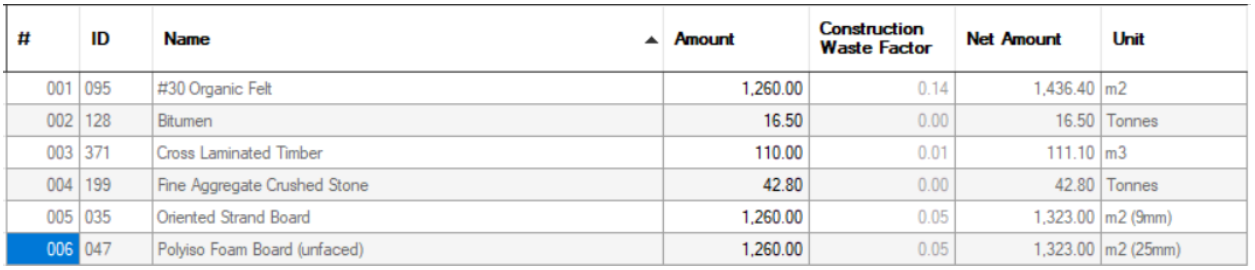
Figure B-14: Composite Decking Inputs



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	438	Concrete Benchmark CAN 35 MPa	117.05	0.05	122.9025	m3
002	024	Rebar, Rod, Light Sections	3.97	0.01	4.0097	Tonnes

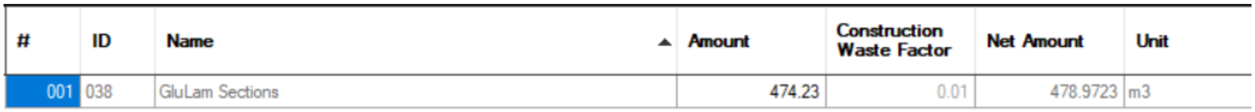
Figure B-15: Foundation Inputs for Steel Building

<u>Mass Timber Building</u>



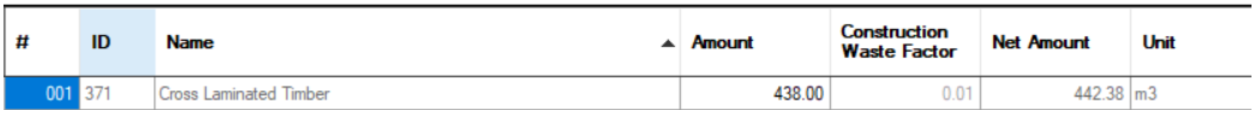
#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	095	#30 Organic Felt	1,260.00	0.14	1,436.40	m2
002	128	Bitumen	16.50	0.00	16.50	Tonnes
003	371	Cross Laminated Timber	110.00	0.01	111.10	m3
004	199	Fine Aggregate Crushed Stone	42.80	0.00	42.80	Tonnes
005	035	Oriented Strand Board	1,260.00	0.05	1,323.00	m2 (9mm)
006	047	Polyiso Foam Board (unfaced)	1,260.00	0.05	1,323.00	m2 (25mm)

Figure B-16: Mass Timber Roof Inputs



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	038	GluLam Sections	474.23	0.01	478.9723	m3

Figure B-17: Glulam Beam Column and Beam Inputs

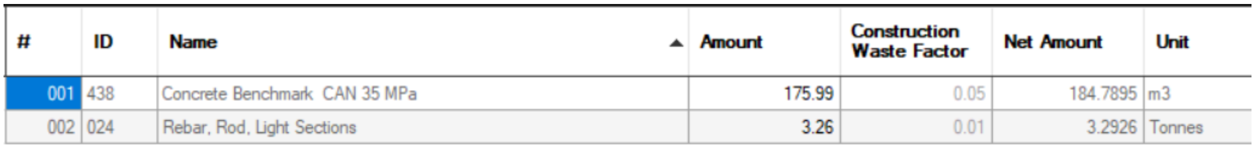


#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	371	Cross Laminated Timber	438.00	0.01	442.38	m3

Figure B-18: CLT Floor Input

#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	371	Cross Laminated Timber	44.95	0.01	45.3995	m3

Figure B-19: CLT Wall Input



#	ID	Name	Amount	Construction Waste Factor	Net Amount	Unit
001	438	Concrete Benchmark CAN 35 MPa	175.99	0.05	184.7895	m3
002	024	Rebar, Rod, Light Sections	3.26	0.01	3.2926	Tonnes

Figure B-20: Foundations for Mass Timber Building Input