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

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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 paper 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.

1 INTRODUCTION

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. 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 of buildings decrease through cleaner energy and more energy efficient buildings, the embodied emissions 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.

The objective of this paper 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 paper 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 reinforce 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 paper 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.

2 LITERATURE REVIEW

A baseline expectation of the contribution of the structural components and architectural components 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%, construction 16%, substructure 13%, external cladding 13%, and various other smaller contributors. 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 paper. 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 were better than steel, in 14 out of 22 papers concrete frames were better than steel, and in 8 out of 8 papers wood structures were better 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.

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 (Buchanan et al. 2013) 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.

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 existing buildings; however, the scope was only until the building's end-of-life. Another study (Skullestad et al. 2016), saw a decrease of 34% to 84% depending on the building height, when timber was used instead of RC depending on the building height. 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.

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 Environmental Product Declarations (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.

3 LIFE CYCLE ASSESSMENT

LCAs reveal the environmental impacts of a product from extraction of the raw material to treatment of waste. The ISO (2006) outlines four steps for a successful LCA which include: 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.

3.1 Goal and Scope

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 span. 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 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 components were most recently updated in 2018.

3.3 Athena Assumptions

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 notes 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. 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-building-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.

4 CASE STUDY

A five-storey rental office building in Toronto with a footprint of 42m x 30m and service life of 60 years was used as the basis for three separate structural models designed with reinforced concrete, steel and wood. The storey heights remained the same between each building, with a first floor height of 4.2m and a typical floor height of 3.7m for other floors. The architectural components stayed the same for each building and consisted of built-up roofing with insulation, a curtain wall system consisting of 70% glazing and 30% metal spandrel panels and steel stud partition walls which have a length of 10% of the gross floor area. 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 (2018).

The changes between each model are in the design of the structural system only. The reinforced concrete and steel models had bay dimensions of 8.4m by 7.5m between columns while the mass timber building had bay dimensions of 7m x 6m. 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 lateral force resisting system for reinforced concrete and mass timber are shear walls while the steel building used chevron bracing. All loads were kept the same between each model with the exception of self-weight of the structural assembly. 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. 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. The beams and columns in the mass timber building were designed with glulam. Complete design details are provided by Moore (2020).

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 are sometimes 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. 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.

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 1. 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 but also to the total primary energy used. Increasing supplementary cementitious material (Smith et al. 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. 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.

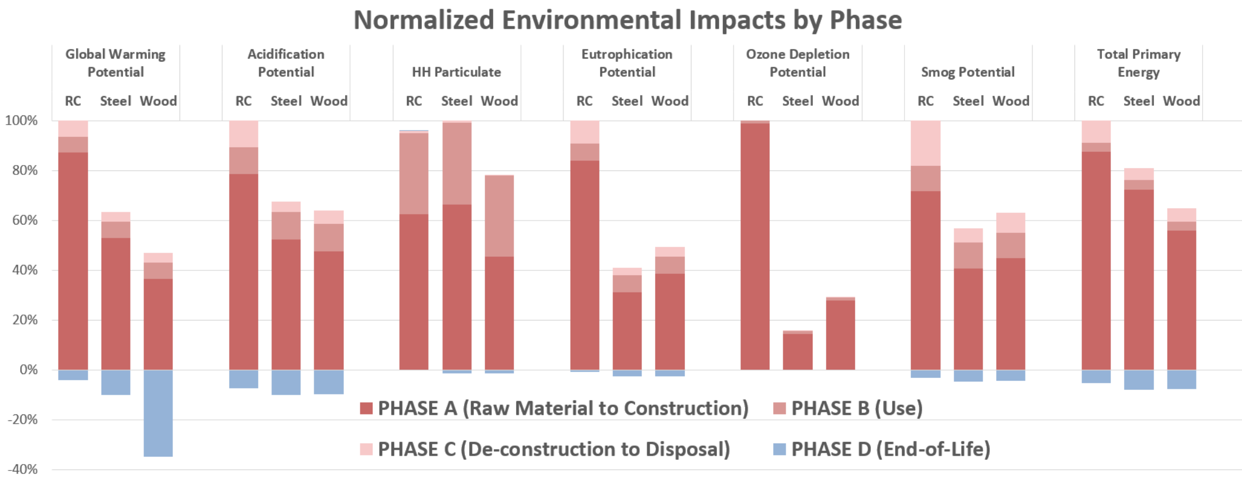

Figure 1: Normalized LCA Results Organized by Phase

Table 1: 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 2 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 2 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 2: 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 structural system whereas the 100 mm composite decking is responsible for 20%. 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.

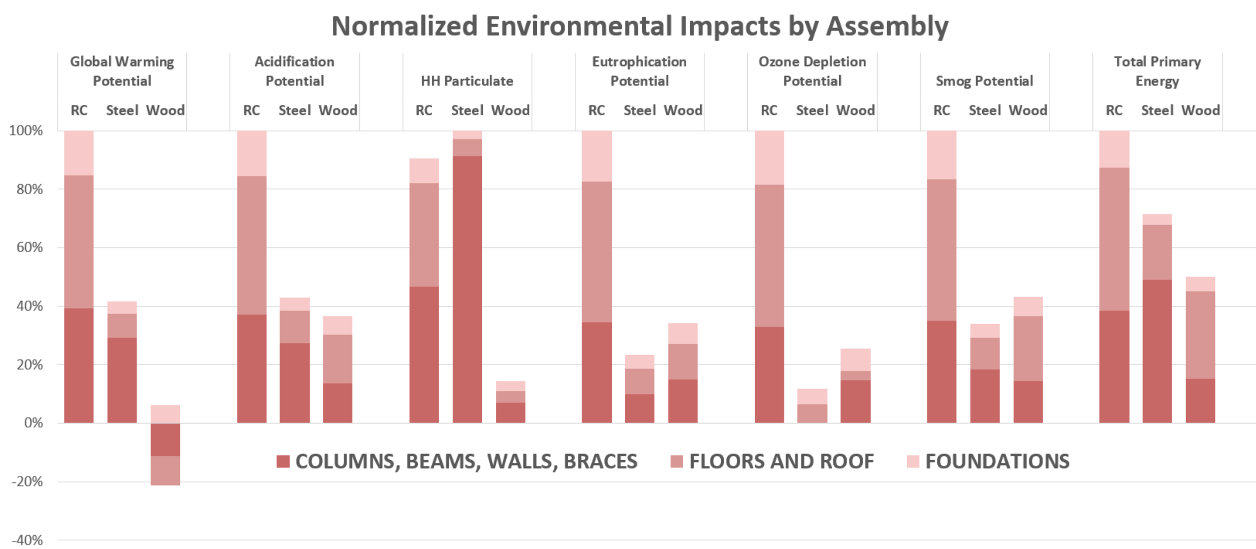

Figure 2: Normalized LCA Results Organized by Structural Assemblies

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 aren't 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

6 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 do 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 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 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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