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A Comparative Life Cycle Assessment Study of Wood and Steel Materials on a Virtual Office Building at the Project End-of-Life Stage

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The disposal of construction and demolition waste has an impact on the environment. This study focuses on the end-of-life stage to assess a virtual office building, by applying a comparative life cycle assessment (LCA) and used Athena software. The study determined LCA methods, and software tools based on a thorough literature review and then assessed the environmental impact of steel versus wood materials on a virtual office building model that was created from an actual construction project. The study quantifies the environmental impact of steel and wood materials into nine categories, including Global Warming Potential, Acidification Potential, etc., by using life cycle inventory (LCI) and life cycle impact assessment (LCIA) analyses. The results of this study show that the wood structure building has greater impact on environment than the steel structure building at the end-of-life stage in four categories of (1) Acidification Potential, (2) Eutrophication Potential, (3) Ozone Depletion Potential, and (4) Smog Potential, but has less impact on other five categories with actually a positive environmental impact in the Global Warming potential. The results of this study can provide valuable information about the environmental impact of different materials to reduce the environmental impact at the end-of-life stage.

Key Words: Life Cycle Assessment, End of Life Stage, Environmental Impact, Global Warming

Introduction

The construction industry is one of the largest resource consumers and waste producers in the United States and in the world. It uses 40% of the world's raw materials and produces 35% of the world's waste (Yuan et al. 2012). In 2017, 569 million tons of construction and demolition debris was generated in the United States, which is more than twice the amount of generated municipal solid waste, and demolition represents more than 90 percent of total construction and demolition debris generation (EPA 2019). In 2018, the construction and demolition debris were increased to 600 million tons, of which 188.8 million tons were generated by building demolition (EPA 2020). All of these

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debris disposal processes result in environmental impact to some degree, such as pollution, and requires actions to reduce such impact.

In order to reduce the environmental impact of the construction and demolition, it is necessary to assess the degree of such impact. By much previous research, such environmental impact is commonly studied by using life cycle assessment (LCA) method, which assesses the life cycle stages of building products, include (1) production stage, (2) construction stage, (3) use stage, and (4) end-of-life stage (ISO 2017). The first stage mainly focuses on the process from raw materials to building products, while the second stage focuses on the installation process during construction. The third stage assesses the use and operation of building after the construction is completed, and finally the last stage focuses on demolition of building when it reaches it's the end of service life. Resource consumption is involved in each of the stages described above, such as raw material collection, raw material processing, transportation, and waste disposal (Huang et al. 2018). Existing research results were focusing on the first three stages but only a few were focusing the end-of-life stage, which were mainly on improving the rate of recycling and reuse and on optimize recycling scheme for the waste generated (Yazdani et al. 2020; Akhtar and Sarmah 2018; Gálvez-Martos et al. 2018; Di Maria, Eyckmans, and Van Acker 2018). However, the end-of-life stage has more scope of work than just recycling and requires further investigation on its impact. Therefore, this study has explored a comparative LCA case study of building materials at the project end-of-life stage. This study will have a contribution to the effort of reducing environmental impact in the construction industry and to the body of knowledge of building LCA.

Methodology

The methodology includes two main parts: (A) Determine the study method, software and scope, and (B) Conduct a case study on a virtual office building model. Literature review has been conducted about in four areas: (1) the LCA method; (2) environmental impact of construction includes four life cycle stages: production, construction, use, and end-of-life stage; (3) impact of steel and wood as a structural building material on the environment; and (4) LCA software tools. Through the review of the literature, the research method, research scope and software use of this article are determined. Then a case study project, a two-story office building was chosen to be used to create a virtual model for assessment. The complete schematic explanation of the methodology is showed in Figure 1.

The total area of the building is 15,700 square feet, in which the original beam and column system of the building was made of steel. Additionally, the study chose to use wood structural materials to compare with steel structure materials. As the office building has only one design scheme that uses steel as the structural material, the wood structural design only uses wood materials to replace the steel materials of the beam and column system in the original structural drawing. The scope of this case study is limited to the impact of steel material and wood material on the environment at the end-of-life stage. The steel structure model is established using the software of Revit based on the original structure drawings (Figure 2). As a comparison, a new wood structure model is established by replacing steel material with wood material in the steel structure model. In those two models, glulam is used for columns and beams of wood structure, wide flange is used for columns and beams of steel structure. Some other details about this case study project can be found in Table 1.

There are three steps to the assessment of the project. The first step is life cycle inventory (LCI) analysis, Athena Impact Estimator for Buildings (IE4B) is used in this part as LCA software. When users input relevant building data into the IE4B, the IE4B provides a cradle-to-grave LCI profile to

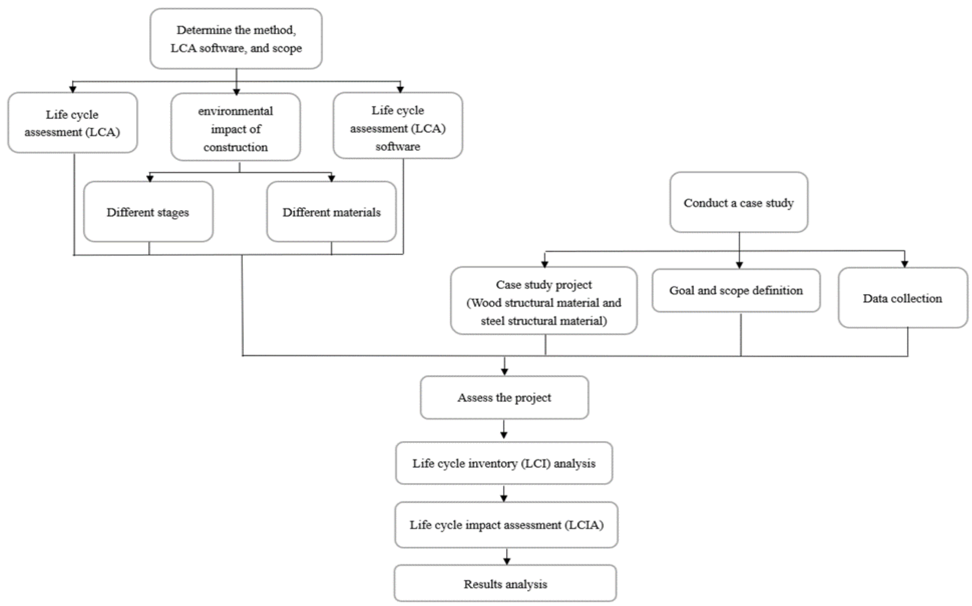

Figure 1. Study methodology

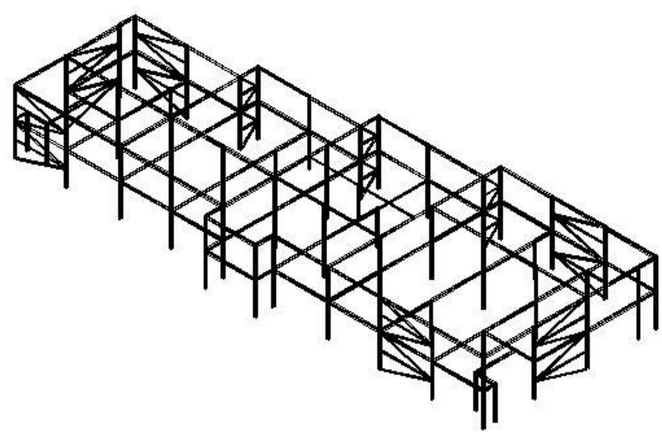

Figure 2. Revit structure model

Table 1. Case study project description.

Item	Specification
Building type	Office Rental
Project location	Minneapolis*
Building life expectancy	60 years
Building Height	33.4 ft
Gross floor area	15,700 ft^2

* The nearest city of Minneapolis is selected here.

assess a building's environmental impact. The LCI results include raw materials input; emission to air, water, and land; and energy consumption. The second step is life cycle impact assessment (LCIA), The LCA results data obtained by IE4B conform to the ISO 14040/14044 standard, and the life cycle impacts were evaluated with the TRACI v2.1. The last step is comparison and analysis of the results from the LCIA. The required data about the office building are from the structural drawings of the office building. The software processing data is from three database: Scenario database, Athena LCI database, and TRACI v2.1 database.

Table 2 summarizes the input data that need to be entered to assess the building. The difference between the input of steel structure building materials and wood structure materials only lies in the types of beams and columns, and the others are the same. Then the software will adjust the algorithm by applying the size of the input material type, load, and geometric conditions, and calculate the amount of structural materials required in the column and beam system. By inputting the data into the software, the life cycle inventory (LCI) and life cycle impact assessment (LCIA) of the end-of-life stage can be obtained. However, this paper only reports the LCIA results.

Table 2. Beams and columns input data.

	Item	Area 1	Area 2	Area3	Area4	Area5	Area6
Steel and Wood structure model	No. of columns	23	31	4	21	26	4
	No. of beams	43	46	3	39	35	3
	Bay size	24 ft	24 ft	22.8 ft	24 ft	24 ft	22.8 ft
	Supported span	8 ft	23.5 ft	8 ft	8 ft	23.5 ft	8 ft
	Supported area	4,801 ft^2	10,596 ft^2	211 ft^2	4,801 ft^2	10,596 ft^2	221 ft^2
	Column height	15.25 ft	15.25 ft	15.25 ft	14 ft	14 ft	14 ft
	Supported element	Floor	Floor	Floor	Roof	Roof	Roof
	Live load	100 psf	100 psf	100 psf	50 psf	50 psf	50 psf
Steel structure model	Column type	WF	WF	WF	WF	WF	WF
	Beam type	WF	WF	WF	WF	WF	WF
Wood structure model	Column type	Glulam	Glulam	Glulam	Glulam	Glulam	Glulam
	Beam type	Glulam	Glulam	Glulam	Glulam	Glulam	Glulam

Key findings

The data from Table 1 and 2 was input into the Athena Impact Estimator for Buildings software, the LCIA results were obtained for the end-of-life stage and are show in Table 3 and 4, which include three parts: (1) de-construction demolition (C1) & disposal (C4), (2) transport (C2), and (3) benefits and loads beyond the system boundary (BBL) (D), for steel and wood structural materials, separately.

The LCIA results of the steel structure building

Table 3 and Figure 3 show the results of LCIA for the steel structure building. Among those nine categories, three are related to energy consumption.

Table 3. The results of LCIA for the steel structure building.

LCA Measures	Unit	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL material (D)
Global Warming Potential	kg CO2 eq	3.84E+03	2.87E+01	8.97E+03
Acidification Potential	kg SO2 eq	3.70E+01	2.76E-01	2.06E+01
HH Particulate	kg PM2.5 eq	1.23E+01	1.53E-02	9.02E+00
Eutrophication Potential	kg N eq	2.26E+00	1.72E-02	1.06E+00
Ozone Depletion Potential	kg CFC-11 eq	1.66E-07	1.00E-09	0.00E+00
Smog Potential	kg O3 eq	1.17E+03	8.72E+00	2.08E+02
Total Primary Energy	MJ	5.59E+04	4.19E+02	4.12E+04
Non-Renewable Energy	MJ	5.58E+04	4.18E+02	4.12E+04
Fossil Fuel Consumption	MJ	5.58E+04	4.18E+02	8.26E+04

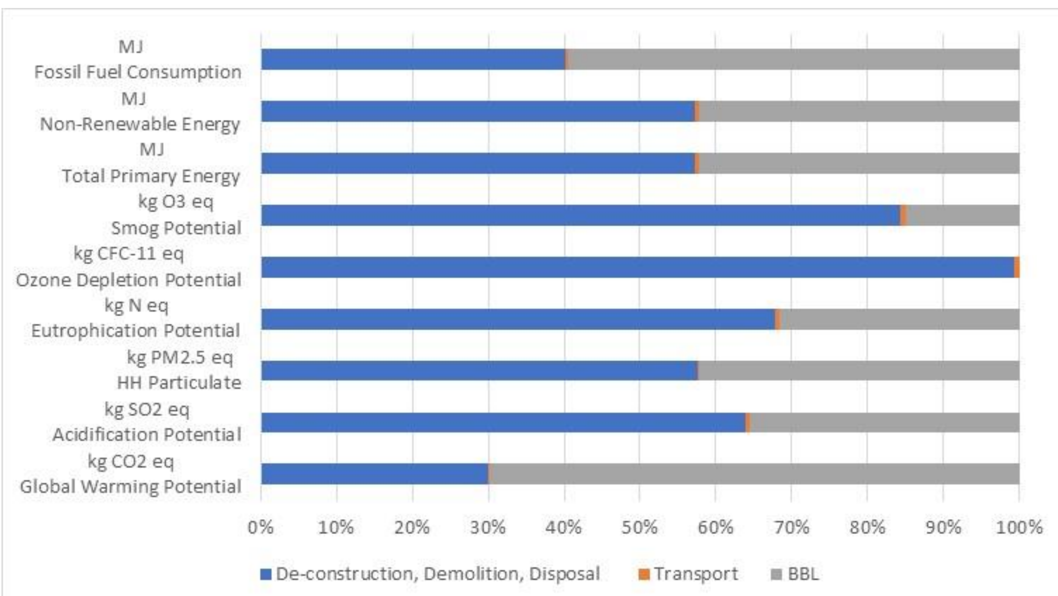

Figure 3. The results of LCIA for the steel structure building.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

In the Total Primary Energy Consumption, module C4 consumes the least energy, followed by module D, and module C1 & C4 consume the most energy. Fossil Fuel Consumption is a subset of Total Primary Energy, meaning the data of Fossil Fuel Consumption should be smaller than Total Primary Energy. However, the Fossil Fuel Consumption of BBL is greater than the Total Primary Energy of BBL, which is abnormal and needs further investigation.

For the rest of (six) categories, Module C1&C4 has the highest proportion of Ozone Depletion Potential and the lowest proportion of Global Warming Potential (GWP). Module C2 has the highest proportion of Smog Potential and the lowest proportion in Human Health Particulate. The highest proportion of module D is GWP, and its lowest proportion is Ozone Depletion Potential. In general, module C2 accounts for the lowest proportion of environmental impact in all nine categories, and module C1 & C4 accounts for the highest proportion of environmental impact in seven categories (except for GWP and Fossil Fuel Consumption categories).

The LCIA results of the wood structure building

The results of the LCIA for the wood structure building shown as Table 4 and Figure 4. Except for GWP, the proportion of module C1 & C4 is greater than module C2 in the other eight environmental impact categories. Among them, module C1 & C4 accounts for the largest proportion of Acidification Potential, while human health particular accounts for the least. However, module D is very different, only showing GWP's value and the value is negative; the other eight environmental impact categories are showing zero (0). When forests grow again, after they have been cut down for making wood structural material, they will absorb carbon dioxide in the air, thus making the GWP value negative. The premise is that the forest is completely regenerated after logging. The forest regeneration after felling not only produce new wood materials, but also absorb carbon dioxide from the air, so as to reduce the environmental impact. Overall, wood is a good structural material to reduce environmental pollution.

The Comparison of LCIA results

Nine categories of LCIA results between steel structure building and wood structure building are compared, respectively. As an example, Figure 5 shows the results of GWP between the steel structure building and the wood structure building. The GWP of the two buildings in module C1 & C4 are similar. In module C2, the GWP's value of the wood structure building is more than the steel structure building. For module D, the GWP's value of the steel structure building is greater than the wood structure building, because the GWP of the wood structure building is negative. Overall, the GWP of the wood structure is negative, and GWP of the steel structure is positive. Therefore, the steel structure building has more environmental impact than the wood structure building.

Acidification Potential of module C1 & C4 and Module C2 for the wood structure building is greater than that for the steel structure building. However, Acidification Potential of module D for the steel structure building is greater than that for the wood structure building. For the total value of Acidification Potential, the wood structure building is greater than the steel structure building. Except for the result of module C2 in Human Health Particulate for the wood structure building is a little bit greater than that for the steel structure building, the results of other modules in Human Health Particulate for the steel structure building are greater than those for the wood structure building. Additionally, the total value of Human Health Particulate for the steel structure building are greater than that for the wood structure building. Eutrophication Potential of module C1 & C4 and module C2 shows that the wood structure building is greater than the steel structure building. However, Eutrophication Potential of module D shows that the steel structure building is greater than the wood structure building. For the total value of Eutrophication Potential, the wood structure is greater than the steel structure building. The steel structure building of Ozone Depletion Potential in module C1 & C4 is similar to the total value of the steel structure building, and the total value of Ozone Depletion Potential for the steel structure building is similar to the value of module C1 & C4 for the wood structure building. Overall, the total value of Ozone Depletion Potential for the wood structure building is greater than the steel structure building. Not only the total value of Smog Potential for the wood structure building is greater than the steel structure building, but also the Smog Potential of module C1 & C4 for the wood structure building is greater than the steel structure building. For the results of Total Primary Energy Consumption, Non-Renewable Energy Consumption, and Fossil Fuel Consumption, the wood structure building use more energy than the steel structure building in module C1 & C4 and module C2. However, the energy consumption of module D for the steel structure building are greater than the wood structure building. The total value of energy consumption includes Total Primary Energy Consumption, Non-Renewable Energy Consumption, and Fossil Fuel Consumption for the steel structure building are greater than wood structure building.

Additionally, the results from the software of the sensitivity analysis for changing project location and changing building life expectancy are the same as the original results from the software. But the reasons for getting the same results are different. The reason why the LCIA results of the sensitivity analysis in changing project location have not changed is that the location of Minneapolis and the location of USA use the same database. And the reason why the LCIA results of the sensitivity analysis in changing building life expectancy have not changed is that changing the building life expectancy will not change the environmental impact. The changing column types of sensitivity analysis shows the results of Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, and Smog Potential for the wood structure building are greater than those in the steel structure building. In addition, the wood structure building at the end-of-life stage of GWP has the positive environmental impact.

Table 4. The results of LCIA for the wood structure building.

LCA Measures	Unit	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)
Global Warming Potential	kg CO2 eq	3.87E+03	8.28E+02	-1.23E+05
Acidification Potential	kg SO2 eq	5.54E+01	7.97E+00	0.00E+00
HH Particulate	kg PM2.5 eq	1.36E+00	4.41E-01	0.00E+00
Eutrophication Potential	kg N eq	3.46E+00	4.95E-01	0.00E+00
Ozone Depletion Potential	kg CFC-11 eq	1.69E-07	2.89E-08	0.00E+00
Smog Potential	kg O3 eq	1.84E+03	2.51E+02	0.00E+00
Total Primary Energy	MJ	5.77E+04	1.21E+04	0.00E+00
Non-Renewable Energy	MJ	5.76E+04	1.21E+04	0.00E+00
Fossil Fuel Consumption	MJ	5.76E+04	1.21E+04	0.00E+00

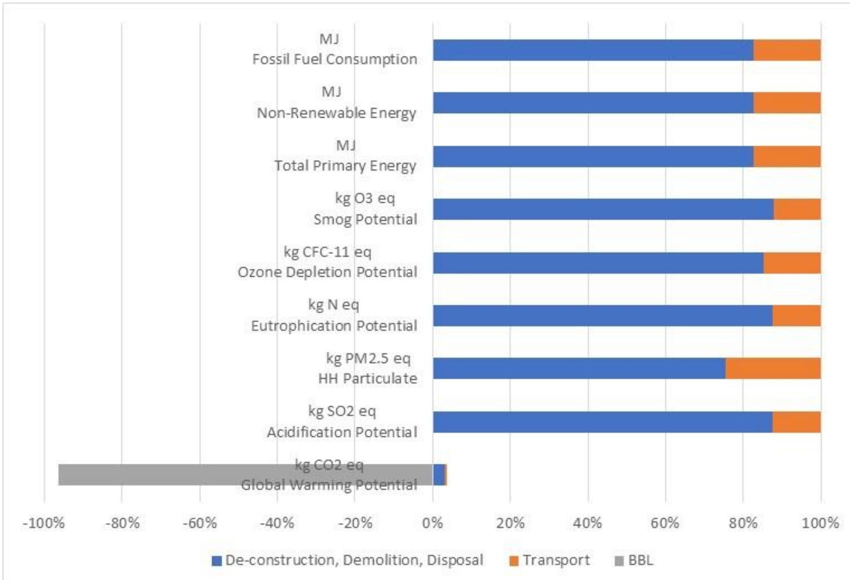

Figure 4. The results of LCIA for the wood structure building.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D)

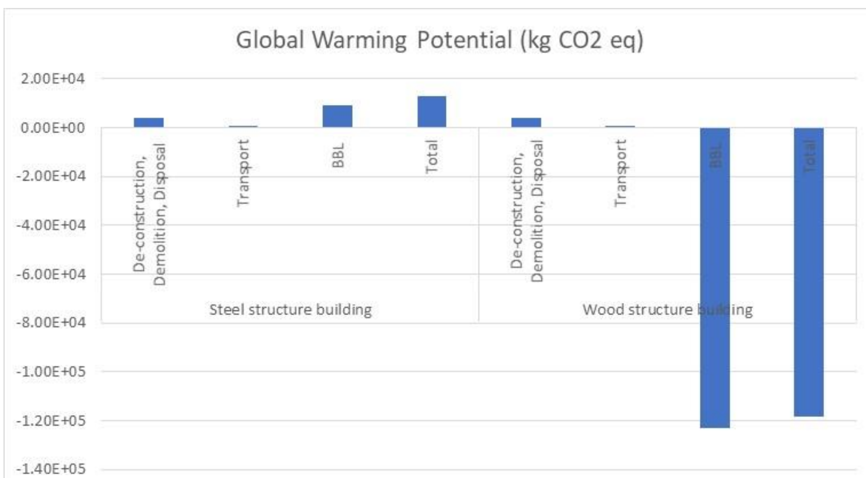

Figure 5. The results of GWP for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

Conclusion

This case study is focused on the environmental impact at the end-of-life stage between a wood structure building and a steel structure building. Life cycle assessment and Athena Impact Estimator for Building software are used in this study. The environmental impact is quantified into nine categories: Global Warming Potential (GWP), Acidification Potential, Human Health Particulate, Eutrophication Potential, Ozone Depletion Potential, Smog Potential, Total Primary Energy Consumption, Non-Renewable Energy Consumption, and Fossil Fuel Consumption. The comparison of LCIA results between the wood structure building and the steel structure building shown that Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, and Smog Potential in the wood structure building are greater than those in the steel structure building. Conversely, the comparison also shown the wood structure building performed worse in GWP, Human Health Particulate, Total Primary Consumption, Non-Renewable Energy Consumption and Fossil Fuel Consumption than the steel structure building. The interesting result is the GWP of the wood structure building, because that result is negative. It means wood structure building at the end-of-life stage for the GWP has a positive environmental impact. Finally, it is concluded that the steel structure building has more environmental impact than the wood structure building at the end-of-life stage. This study's results can help decision-makers choose the structural material better to reduce the environmental impact and energy consumption of buildings at the end-of-life stage.

Due to the difficulty caused by COVID-19 pandemic, some limitations still exist in this study and are listed here: (1) There was only one type of frame design for each type of materials, i.e., the wood structure building design is obtained by replacing steel with wood materials. A future study should choose a building with two or more types of frame design for different structural materials; (2) The project location of Fargo is not provided in the database; therefore, Minneapolis was used, but these two cities are so different. For future study, the researcher should find a case study project in which location is provided in the software or more locations should be added to the software.

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