A COMPARATIVE LIFE CYCLE ASSESSMENT STUDY OF WOOD AND STEEL MATERIALS AT THE PROJECT END-OF- LIFE STAGE

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

The disposal of construction and demolition waste will have an impact on the environment. However, the currently limited research on the end-of-life stage waste is too general lacking separation and comparison of different material types. This study focuses on the end-of-life stage to assess two primary construction materials (wood and steel) and an office building, used as a case study. This study is performed applying life cycle assessment (LCA) and used Athena software to assess the impact of both materials. The software quantifies the environmental impact of two materials into nine categories, including Global Warming Potential, Acidification Potential, etc. The results of this study show that steel generates more impact than wood on the environment. In the future, the results of this study can provide valuable information about the environmental impact of wood and steel materials to reduce the environmental impact at the end-of-life stage.

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CHAPTER ONE: INTRODUCTION

1.1. Background

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 was increased to 600 million tons, of which 188.8 million tons were generated by building demolition (EPA 2020). Construction and demolition debris commonly includes concrete, wood products, drywall and plasters, steel, and brick materials, each of which uses different disposal process. For examples, concrete debris is used to produce aggregates and steel debris is recycled for remanufacturing of steel products, while other types of debris go to landfill. However, all of these 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 many previous researches, 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 above described stages, 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 includes the optimization and innovation of processing raw materials in the production stage, the optimization of the use and construction scheme of on-site equipment in the construction stage, and the optimization of transportation process by switching building materials from unnecessary remote purchase to local resources in the production and construction stages. At the use stage, research were mostly focusing on finding new technologies and solutions to reduce the impact on the environment by the operation of buildings, such as lighting, heating, and cooling. 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 previous research on the end-of-life stage lacks a systematic assessment on how different building materials impact the environment differently and how they can be treated differently at the end-of-life stage. Furthermore, the end-of-life stage has more scope of work than just recycling and requires further investigation on its impact. Therefore, this project has explored a comparative life cycle assessment study of building materials at the project end-of-life stage with a focus just on wood and steel materials.

This study can cover the research gap regarding steel and wood structural materials at the end-of-life stage. A further exploration in this area will provide researchers and the industry professionals a better understanding on the environmental impact that selected construction materials can impose even on its end-of-life stage. The study results are expected to be a good tool or data source for project designers and constructors to adopt the appropriate materials considering their environmental impact during their life cycle. Eventually, 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.

1.2. Problem statement

As described above, although intensive research and related implementation have been done to significantly reduce the construction and demolition waste, and to reduce its impact on the environment imposed by the processing of construction wastes (Yüksek and Karadayi 2017; Kabirifar et al. 2020; Yazdani et al. 2020), such effort and effects have been mostly focusing on the first three stages of building life cycle, i.e., (1) production stage, (2) construction stage, and (3) use stage, especially when focusing on the development of low energy consumption or flat environmental impact design. Only very limited work has been done on the last (4th) stage of the building life cycle, i.e., the end-of-life stage. However, the demolition waste generated at the end-of-life stage has more impact on the environment and needs to be addressed. Furthermore, the currently limited research on the end-of-life stage waste is too general lacking separation and comparison of different material types. Therefore, a systematic comparative assessment of construction waste at the end-of-life stage is necessary and will be beneficial to further reduce its impact on the environment such as reducing Global Warming Potential. Additionally, knowing the impact of the end-of-life stages can, in turn, help inform design and construction decisions to improve the relative environmental impacts on the first three stages again.

1.3. Objectives

In order to solve the problem described above, this study used a comparative assessment method to compare the environmental impact of two different building construction materials at the end-of-life stage: (1) wood materials and (2) steel materials. The goal of this study was to quantify the difference of impact on environment at the end-of-life stage among different building materials using the comparative LCA method.

To assess this comparison, the following specific research objectives have been conducted through this study.

1) Determine the assessment method and software by reviewing existing literature on the environmental impact of buildings.
2) Determine the impact of the wood and steel materials on the environment at the end-of-life stage by using LCA software.
3) Determine which material has more impact on the environment.

1.4. Thesis organization

This thesis is divided into six chapters and one appendix to provide and meet the required information of the aforementioned objectives. Chapter 1 offers a concise introduction, background, problem statement and a general scope of this study. Chapter 2 presents a summary of the methodology used for the current study. Chapter 3 is the detailed literature review. This chapter reviews the literature on the impact of buildings on the environment and determines the methods and software that will use in the case study. Chapter 4 presents a case study to address the specific objectives of the current study. The case study project was a two-story office building with a steel structure. Meanwhile, another structural material, wood, was chosen to replace steel as the building's structural material. In this chapter, the methods and software determined by the literature review were used to compare the environmental impact of the different structural materials. The results of the study are presented in Chapter 5 and Chapter 6. Chapter 7 presents study conclusion, and discusses limitations of this study and recommendations for the potential future work, followed by a list of references used. In the end, the Appendix shows the case study project structure drawings, complete tables of LCI emission, and the actual interface window of the LCA software.

CHAPTER TWO: METHODOLOGY

Environmental problems are important topics in almost all industries, and the construction industry is no exception. The study focused on a comparative environmental impact between wood material and steel material at the end-of-life stage, and the methodology used for this study is summarized as a flow chart in figure 2.1.

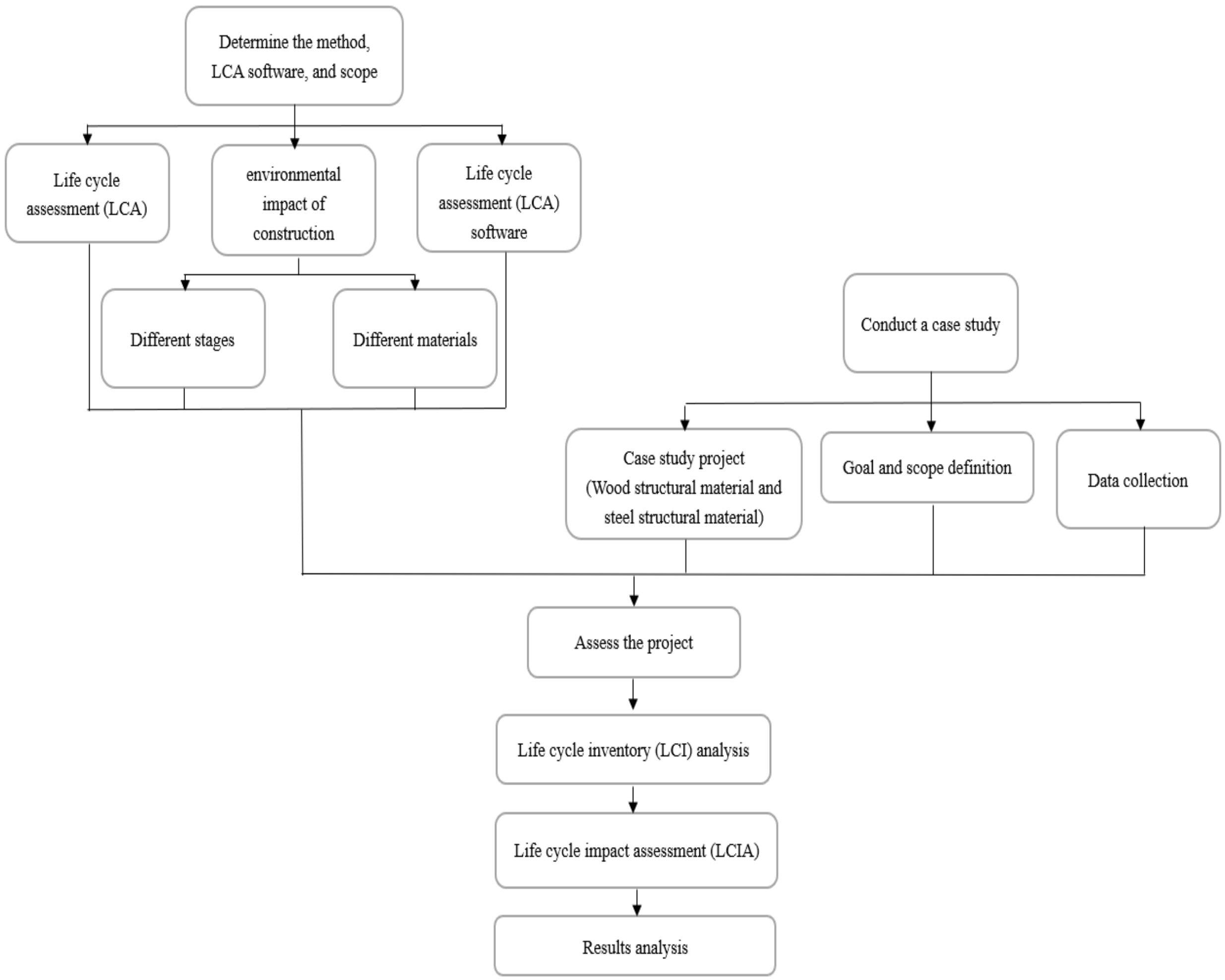

Figure 2.1. A summary flow chart of methodology.

2.1. Determine the method, software, and scope

This section has four parts. First, review literature about the LCA method. Second, review literature about environmental impact of construction includes four life cycle stage: (1)

production stage, (2) construction stage, (3) use stage, and (4) end-of-life stage. Third, literature was reviewed about the impact of wood as a structural building material and steel as a structural building material on the environment. Fourth, literature was reviewed about LCA software tools. Through the review of the literature, the research method, research scope and software use of this article are determined.

2.2. Conduct a case study

For a case study, a two-story office building was chosen, which is Woodhaven Office Complex. The total area of the office building is 15,700 square feet. The building is in Fargo, North Dakota.

From the structural drawings of the office building, it can be seen that the beam and column system of the building is made of steel. However, if the study wants to compare the environmental impact between two different structural materials, the study needs to use another material to compare with steel. Common structural materials are concrete, steel, wood, brick, and stone. Since Fargo is in the north-central United States, near Canada, and Fargo has long winter with low temperature, the final choice is 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 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.

Through the review of the literature and case study project, the scope of this study is the impact of steel material and wood material on the environment at the end-of-life stage. The goal of this study is to find out which one material (wood or steel) has less impact on the environment by comparing the environmental impact assessment at the end-of-life stage.

2.3. Assess the project

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 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 results analysis, the results that get from the LCIA part are compared, discussed, and analyzed to get the final conclusion. Below is detailed description of LCI and LCIA.

2.3.1. Life cycle inventory

LCI analysis involves creating an inventory of flows from and to nature (ecosphere) for a product system (Standardization 2006)(Standardization 2006). LCI usually includes inputs of raw materials and energy, and output of emissions to the air, land, and water. In this study, Athena Impact Estimator for Buildings was used as LCI software. The heart of the LCA analysis is the Athena LCI database. The determination of transportation mode and distance depends on the selection of project location. The software will use appropriate data according to the location of the selected area to carry out specific internal calculations. Software supported LCI data for structural materials as (Athena 2019).

- Steel Products – North America 2010
- Glulam – U.S. 2012

2.3.2. Life cycle impact assessment categories

LCIA is aimed at evaluating the significance of potential environmental impacts based on the LCI. In this step, LCIA transfers LCI data into an understandable and quantifiable results. The LCIA tool used in this study is a Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) that has been developed by the U.S. Environmental Protection Agency (EPA). For this case study, TRACI V2.1 was used to perform LCIA in Athena Impact Estimator for Buildings, which translates the environmental loads identified by the LCI into nine different categories as described with a bit more details below (Athena 2019) in Table 2.1.

Table 2.1. Descriptions of LCI categories.

LCIA category	Unit	Description
Global Warming Potential (GWP)	kg CO2 eq	GWP usually relates to CO2, CH4, and N2O.
Acidification Potential	kg SO2 eq	Acidification affects human health, and usually relates to NOx and SO2.
Human Health (HH) Particulate	kg PM2.5 eq	The main contributor to this impact is the particles with a size between PM2.5 and PM10. Particulate matter in this range has a considerable impact on human health, mainly reflected in respiratory diseases (such as asthma, acute lung disease, etc.).
Eutrophication Potential	kg N eq	The main harm of aquatic eutrophication is that when a previously deficient nutrient is added to the water, it will lead to the reproduction of aquatic light and plants, thus destroying the stability of the ecosystem and leading to a series of consequences.
Ozone Depletion Potential	kg CFC-11 eq	Ozone depleting substances emitted into the air include CFCs, HFCS, and halons.
Smog Potential	kg O3 eq	Smog impacts the environment because, in some climates, the exhaust gas emitted by industries such as industry does not disperse in time. If it is exposed to sunlight, photochemical smoke will be generated, which will affect the environment. Smoke potential is usually related to volatile organic compounds, nitrogen oxides (NOx) and O3.
Total Primary Energy	MJ	Total Primary Energy includes all energy (direct and indirect).
Non-Renewable Energy	MJ	Non-Renewable Energy is part of the Total Primary Energy, includes all the fossil fuels and nuclear.
Fossil Fuel Consumption	MJ	Fossil Fuel Consumption is a subset of Total Primary Energy Consumption, namely all the fossil fuels.

CHAPTER THREE: LITERATURE REVIEW

The literature review section includes 4 steps:

1) Review the life cycle assessment method.
2) Review the research on environmental impact of construction in each stage.
3) Review the studies on the impact of wood structural material building and steel structural material building on the environment.
4) Review the life cycle assessment software tool.

3.1. Overview of life cycle assessment (LCA)

The concept of environmental life cycle assessment (LCA) was put forward in Europe and the United States in the late 1960s and early 1970s. The first appearance of LCA in modern environmental understanding was in a Coca-Cola study aimed at quantifying the environmental impact of packaging from the cradle to the grave (Hunt, Sellers, and Franklin 1992). After that, LCA is used as a tool to investigate the environmental burdens of a product or process, considering the whole life cycle, from the cradle to the grave (Standardization 2006). The International Standardization Organization (ISO) and the American National Standards Institute (ANSI) have worked together to standardize LCA. In current practice, LCAs are executed according to the framework of the ISO 14040 series (Standardization 2006). To analyze the environmental burdens of processes and products during their entire life cycle, there are four steps to go through: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and an interpretation (Standardization 2006). LCA has a wide range of applications. LCA was first used in plastics, detergents, personal care products, and automobile industries. Then came agriculture, gas and oil extraction, construction, and retail. Next came the infrastructure industry, including electricity, water supply, communications, etc. LCA has been widely used in the construction industry since 1990, and it is an important tool to evaluate buildings (Fava et al. 2006). Using the LCA method can better help the construction practitioner to make decisions and optimize the process, to reduce the impact of the building on the environment. For example, how the effect of different materials selection on the environment is diverse, to help design and construction personnel better choose building materials (Gerilla, Teknomo, and Hokao 2007; Guggemos and Horvath 2005; Ding 2014; Bribián, Capilla, and Usón 2011).

3.2. Environmental impact of building in each stage

Generally, the life cycle of a building is divided into four stages: the product stage, the construction stage, the use stage, and the end-of-life stage. In this section, the environmental impact of each stage and how to reduce the impact are reviewed by the literature. EN 15804—2012, Sustainability of construction works, Environmental product declarations, is the most commonly used standard to categorize construction products (usgbc.org 2021). This standard provides core product category rules (PCR) for major construction products, which the contents of the life cycle building at four stages, show as Figure 3.1. Product categories are designated as A, B, C with numbers for different stages, respectively.

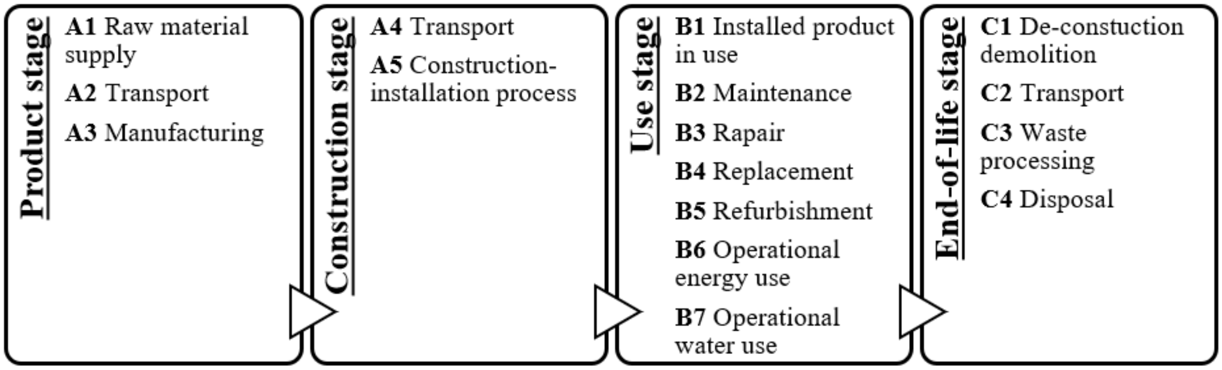

Figure 3.1. Building life cycle.

3.2.1. Product stage

The production/manufacturing stage is the first stage in the building life cycle. This stage includes raw material supply (A1), Transport (A2), and manufacturing (A3) (EN 2012). Then the study will review the environmental impact of buildings at the product stage.

Through the review of the literature, Global Warming Potential (GWP) is the most important environmental factor in the product stage (Gervásio et al. 2014; Petrovic et al. 2019; Wu et al. 2012; Santos et al. 2020; Pierobon et al. 2019). However, there are also some differences between different cases. Gervasio et al. (2014) found the material production phase dominated all impact categories, contributing more than 60%. But in other cases, the proportion is not so large; the reason should be that some aspects (such as A5, B1, B6, and B7) have not been assessed in the next few stages. Petrovic et al. (2019) got the results that GWP mainly comes from the foundation and substructure of structure part and concrete of material part. But Santos et al. (2020) found the GWP mainly comes from steel material. Wu et al. (2012) got the result that concrete, and steel are the main factor of GWP. The main reason for this difference could be the difference in design and main building materials.

GWP is the most important factor in the production stage, and GWP is determined by CO2 emission. There are many studies on reducing GWP or CO2 emissions. Among them, concrete and steel are the most serious CO2 emission projects in the material production stage. To reduce the CO2 emission of concrete in the product stage, Kurad et al. used high volumes of fly ash and recycled concrete aggregates to reduce CO2 emission (Kurad et al. 2017). In addition, natural materials can be used instead of high CO2 emission materials to reduce GWP and CO2 emissions, such as wood (Nässén et al. 2012), and bamboo. Except for the research on materials, there are also studies on energy, such as using green energy (Salas et al. 2018) and using local materials as much as possible to reduce the energy consumption of long-distance transportation (Achenbach, Wenker, and Rüter 2018; Mankelow, Oyo-Ita, and Birkin 2010).

3.2.2. Construction stage

The construction phase includes transportation (A4), and construction-installation process (A5). The construction-installation process includes construction equipment energy use, and A1-A4 effects of construction waste (EN 2012).

By reviewing the literature, GWP is the most important environmental impact in the construction stage (Gerilla, Teknomo, and Hokao 2007; Sandanayake, Zhang, and Setunge 2018, 2016; Li, Zhu, and Zhang 2010). Greenhouse gas (GHG) emission in the construction process is the main factor causing GWP. Many studies focus on the impact of GHG emissions in the construction stage on the environment (Sandanayake, Zhang, and Setunge 2016, 2018; Hong et al. 2015; Takano et al. 2014; Sandanayake et al. 2018). Sandanayake et al. (2016) found that material emissions accounted for 67% of the GHG emissions in the foundation construction stage. Similarly, Li et al. (2010) found that the construction of pit support construction has the greatest impact on the environment (59.4%), followed by excavation (18.3%), site clearing (12.3%), and backfilling (7.5%). Due to the amount of steel used in the pit support construction, the study found that steel has a great impact on the environment, so the construction part of the pit support construction has a great impact on the environment at the construction because of the impact of materials on the environment (Li, Zhu, and Zhang 2010). Taking a residential building as the research object, Sandanayake et al. (2018) also found that GWP is the most important environmental impact in the construction stage due to the GHG emissions caused by the large use of building materials in the construction stage. In addition to the impact of GHG emissions on the environment in the construction phase, Gerilla, Teknomo, and Hokao (2007) studied the impact of non GHG on the environment and found that the emissions of nitrogen oxides (NOx), sulfur oxides (SOx), and suspended particulate matter (SPM) were high. Still, the biggest environmental impact in the construction phase was GWP, because much of the emission in the construction phase came from carbon emissions. To reduce the impact of materials on the environment at the construction stage, some studies proposed reducing the use of highly polluting materials (such as steel, concrete, etc.), or adopting new materials, new designs or new technologies.(Li, Zhu, and Zhang 2010; Sandanayake et al. 2018; Gerilla, Teknomo, and Hokao 2007; Takano et al. 2014).

In addition to the impact of materials on the environment during the construction stage, what surprised Sandanayake, Zhang, and Setunge (2016) was that the use of equipment and transportation accounted for 19% and 14% of GHG emissions. This is only in the foundation construction stage. If from the perspective of the whole construction stage, equipment usage and transportation have a great impact on the environment. Takano et al. (2014) evaluated the environmental impact of GHG emissions from a wooden building in the construction stage and concluded that the transportation process of building components seems to have greater emission reduction potential than the actual construction process. Sandanayake, Zhang, and Setunge (2016), through the research on the foundation construction stage, it is concluded that reducing the environmental impact in the construction stage should be more focused on equipment usage and transportation. However, Li, Zhu, and Zhang (2010) found that the change of construction equipment had no significant effect on improving the environment through using different construction equipment for the two schemes. It can be seen from Li’s study that reducing the impact on the environment through the use of equipment cannot be a simple change of construction equipment.

3.2.3. Use stage

The use stage includes installed product in use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7) (EN 2012).

Since the use stage is the longest stage in the building life cycle, typically 50-75 years, it has a greater impact on energy consumption and the environment than any other stages. Due to study methods used in the literature were different, such impact of pollution emission has been measured in several different ways. Adalberth (2000) points out that about 85% of energy use and 70% - 90% of environmental impacts come from the use stage. Through the study of a house, Gerilla, Teknomo, and Hokao (2007) found that the emission of carbon pollutants in the operation stage was relatively high, accounting for about 79% of the total emission. Similarly, through the study of carbon dioxide emissions, Oh, Choi, and Park (2017) found that the stage with the most carbon dioxide emissions is the operation stage, in which a large amount of carbon dioxide is generated due to the operation of equipment such as heating, ventilating, and air conditioning. In addition to carbon and carbon dioxide emissions, Sharma et al (2011) also found that the GHG emissions in the operation stage accounted for more than 50% of the total GHG emissions (Sharma et al. 2011). Regardless of what measures were used, it can be concluded that the pollution emission is the largest in the use stage. Whether it is carbon emissions, carbon dioxide emissions, or GHG emissions will impact the environment.

Impact on energy consumption has also been studied intensively in the past for the use stage. Sharma et al (2011) found the energy consumption in the use stage accounting for 80% - 85% of the total energy consumption. Morales et al (2019) found the operating energy use (model B6) is the most impactful stage over the whole life cycle. Ortiz-Rodríguez, Castells, and

Sonnemann (2012) evaluated a house in Colombia and found that the major energy consumption was due to domestic hot water, lighting devices, and household appliances.

On the other hand, from studies in the literature for the use stage, it can be seen that the consumption of energy is the main factor causing the environmental impact in this stage. Researchers have found that different types of energy consumption have different impact on the environment in the use stage. Asdrubali, Baldassarri, and Fthenakis (2013) evaluated three different types of buildings (a detached residential house, a multi-family, and a multi-story office building) in Italy and concluded that the use of fossil fuel heating in the detached residential house in winter has a greater impact on the environment, while the use of electricity in the other two buildings has a greater impact on the environment.

Therefore, many studies have tried to reduce the environmental impact by reducing the energy consumption in the use stage. For example, Ortiz-Rodríguez, Castells, and Sonnemann (2012) reduced the energy consumption of residential buildings in the use stage by using more efficient household appliances to reduce the impact on the environment. However, these efficient household appliances will increase the investment cost. Gerilla, Teknomo, and Hokao (2007) proposed to use solar energy as clean energy in the operation stage to reduce environmental impact. Assuming that 100% of the total energy consumption can be provided by solar energy, the carbon emission in the operation phase will be reduced by 93%, which will greatly reduce the environmental impact in the use stage.

3.2.4. End-of-life stage

End-of-life stage includes de-construction demolition (C1), transport (C2), waste processing (C3), and disposal (C4). Some studies also include benefits and loads beyond the system boundary (designated as D), such as recycling (EN 2012).

The past research on the end-of-life stage mainly includes the impact of the demolition process, landfill process, and recycling process on the environment. In the demolition process, the most environmental impact comes from energy consumption. Kofoworola and Gheewala (2008) evaluated a commercial office building in Thailand and found that the greatest impact on the environment during the demolition stage is the energy consumption of the demolition machinery. Wang et al. (2018), through the study of carbon emissions at the end-of-life stage, found that the equipment that has the greatest impact on the environment is the equipment for collecting and sorting waste, followed by the equipment for demolition of buildings; however, this impact in the demolition site has been largely ignored by many studies. Additionally, Robertson, Lam, and Cole (2012) found that the demolition of concrete structures during the demolition stage requires more energy than the demolition of wooden structures, which indicates that the demolition of concrete buildings has greater environmental impact than the demolition of wooden structures.

After the demolition of the building is completed, the next step is to landfill or recycle. In the landfill process, the environmental impact mainly comes from the landfilling of different materials. Ortiz, Pasqualino, and Castells (2010) found that stone waste is the main contributor to landfill in the construction process, followed by metals, plastics, and wood. Those landfill materials have different impact on environment, Landfills of metals and plastics are the main contributors to the toxicity category. The landfill of paper and cardboard is the main contributor to GWP (Ortiz, Pasqualino, and Castells 2010).

Compared with landfill, recycling is a program with less impact on the environment. Effective recycling can save energy, equivalent to 29% of energy used in the manufacturing and transportation of building materials (Blengini 2009). The recycling of both metals and plastics produces environmental benefits (Ortiz, Pasqualino, and Castells 2010). Coelho and De Brito (2012) found that recycling or reusing core materials brings environmental benefits, among which the impact categories of climate change, acidification potential, and summer smog impact are reducing the most prominent. Blengini (2009) found that the recycling of the main building materials reduces life cycle energy consumption and greenhouse gas emissions, thereby reducing the impact on the environment.

Through the review of the four stages of the building life cycle, there are many studies on the construction and use stages, followed by the production stage. Although many LCA studies involve data and assessments at the end-of-life stage, most articles did not analyze and summarize the results obtained at the end-of-life stage. In general, very few articles have studied end-of-life stage in a way systematically considering all three parts of demolition, landfill, and recycling together, although some research have studied one of these parts separately. Additionally, it was shown different building structure materials have different degree of impact on environment at its end-of-life stage and therefore need further comparative study.

3.3. Environmental impact of different building structure materials

Although many different structure materials can be found in buildings, this study only focuses on a comparison between a wood structure building and a steel structure building since these are two most commonly used materials in building construction, as elaborated earlier.

3.3.1. Steel structure material

Because of its excellent tensile and compressive properties, steel has always been a popular commercial and industrial building construction material. Common structural steel shape includes the wide flange (WF) and the hollow structural section (HSS) shape. Steel makes the structure lighter, and meanwhile, durable, and highly malleable. Most importantly, steel has a high recycling rate. There are many studies on the impact of steel as a main building material on the environment. Oladazimi, Mansour, and Hosseinijou (2020) found that structural steel in a steel frame building has big environmental impact accounting for the largest proportion of carbon dioxide and methane resulting in GWP. Li, Zhu, and Zhang (2010) found that reinforcing steel in a reinforced concrete frame building has the greatest impact on the environment among all materials used in that building, accounting for 54% of the total impact. As a comparison, Zygomalas et al. (2016) found out that in a steel-framed residential building with reinforced concrete is only used for the foundation and ground floor, the impact of small amount of reinforced concrete is about the same as large amount of structural steel on the environment, surprisingly. Therefore, it can be concluded that the impact of unit steel was much less than unit reinforced concrete to the environment although both of them accounted for the largest proportion of environmental impact.

However, not all the past studies agree with this conclusion. For example, Kim et al. (2013) studied four buildings which were either steel or reinforced concrete frames and found that the carbon dioxide emission and energy consumption of reinforced concrete frames were 26% lower than those of steel frames, indicating that reinforced concrete frame is a better choice to reduce environmental impact.

Therefore, further comparative study is obviously needed to compare the environmental impact of the steel structure building with other structure buildings. Guggemos and Horvath (2005) compared a steel frame building with a concrete frame building and found that the concrete frame structure emitted more CO_2, CO, and NO_2, and consumed more energy. The steel frame building emitted more organic compounds and heavy metals. The results showed that the two kinds of frame structures have almost the same impact on the environment. However, Oladazimi, Mansour, and Hosseinijou (2020) also compared steel frame buildings and concrete frame buildings, and the results showed that the pollution of the concrete frame building was significantly higher than the steel frame building. Similarly, Gervasio et al. (2007) selected two residential buildings, one is a concrete frame, and the other is a steel frame for evaluation. The results showed that the concrete frame house produced more pollution than the steel frame house regarding resource consumption and human health.

Except for the comparison with the concrete frame building, there is also the comparison with the wood frame building. Gerilla, Teknomo, and Hokao (2007) compared a reinforced concrete structure house with a wooden type of house and concluded that the wooden type of house has less impact on the environment. Lu, El Hanandeh, and Gilbert (2017) chose a four-story building and evaluated its concrete, wood, and steel frames, respectively, and finally concluded that the concrete frame is more polluted than the other two frames.

Therefore, the whole section showed that steel structures have many advantages regarding its environment impact, while reinforced concrete structures have too much impact on environment and can be excluded from this study.

3.3.2. Wood structure material

Wood has been used as building materials for thousands of years. One of the biggest advantages of using wood as a building material for such a long history that wood is a natural resource. Common engineering wood includes plywood and glued laminated timber (glulam). Engineering wood products are widely used in various residential, commercial, and industrial construction projects. Wood is the most substantial building material and can be well insulated from the cold(Stojic, Markovic, and Stojkovic 2011). Wood also has extreme plasticity, can be processed into various shapes and sizes, plans can meet any building needs. At the same time, compared with other common building materials, wood in the processing stage does not need high-energy fossil fuel to produce (Buchanan and Levine 1999). Meanwhile, wood is biodegradable and renewable (Peltola, Juhanoja, and Salkinoja-Salonen 2000; Blanchet and Breton 2020).

In the past, there was much research compared wood structure building with reinforced concrete building on environmental impact. The research showed that the wood structure building consumes less energy than the reinforced concrete structure, had lower GWP, emitted less carbon and carbon dioxide, and had less impact on human health (Robertson, Lam, and Cole 2012; Sathre and Gustavsson 2009; Guardigli, Monari, and Bragadin 2011). Guardigli, Monari, and Bragadin (2011) found that compared with the reinforced concrete building, wood structure building was more convenient. Furthermore, the comparison between wooden structure building and concrete frame building showed that the wood frame had less energy consumption and less carbon dioxide emission(Gustavsson and Joelsson 2010). In addition, the research on wood structure building and brick structure building showed that wood structure building had less energy consumption and less environmental pollution than brick structure building, and the carbon footprint of brick structure building in the environment was twice that of wood structure building(Scharai-Rad and Welling 2002; Mitterpach and Štefko 2016). In a special study, Meil et al. (2002) compared a wood structure building and a steel structure building in Minneapolis and Atlanta, respectively. The results showed that the GWP and energy consumption of the wood structure building was lower than that of the steel structure building in Minneapolis and Atlanta. On the other hand, the GWP and energy consumption of wood structure building in Minneapolis was higher than those in Atlanta. It clearly showed that wood structures have many advantages regarding its environment impact.

However, while both steel and wood structures can be distinguished from reinforced concrete structures on their environment impact, most of the comparative studies did not compare these two systematically and therefore need a further comparison study between steel and wood structures for their impact on environment, especially at their end-of-life stage.

3.4. LCA software

LCA is widely used in many industries including construction industry. Therefore, this study has adopted LCA as comparative study tool. Such a method can be implemented using many different software programs including Gabi, SimaPro, One click LCA, Athena Impact Estimator for Buildings, etc. (Oladazimi, Mansour, and Hosseinijou 2020; Adaei Khezri and Kamalan 2020; Petrovic et al. 2019; Chen et al. 2020). Different software uses different databases and algorithms, so the results will be different.

Athena Impact Estimator for Buildings is the only free software tool in North America, designed to evaluate whole buildings and assemblies based on internationally recognized LCA methodology (Athena 2019). This software is capable of modeling 95% of the building types in North America with available data. Simultaneously, the software considers many aspects of environmental impact, including material manufacturing, related transportation, site construction, energy use, demolition, and disposal, in different locations. Especially, the equipment and energy used to remove all structural materials, and energy consumption during transportation, etc. are considered for the end-of-life stage. Therefore, it is very suitable and is selected for the case as the LCA software tool. The key element of the software is the Athena life cycle inventory (LCI) database that is comprised of ISO 14040/14044 LCI data related to basic materials, building products and components, fuel use, and transportation.

CHAPTER FOUR: CASE STUDY PROJECT AND PROCESS

In this study, a previously built office building of 15,700 square feet, in Fargo, North Dakota, has been selected as case study project. Some other details about this case study project can be found in Table 4.1. In this building, steel material is mainly used in the column and beam frames. Then the steel structure model is established using the software of Revit based on the original structure drawings (Figure 4.1). 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.

Table 4.1. 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

* Since there is no Fargo in the project location option, the nearest city of Minneapolis is selected here.

4.1. Goal and scope

The goal of this case study was to conduct two structure materials (wood and steel) building by LCA using the Athena Impact Estimator for Buildings to estimate environmental impacts at the end-of-life stage. The life expectancy of both building models is 60 years. By comparing the LCA of the steel structure building and wood structure building, some suggestions can be given for early structure material selection to reduce the impact of building on the environment at the end-of-life stage.

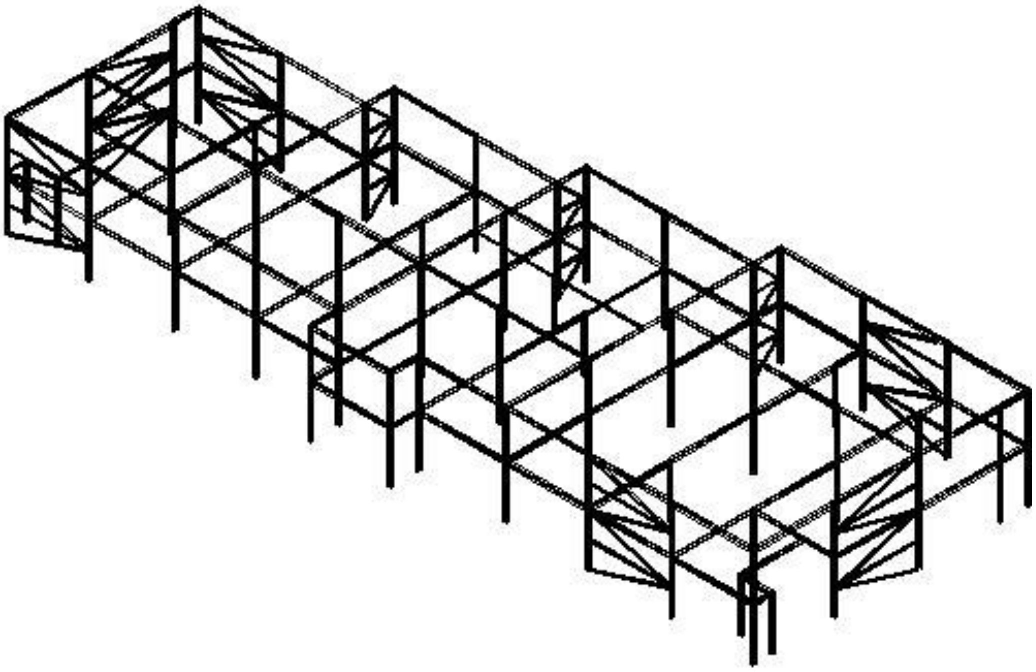

Figure 4.1. Steel structure model.

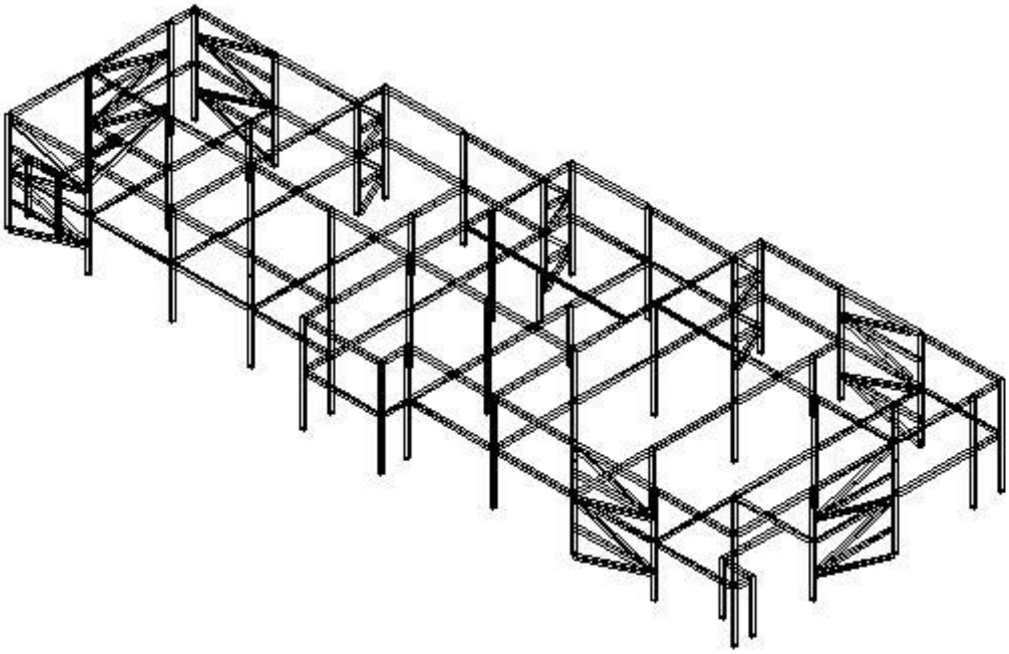

Figure 4.2. Wood structure model.

In this study, the system boundary was defined as the end-of-life stage, which includes four processes: de-construction demolition (C1), transport (C2), disposal (C4), benefits and loads beyond the system boundary (D), as shown in Figure 4.3. In addition, there are other impact factors, including cost, labor, market, location, might impact the boundary setting. For example, the price of wood materials in a location with forest resources will be lower than that in a location without forest resources. Other factors will affect the study. Because of the lack of information and impact factors involve a wide range, the system boundary of this study does not include these factors yet.

The case study has run four processes: (1) the de-construction demolition (C1) process includes demolition equipment energy use; (2) the transport (C2) process includes transportation of materials from site to landfill; (3) the disposal (C4) process includes disposal facility equipment energy use and landfill site effects; (4) the benefits and loads beyond the system boundary (D) process includes carbon sequestration and metals recycling (Athena 2019).

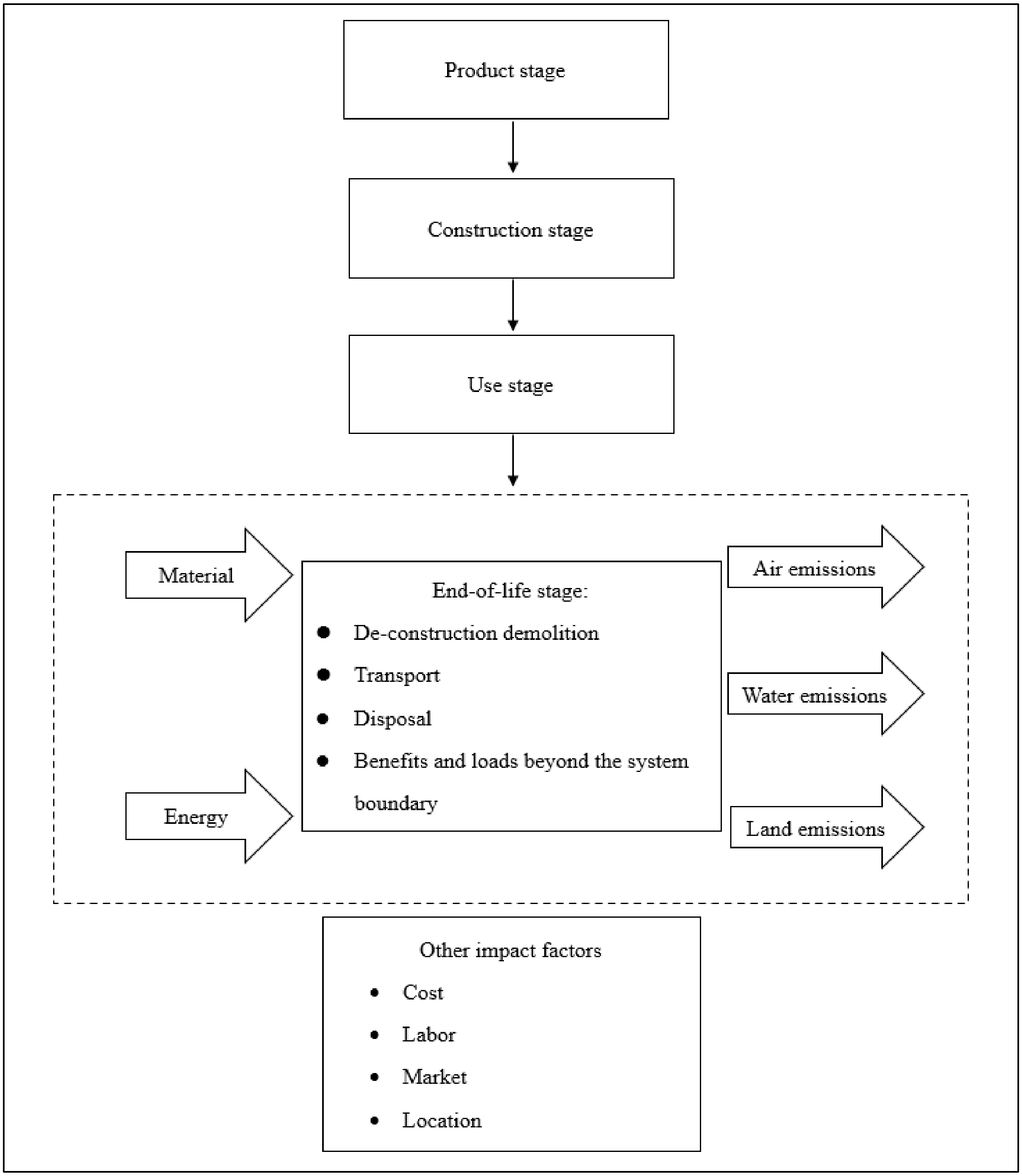

Figure 4.3. System boundary.

4.2. Simulation process

In this step, related data inventory is collected from the selected software: Athena Impact Estimator for Buildings. Athena Impact Estimator for Buildings can evaluate the whole life cycle of a building, but this case study only focused on the end-of-life stage of the building. In the software, the impact of different locations of buildings on the environment will have different results. Because the software selects the suitable transportation mode, transportation distance, and appropriate power grid, etc., for the selected location so that the results will be different. For example, different locations, using different kinds of transportation trucks with different transportation distance, will lead to the different fuel consumption and the different carbon dioxide emissions in the air during the transportation process. So that the impact of the transportation process on the environment will be different. In the process of running the software, the energy required to demolish the building is estimated first. Then the building materials obtained after demolition are proportionally divided into recycling, reuse, or landfill based on the software presetting, among which recycling, reuse, and incineration belong to module D of Benefit and loads beyond the system. In the landfill process, the software considers the energy use and emissions associated with transportation to the landfill site. In the above process, the data on steel was provided by Steel Recycling Institute and World Steel Association, in cooperation with the American Iron and Steel Institute in 2013. The fate of wood at the end-of-life is landfill (80%), combustion (10%), and recycling (10%). For the landfilled wood, 90% is sent to anaerobic landfills, and 10% is sent to aerobic landfills. The software running process is shown in Figure 4.4. According to the structural drawing of the building, the building is divided into six areas. Table 4.2 summarize 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. The illustration of full running process of the software is shown in Appendix C.

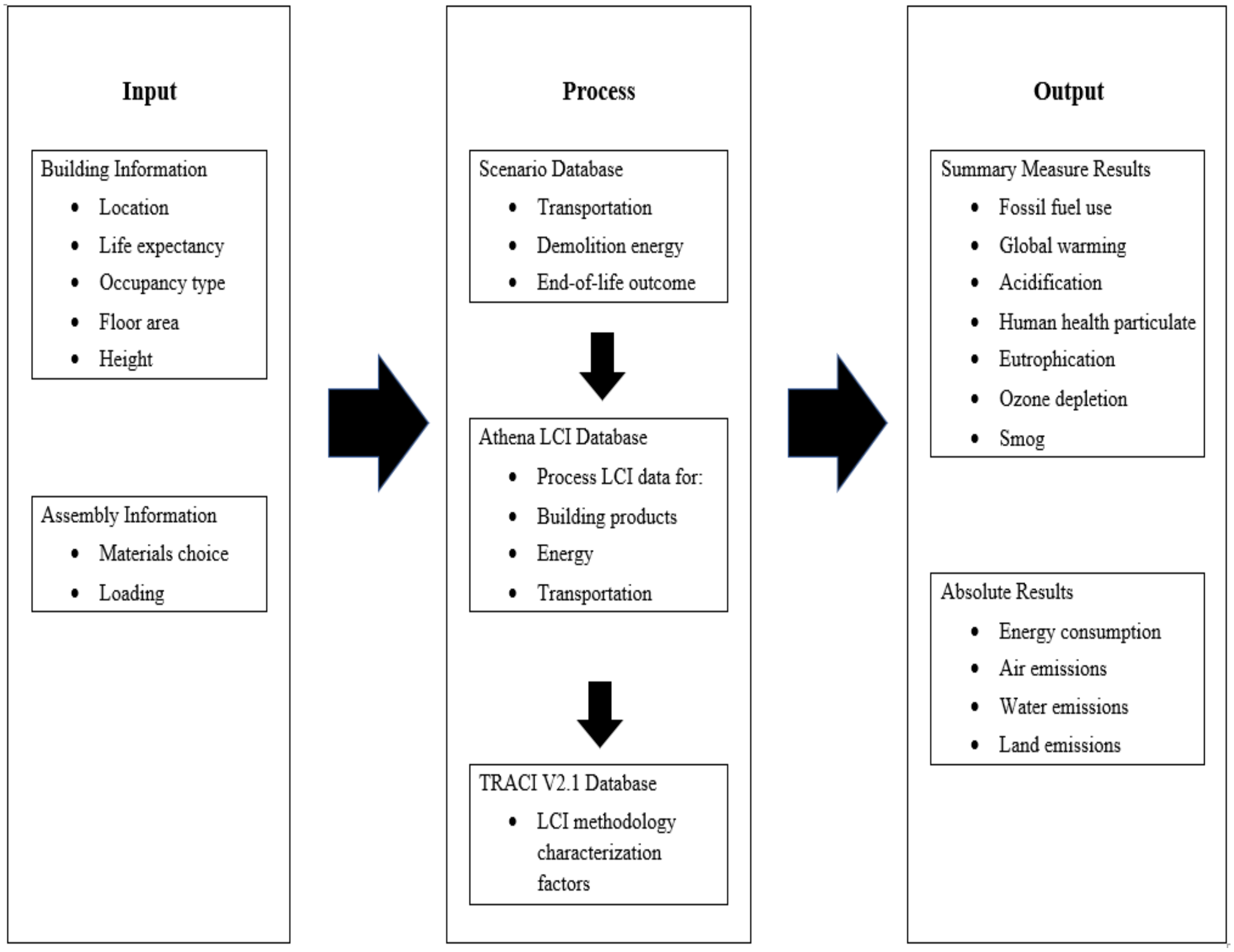

Figure 4.4. The running process of Athena Impact Estimator for Buildings.

Table 4.2. Beams and columns input data.

	Item	Area 1	Area 2	Area3	Area4	Area5	Area6
Steel structure model	No. of columns	23	31	4	21	26	4
	N0. 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
	Column type	WF	WF	WF	WF	WF	WF
	Beam type	WF	WF	WF	WF	WF	WF
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	211 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
	Column type	Glulam	Glulam	Glulam	Glulam	Glulam	Glulam
	Beam type	Glulam	Glulam	Glulam	Glulam	Glulam	Glulam

* WF=Wide flange

CHAPTER FIVE: LIFE CYCLE INVENTORY ANALYSIS RESULTS

Based on the input data, the simulation process has generated the life cycle inventory results of the end-of-life stage. Table 5.1, 5.2, and 5.3 show a part of the results of emissions to air, land, water at the end-of-life stage respectively. The complete version of these tables can be found in Appendix B. Additionally, Table 5.4 shows energy consumption LCI results at the end-of-life stage.

For the emission to air, from Table 5.1, at the end-of-life stage of wood structure buildings, in the process of de-construction, demolition, and disposal, the use of fossil fuel by machines will cause more carbon dioxide in the air. Similarly, the carbon dioxide emission of steel structure buildings in the process of deconstruction, demolition, and disposal is almost the same as that of the wood structure due to the use of fossil fuel. However, due to the use of fossil fuel in steel recycling, the carbon dioxide emitted from the air is more than twice as much as that from the de-construction, demolition, and disposal. In Table 5.1, there is another point worthy of attention: the carbon dioxide emission in the landfill stage of the wood structure is negative, which indicates that carbon dioxide is reduce in the landfill process (in benefit and loads beyond the system boundary process). Through table 5.1, the air emissions of the steel structure building are more than that of the wood structure building except for PM 2.5,

For the emission to land, the LCI results at the end-of-life stage (Table 5.2) shows the emission of the wood structure building in solid waste to landfill part is much more than the steel structure building, mainly from the process of de-construction, demolition, and disposal. The emission of other wastes is almost the same.

For the emission to water at the end-of-life stage, only nitrogen emission to water is selected from the results (Table 5.3) as an example. The nitrogen emission of the steel structure building is much greater than that of the wood structure building, and the main contribution comes from the recycling of steel.

Regarding the energy consumption at the end-of-life stage, as shown in Table 5.4, for both wood and steel structure buildings, the consumption of primary energy, non-renewable energy, and basic fuel is almost the same, but the consumption of renewable energy is far less than the above three. However, the total energy consumption by the steel structure building is more than that by wood structure building except for renewable energy. Additionally, the energy consumption of the wood structure building is concentrated in de-construction, demolition, disposal, and transport, while the energy consumption of steel structure building is less in transport, but more in recycling.

Table 5.1. Emission to air LCI results at the end-of-life stage*.

Emission	Unit	Type	De-construction, Demolition, Disposal	Transport	Benefit and loads beyond the system boundary	Total
Carbon dioxide, biogenic	kg	Wood	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Steel	5.54E-05	0.00E+00	0.00E+00	5.54E-05
Carbon dioxide, biogenic, landfill	kg	Wood	0.00E+00	0.00E+00	-1.51E+05	-1.51E+05
		Steel	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carbon dioxide, fossil	kg	Wood	3.75E+03	8.06E+02	0.00E+00	4.56E+03
		Steel	3.72E+03	2.79E+01	8.34E+03	1.21E+04
Carbon dioxide, land transformation	g	Wood	1.81E-05	4.10E+01	0.00E+00	4.10E+01
		Steel	6.43E+01	1.42E+00	0.00E+00	6.57E+01
Sulfur dioxide	g	Wood	1.38E-04	2.67E+02	0.00E+00	2.67E+02
		Steel	4.16E+02	9.26E+00	1.06E+04	1.10E+04
Particulates, > 2.5 um, and < 10um	g	Wood	2.29E+03	2.74E+02	0.00E+00	2.57E+03
		Steel	1.43E+03	9.49E+00	0.00E+00	1.44E+03

* This is only of portion of the table. The full table is shown in Appendix B

Table 5.2. Emission to land LCI results at the end-of-life stage*.

Emission	Unit	Type	De-construction, Demolition, Disposal	Transport	Benefit and loads beyond the system boundary	Total
Other Solid Waste	kg	Wood	3.92E+01	9.48E+00	0.00E+00	4.87E+01
		Steel	4.01E+01	3.29E-01	0.00E+00	4.04E+01
Solid Waste to Landfill	kg	Wood	1.03E+05	0.00E+00	0.00E+00	1.03E+05
		Steel	3.55E+03	0.00E+00	0.00E+00	3.55E+03

*This is only of portion of the table. The full table is shown in Appendix B

Table 5.3. Emission to water LCI results at the end-of-life stage*.

Emission	unit	Type	De-construction, Demolition, Disposal	Transport	Benefit and loads beyond the system boundary	Total
Nitrogen	mg	Wood	6.50E+01	0.00E+00	0.00E+00	6.50E+01
		Steel	2.25E+00	0.00E+00	7.22E+05	7.22E+05

* This is only of portion of the table. The full table is shown in Appendix B

Table 5.4. Energy consumption LCI results at the end-of-life stage*.

Energy Source	unit	type	De-construction, Demolition, Disposal	Transport	Benefit and loads beyond the system boundary	Total
Renewable Energy	MJ	Wood	2.44E+01	5.09E+00	0.00E+00	2.95E+01
		Steel	2.25E+01	1.76E-01	0.00E+00	2.27E+01
Primary Energy	MJ	Wood	5.77E+04	1.21E+04	0.00E+00	6.98E+04
		Steel	5.59E+04	4.19E+02	4.12E+04	9.74E+04
Non-Renewable Energy	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.97E+04
		Steel	5.58E+04	4.18E+02	4.12E+04	9.74E+04
Fossil Fuel	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.96E+04
		Steel	5.58E+04	4.18E+02	8.26E+04	1.39E+05

*This is only of portion of the table. The full table is shown in Appendix B

CHAPTER SIX: LIFE CYCLE IMPACT ASSESSMENT RESULTS

6.1. The results of LCIA

The data from Table 4.1 and 4.2 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 6.1 and 6.2, 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.

6.1.1. The LCIA results of the steel structure building

Table 6.1 and Figure 6.1 show the results of LCIA for the steel structure building. Among those nine categories, three are related to energy consumption. 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).

Table 6.1. 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

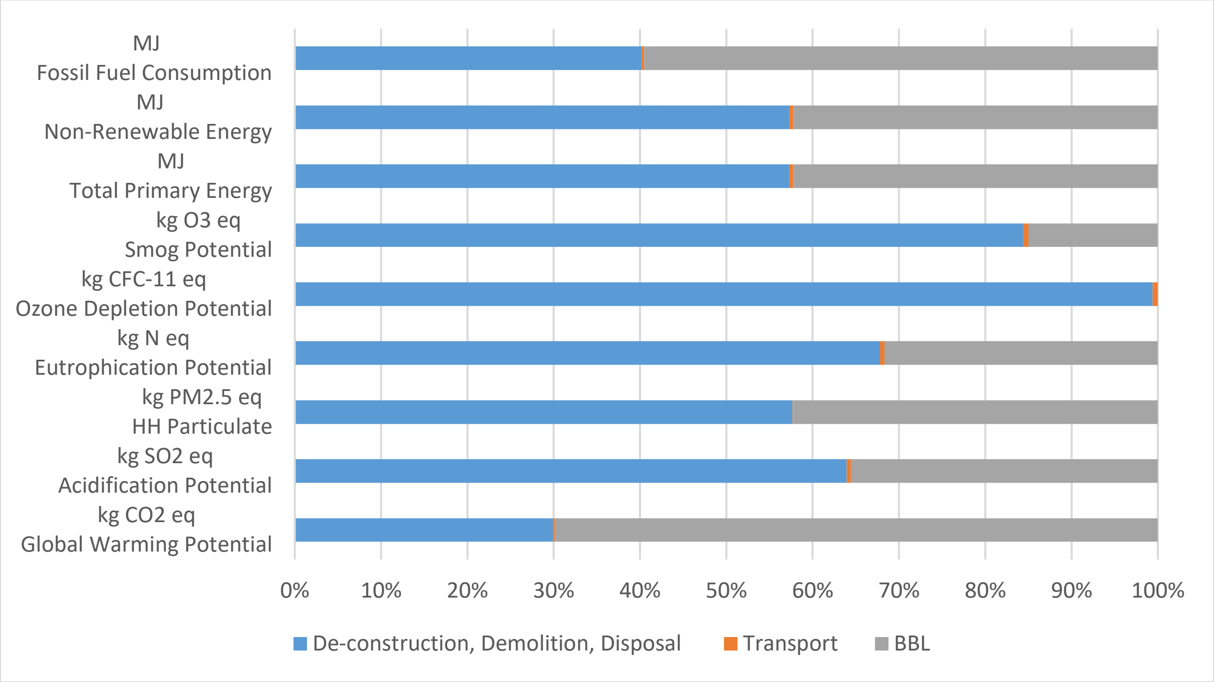

Figure 6.1. The results of LCIA for the steel structure building.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

6.1.2. The LCIA results of the wood structure building

The results of the LCIA for the wood structure building shown as Table 6.2 and Figure 6.2. 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.

Table 6.2. 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

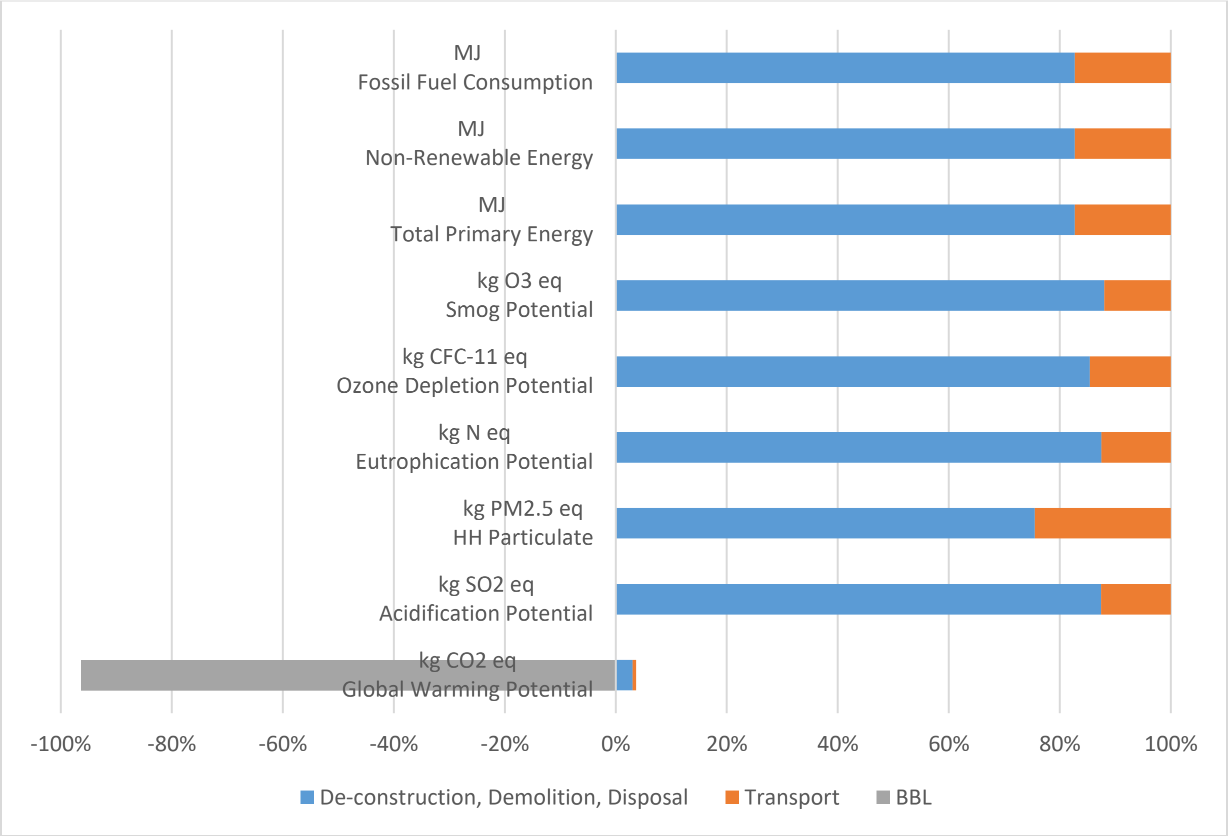

Figure 6.2. The results of LCIA for the wood structure building.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D)

6.1.3. Comparison of LCIA results between steel and wood structure buildings

Nine categories of LCIA results between steel structure building and wood structure building are compared, respectively. Figure 6.3 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.

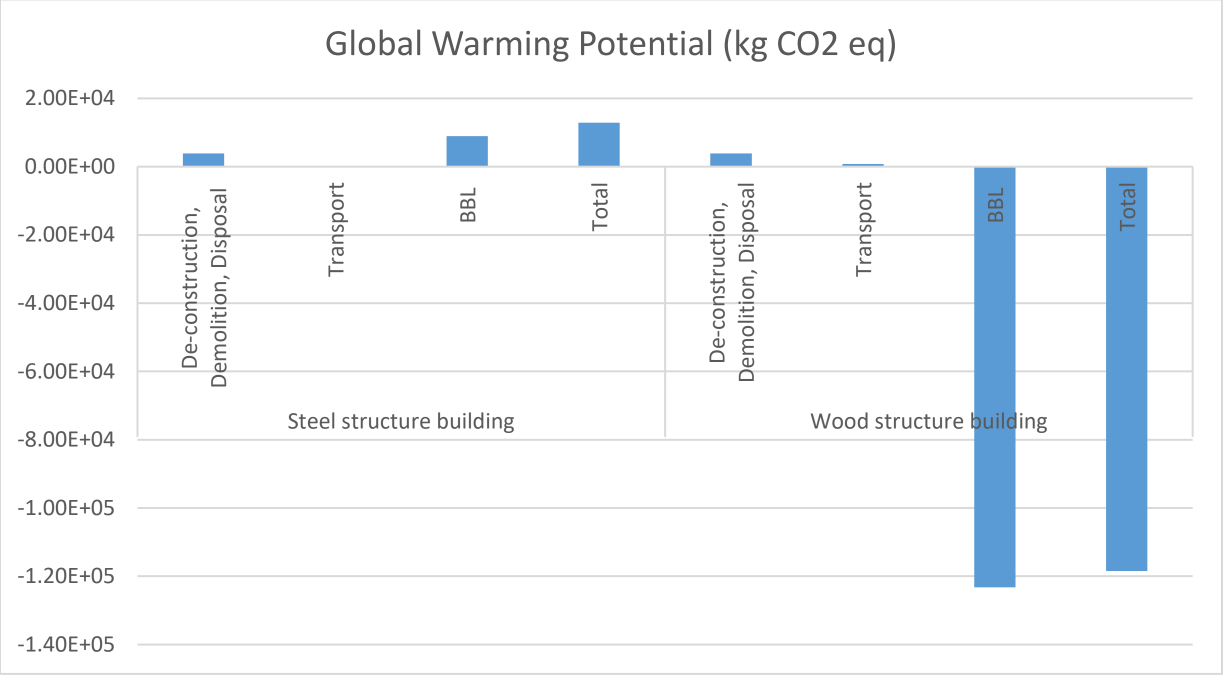

Figure 6.3. The results of GWP for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

Figure 6.4 shows the results of Acidification Potential for both buildings. The 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.

Figure 6.5 shows the results of Human Health Particulate for both buildings. 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.

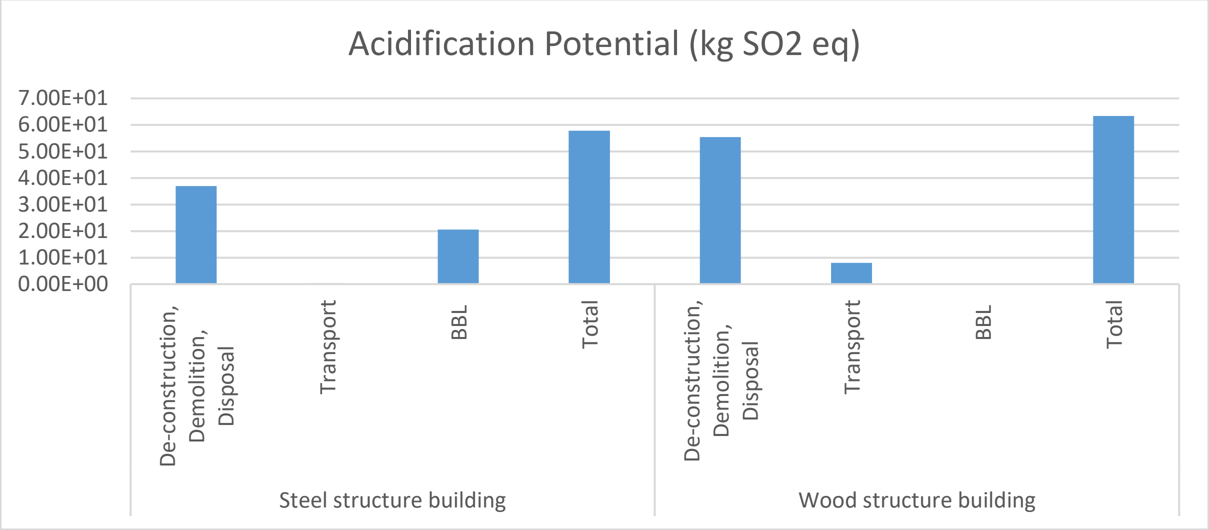

Figure 6.4. The results of Acidification Potential for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

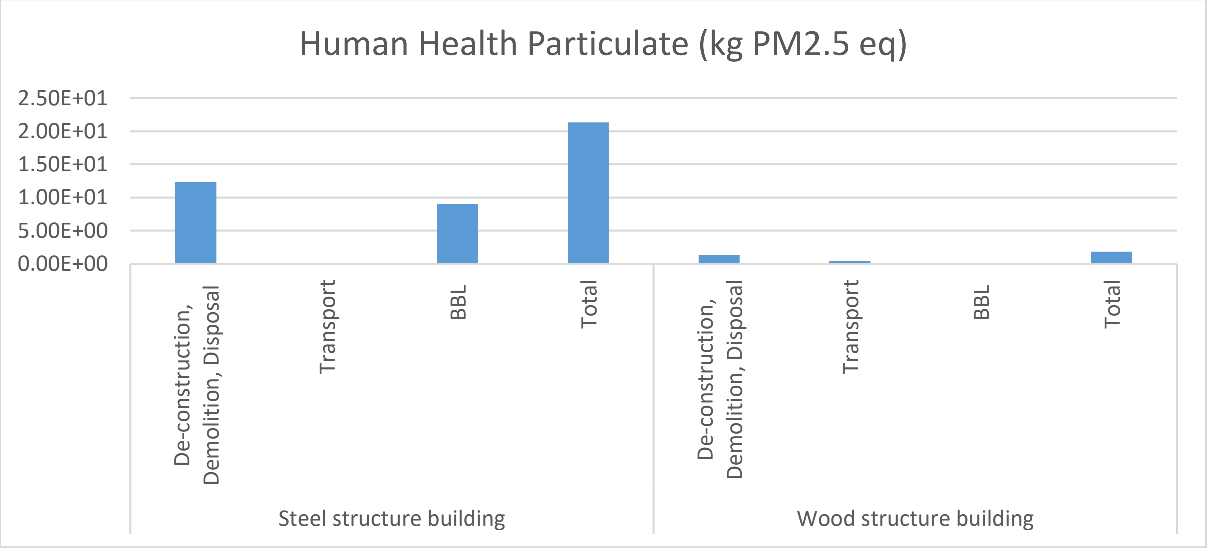

Figure 6.5. The results of Human Health Particulate for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

Figure 6.6 shows the results of Eutrophication Potential for both buildings. 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.

Figure 6.7 shows the results of Ozone Depletion Potential for both buildings. 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.

Figure 6.8 shows the results of Smog Potential for both buildings. 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.

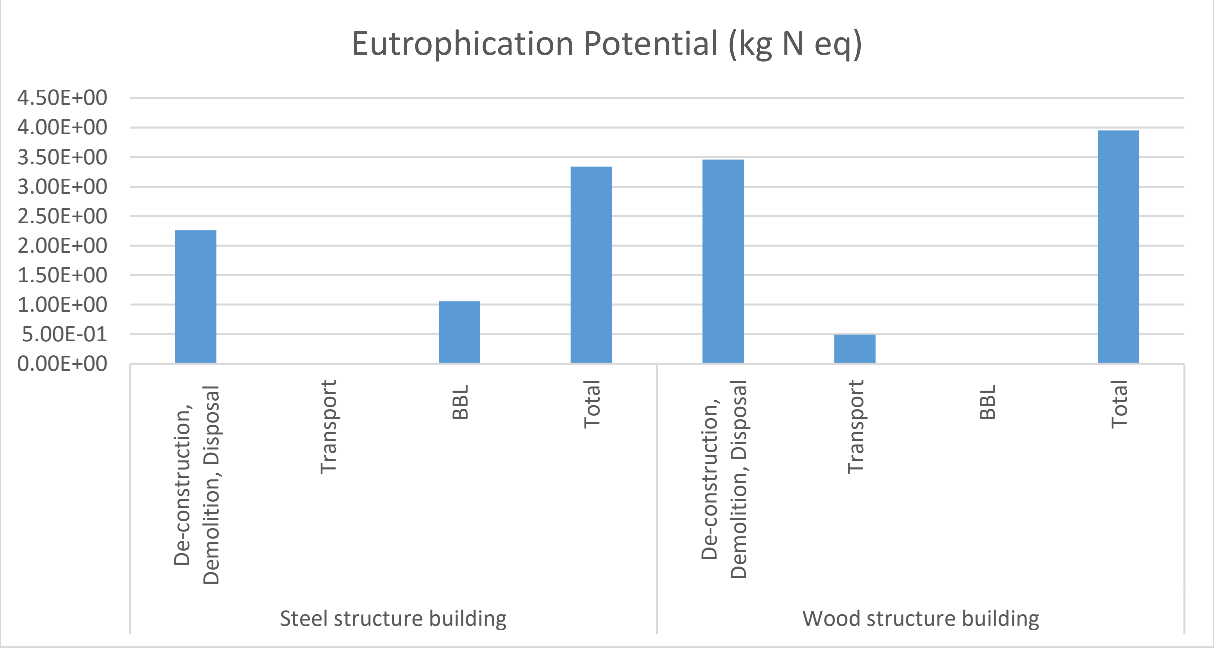

Figure 6.6. The results of Eutrophication Potential for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

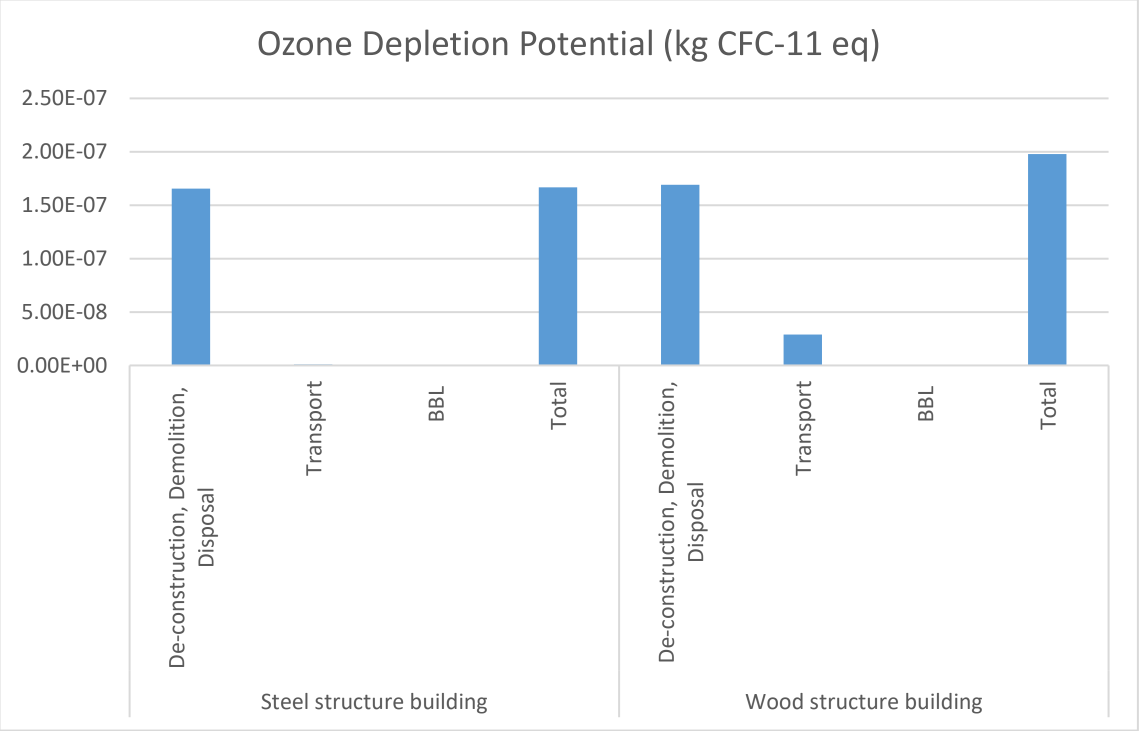

Figure 6.7. The results of Ozone Depletion Potential for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

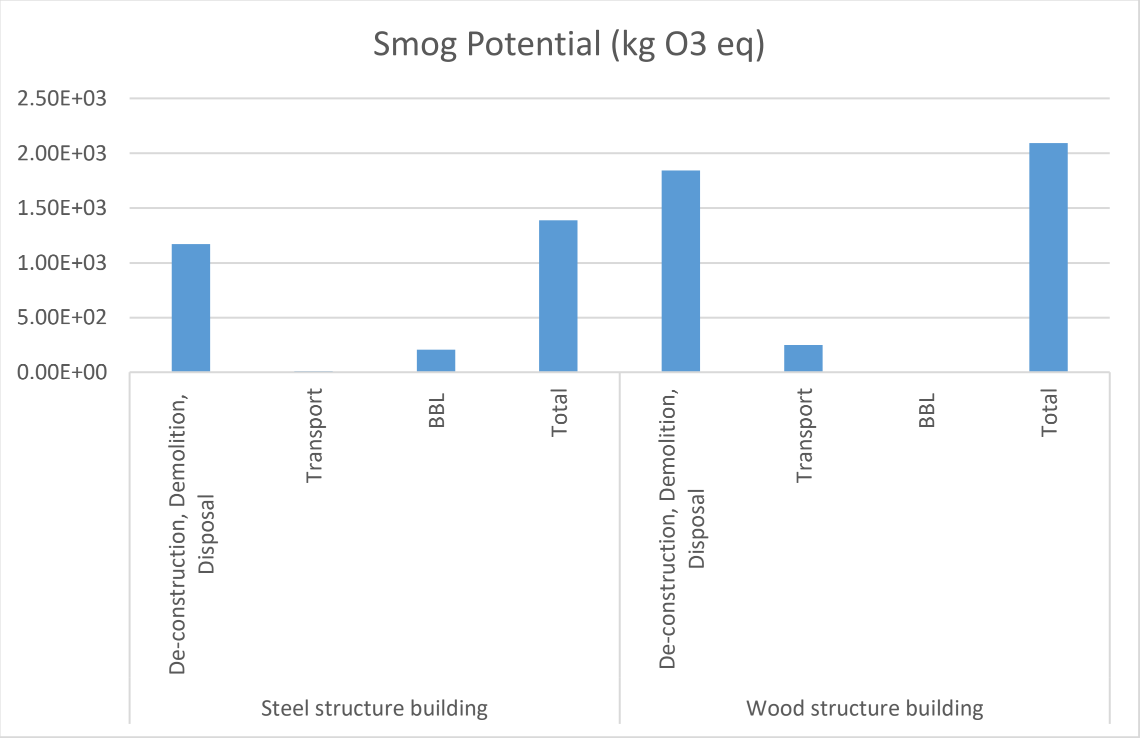

Figure 6.8. The results of Smog Potential for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

Regarding the results of energy consumption for both buildings, as shown in Figures 6.9, 6.10, and 6.11. 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.

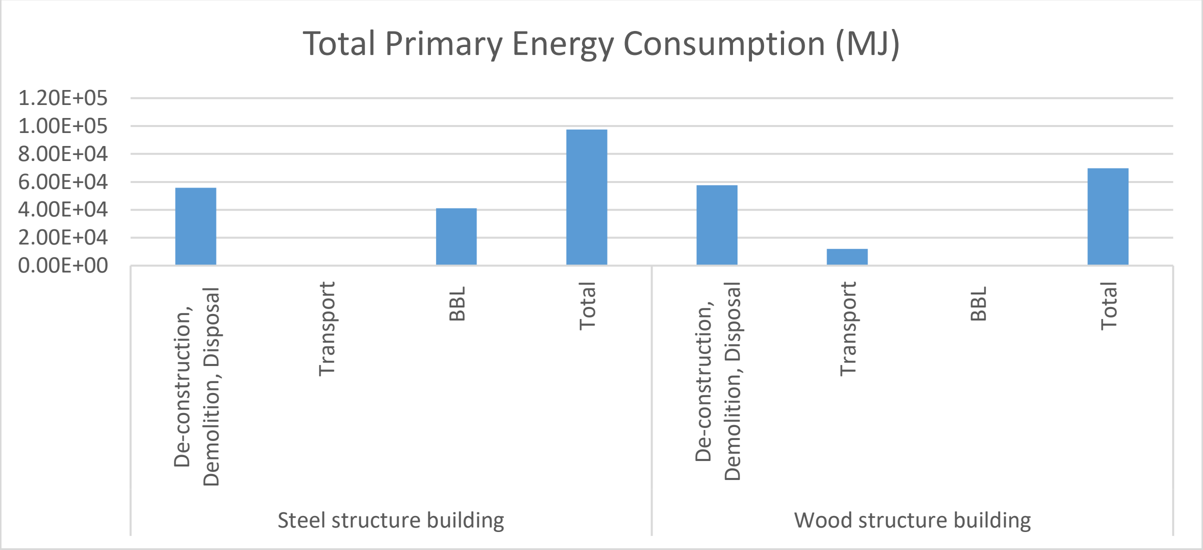

Figure 6.9. The results of Total Primary Energy Consumption for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

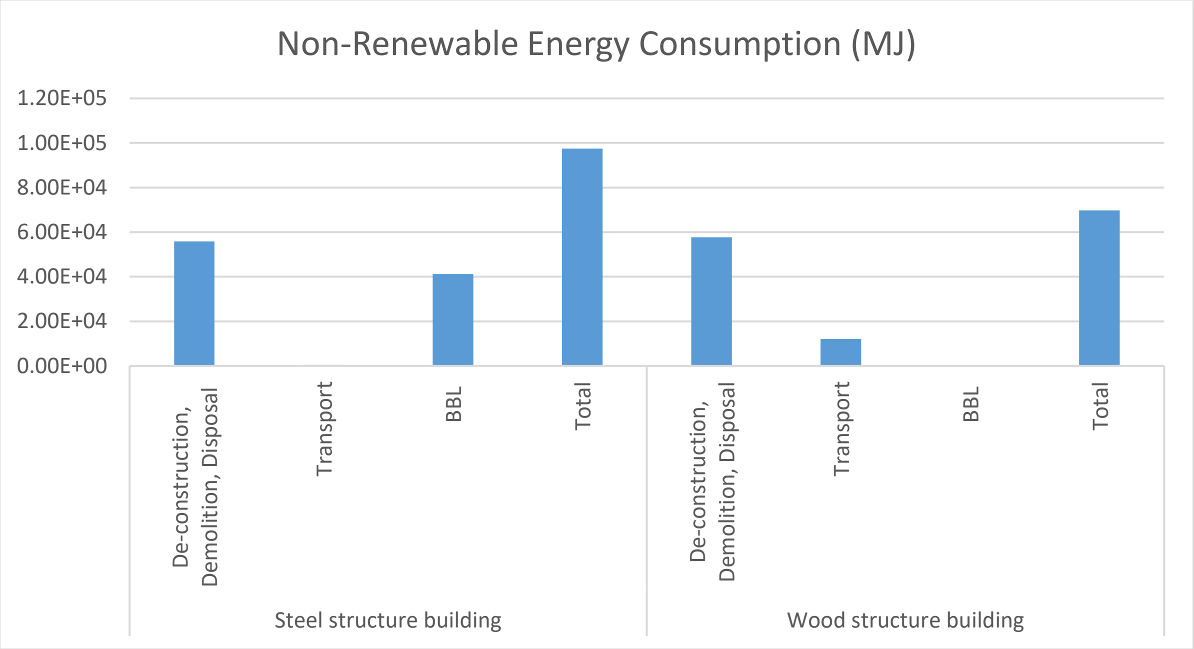

Figure 6.10. The results of Non-Renewable Energy Consumption for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

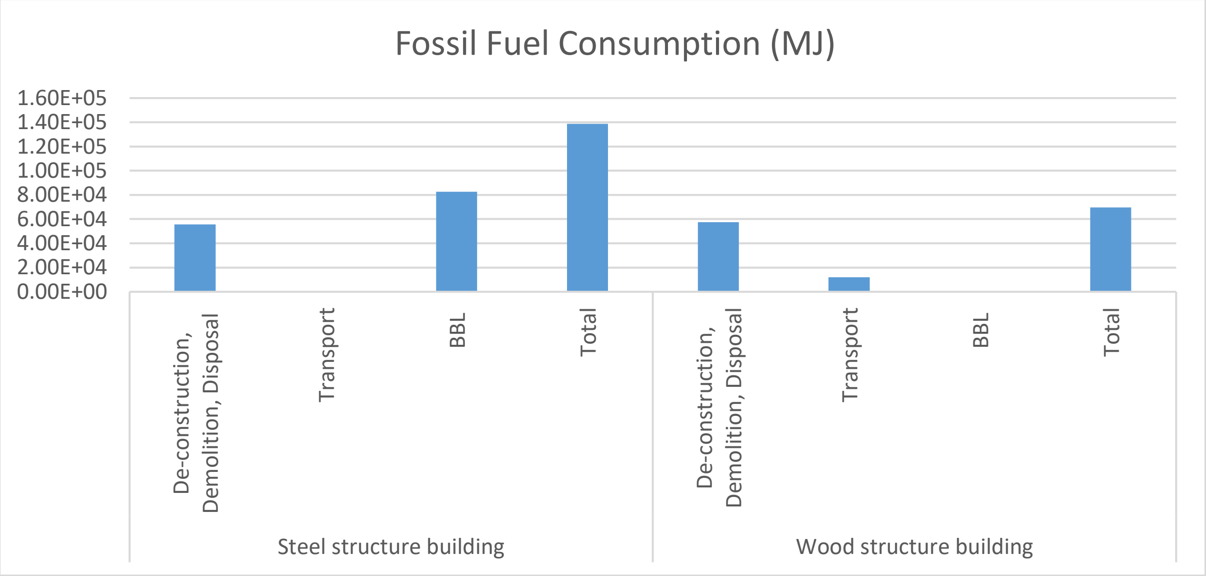

Figure 6.11. The results of Fossil Fuel Consumption for both buildings.
Note: De-construction, Demolition, Disposal (C1 & C4), Transport (C2), and BBL (D).

6.2. Sensitivity analysis

The results above may vary due to changes of project location, column types and project life span; therefore, three sensitivity analyses have been performed in this study to see their effects to the results: (1) changing the location, (2) changing the type of the columns, (3) changing the building life expectancy.

6.2.1. Changing the location

The location of the case study project is Fargo, ND, but there is no Fargo in the project location option of Athena Impact Estimator for Buildings software, so Minneapolis was chosen, which is relatively close to Fargo. In this sensitivity analysis, the location option is changed from Minneapolis to USA and the results of LCIA for both buildings as shown in Table 6.3.

Table 6.3. The results of LCIA for both buildings (project location: USA).

LCA Measures	Unit	Type	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)	Total
Global Warming Potential	kg CO2 eq	Wood	3.87E+03	8.28E+02	-1.23E+05	-1.19E+05
		Steel	3.84E+03	2.87E+01	8.97E+03	1.28E+04
Acidification Potential	kg SO2 eq	Wood	5.54E+01	7.97E+00	0.00E+00	6.34E+01
		Steel	3.70E+01	2.76E-01	2.06E+01	5.78E+01
HH Particulate	kg PM2.5 eq	Wood	1.36E+00	4.41E-01	0.00E+00	1.80E+00
		Steel	1.23E+01	1.53E-02	9.02E+00	2.14E+01
Eutrophication Potential	kg N eq	Wood	3.46E+00	4.95E-01	0.00E+00	3.95E+00
		Steel	2.26E+00	1.72E-02	1.06E+00	3.34E+00
Ozone Depletion Potential	kg CFC-11 eq	Wood	1.69E-07	2.89E-08	0.00E+00	1.98E-07
		Steel	1.66E-07	1.00E-09	0.00E+00	1.67E-07
Smog Potential	kg O3 eq	Wood	1.84E+03	2.51E+02	0.00E+00	2.09E+03
		Steel	1.17E+03	8.72E+00	2.08E+02	1.39E+03
Total Primary Energy	MJ	Wood	5.77E+04	1.21E+04	0.00E+00	6.98E+04
		Steel	5.59E+04	4.19E+02	4.12E+04	9.74E+04
Non-Renewable Energy	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.97E+04
		Steel	5.58E+04	4.18E+02	4.12E+04	9.74E+04
Fossil Fuel Consumption	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.96E+04
		Steel	5.58E+04	4.18E+02	8.26E+04	1.39E+05

Because part of the data is from the average value of the selected location. For example, the distance of the landfill will change. By comparing Table 6.3 with Table 6.1 and 6.2, the results of LCIA using USA as the project location are the same as the project location using Minneapolis, as shown in Figure 6.12 to 6.17. It means both use the same database at the end-of-life stage. However, the database used is different, the change of the project location will have different results on environment impact.

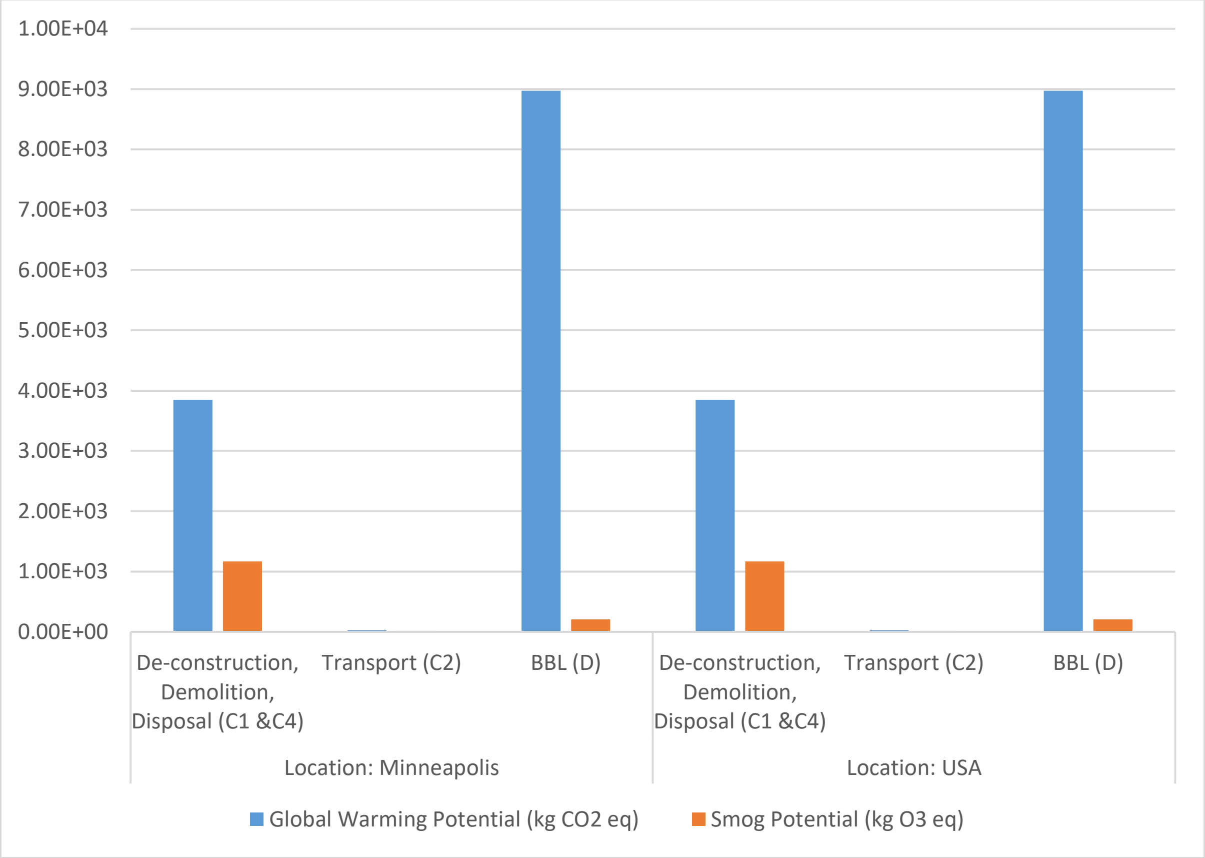

Figure 6.12. The comparison of Global Warming Potential and Smog potential in different locations for steel structure building.

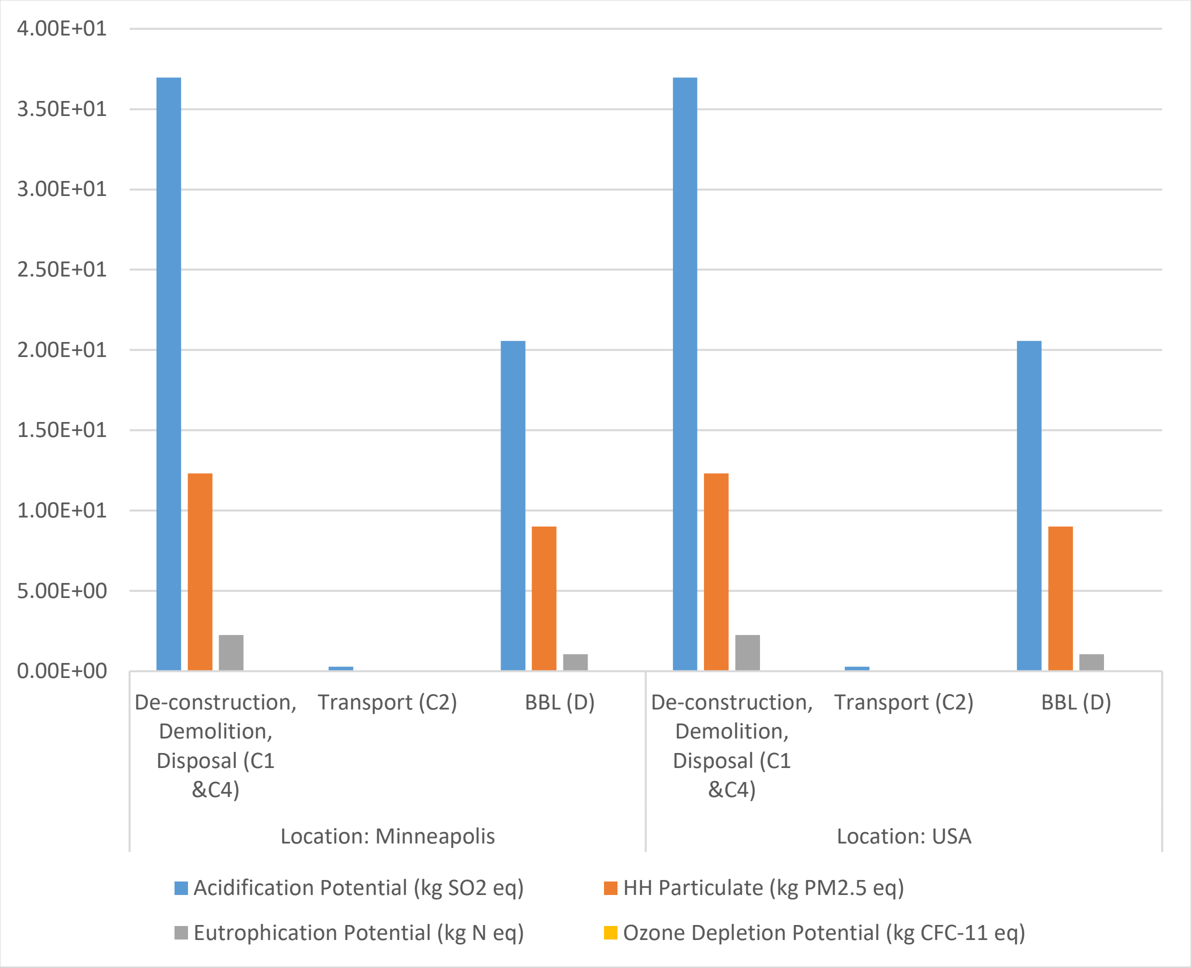

Figure 6.13. The comparison of Acidification Potential, Human Health potential, Eutrophication Potential, and Ozone Depletion Potential in different locations for steel structure building.

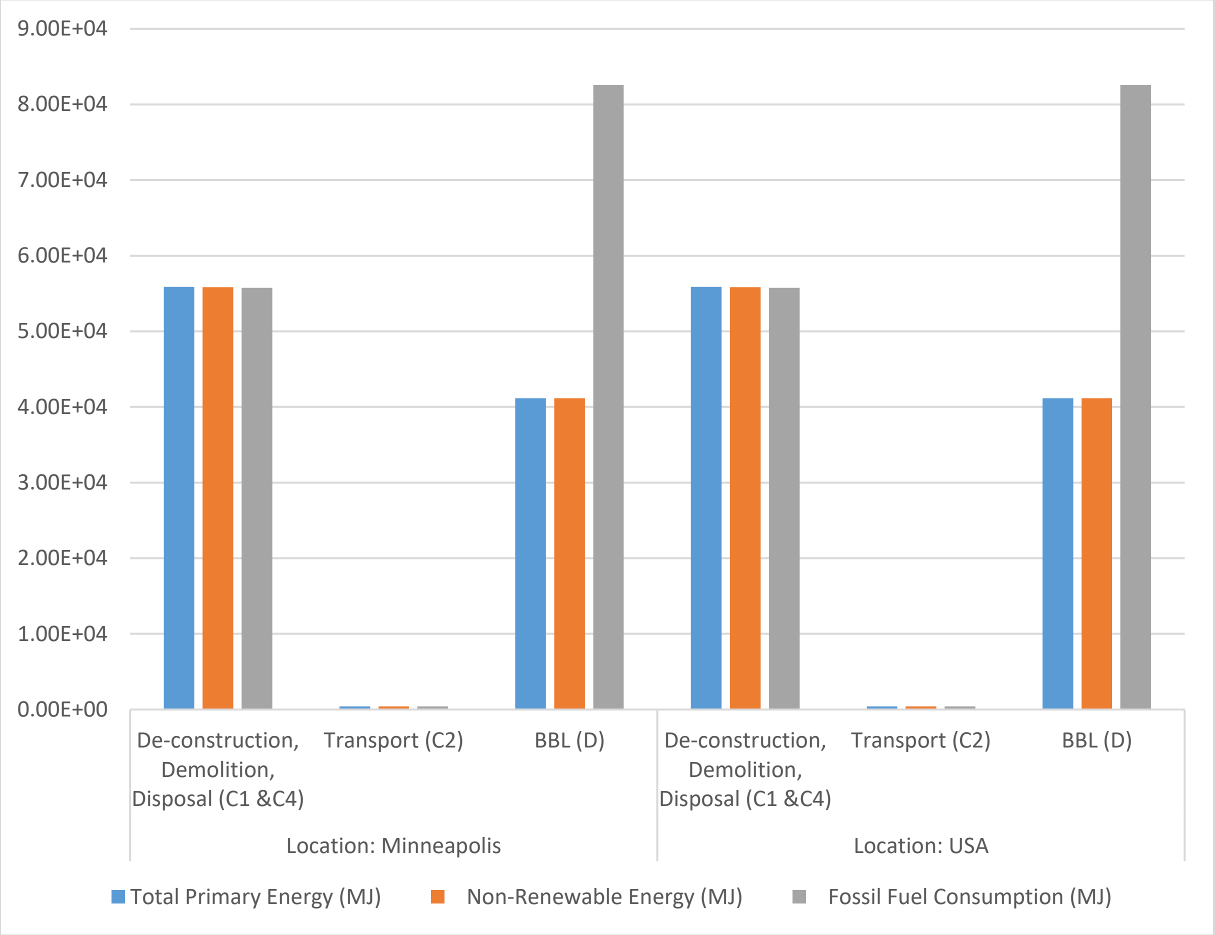

Figure 6.14. The comparison of Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption in different locations for steel structure building.

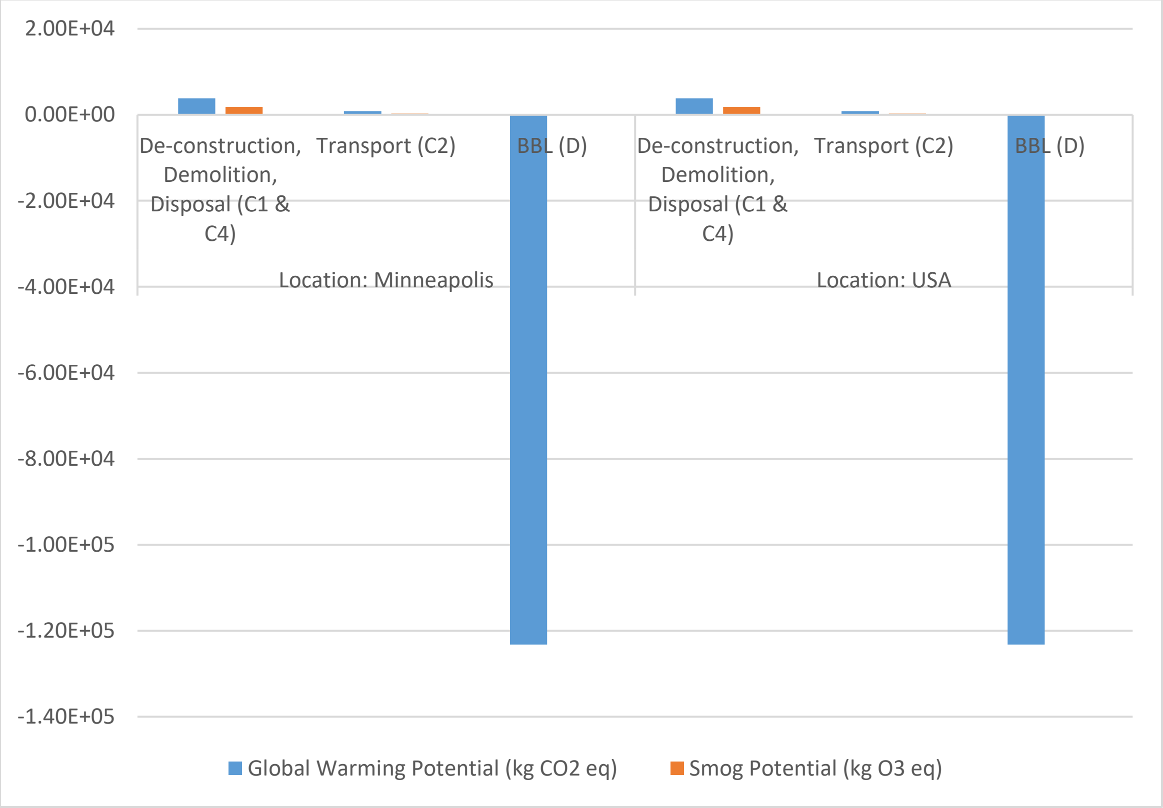

Figure 6.15. The comparison of Global Warming Potential and Smog potential in different locations for wood structure building.

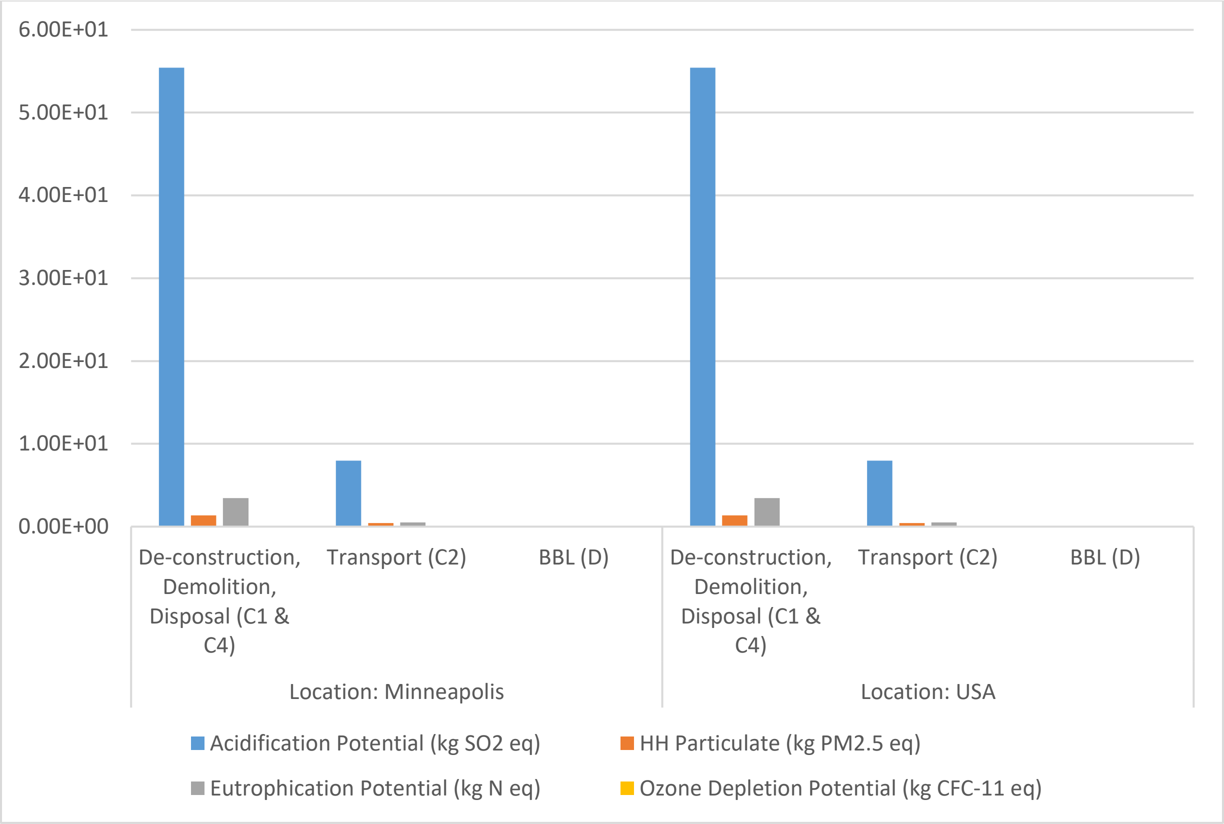

Figure 6.16. The comparison of Acidification Potential, Human Health potential, Eutrophication Potential, and Ozone Depletion Potential in different locations for wood structure building.

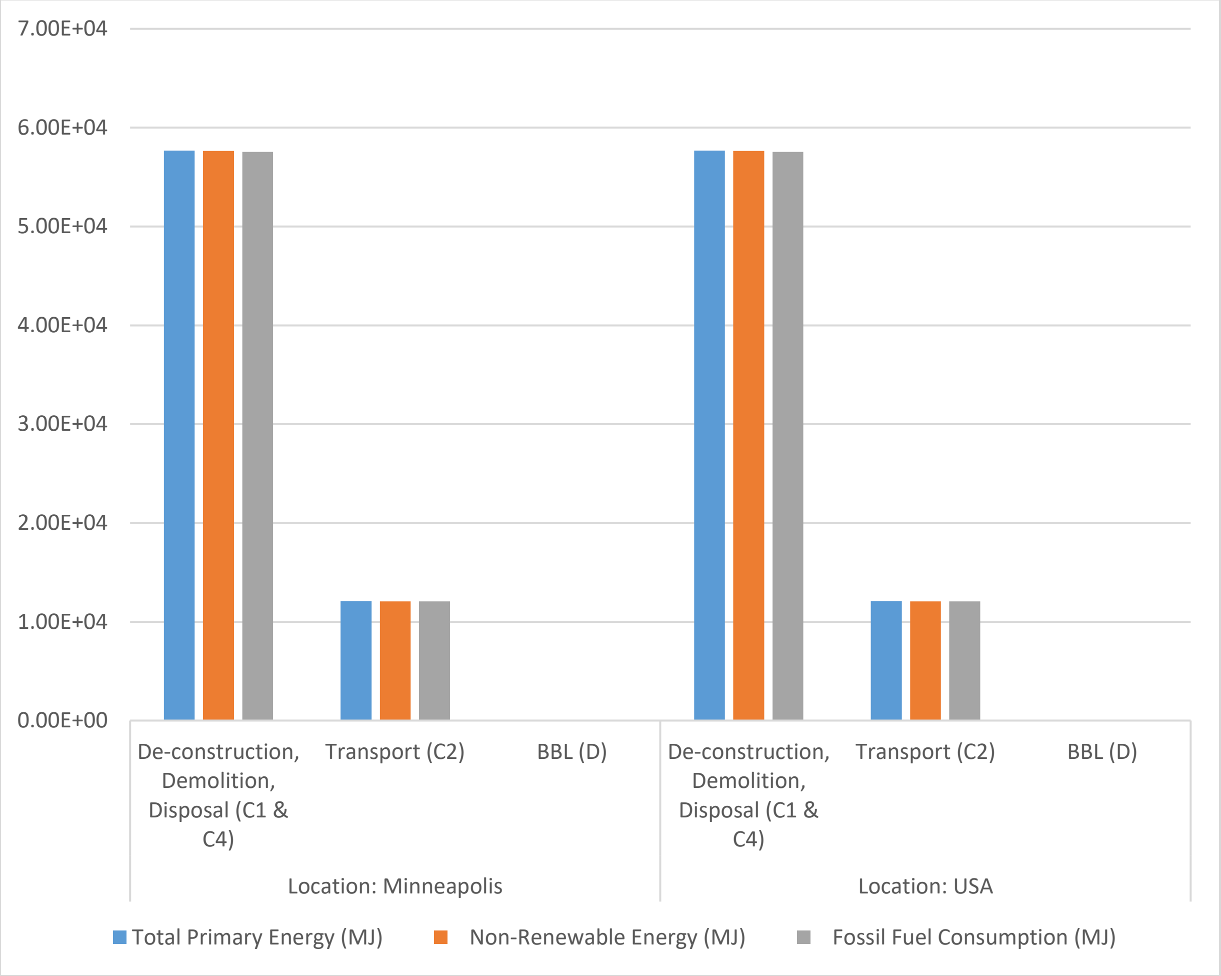

Figure 6.17. The comparison of Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption in different locations for steel structure building.

6.2.2. Changing the type of the columns

In this sensitivity analysis, the type of column in steel structure building is changed from WF to hollow structure steel, and the type of column in wood structure building is changed from glulam to software lumber. The LCIA results for both buildings are shown in Tables 6.4 and 6.5.

Comparing the two different types of wood structure buildings, it was found that most LCIA results have been greater after changing the type of column from glulam to software lumber. After changing the type of column from WF to hollow structure steel, the results of module C1 & C4 and module C2 do not change. However, all the results of module D reduce 50%.

Table 6.4. The results of LCIA for the steel structure building (column: hollow structure steel).

LCA Measures	Unit	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)
Global Warming Potential	kg CO2 eq	3.84E+03	2.87E+01	4.12E+03
Acidification Potential	kg SO2 eq	3.70E+01	2.76E-01	9.44E+00
HH Particulate	kg PM2.5 eq	1.23E+01	1.53E-02	4.14E+00
Eutrophication Potential	kg N eq	2.26E+00	1.72E-02	4.85E-01
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	9.54E+01
Total Primary Energy	MJ	5.59E+04	4.19E+02	1.89E+04
Non-Renewable Energy	MJ	5.58E+04	4.18E+02	1.89E+04
Fossil Fuel Consumption	MJ	5.58E+04	4.18E+02	3.79E+04

Table 6.5. The results of LCIA for the wood structure building (column: softwood lumber).

LCA Measures	Unit	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)
Global Warming Potential	kg CO2 eq	3.90E+03	8.35E+02	-1.23E+05
Acidification Potential	kg SO2 eq	5.59E+01	8.03E+00	0.00E+00
HH Particulate	kg PM2.5 eq	1.37E+00	4.45E-01	0.00E+00
Eutrophication Potential	kg N eq	3.49E+00	4.99E-01	0.00E+00
Ozone Depletion Potential	kg CFC-11 eq	1.70E-07	2.91E-08	0.00E+00
Smog Potential	kg O3 eq	1.86E+03	2.53E+02	0.00E+00
Total Primary Energy	MJ	5.81E+04	1.22E+04	0.00E+00
Non-Renewable Energy	MJ	5.81E+04	1.22E+04	0.00E+00
Fossil Fuel Consumption	MJ	5.80E+04	1.22E+04	0.00E+00

Comparing Table 6.4 with Table 6.5, the results of Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, and Smog Potential for the wood structure building are greater than the steel structure building, as shown in Figure 6.18 to 6.21.

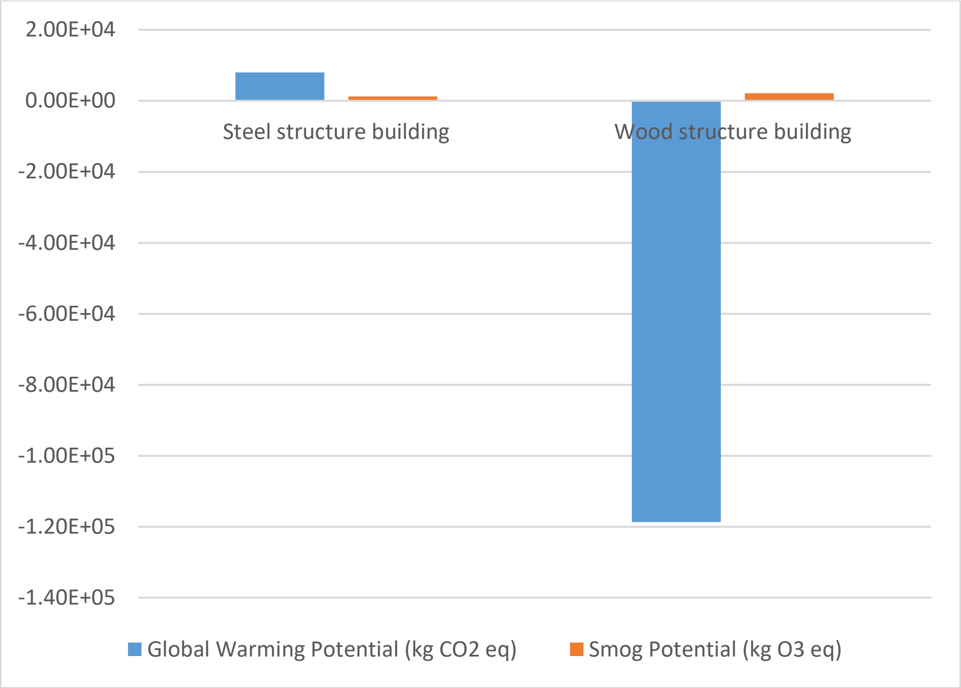

Figure 6.18. The comparison of Global Warming Potential and Smog potential in changing the type of the columns for both buildings.

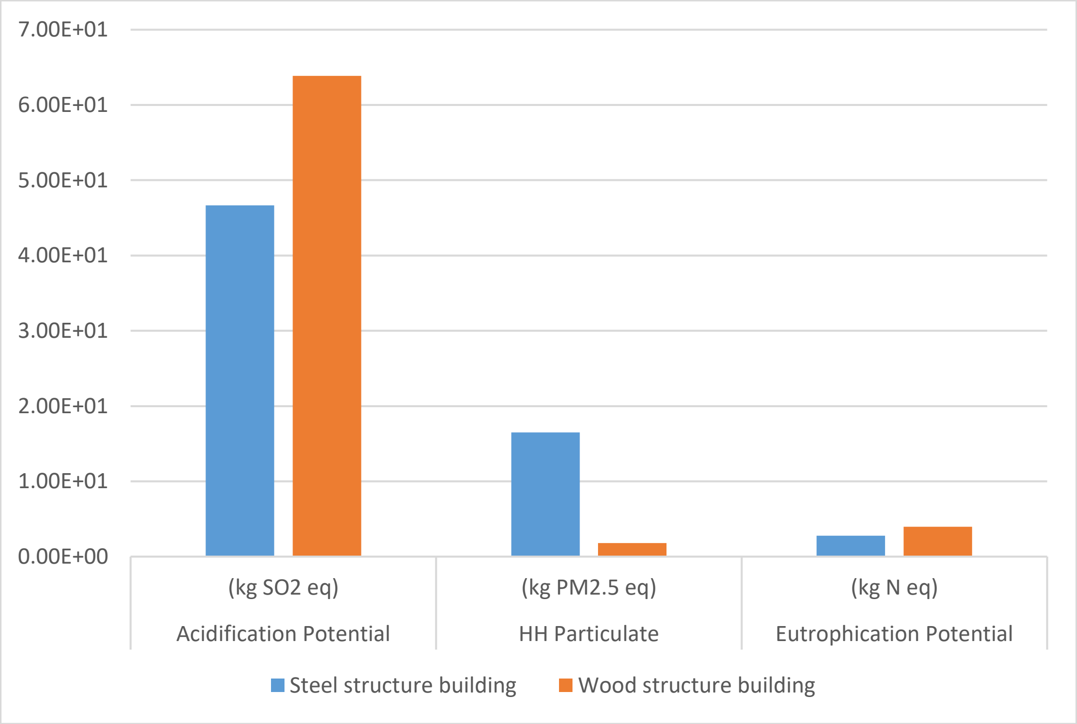

Figure 6.19. The comparison of Acidification Potential, Human Health potential, and Eutrophication Potential, in changing the type of the columns for both buildings.

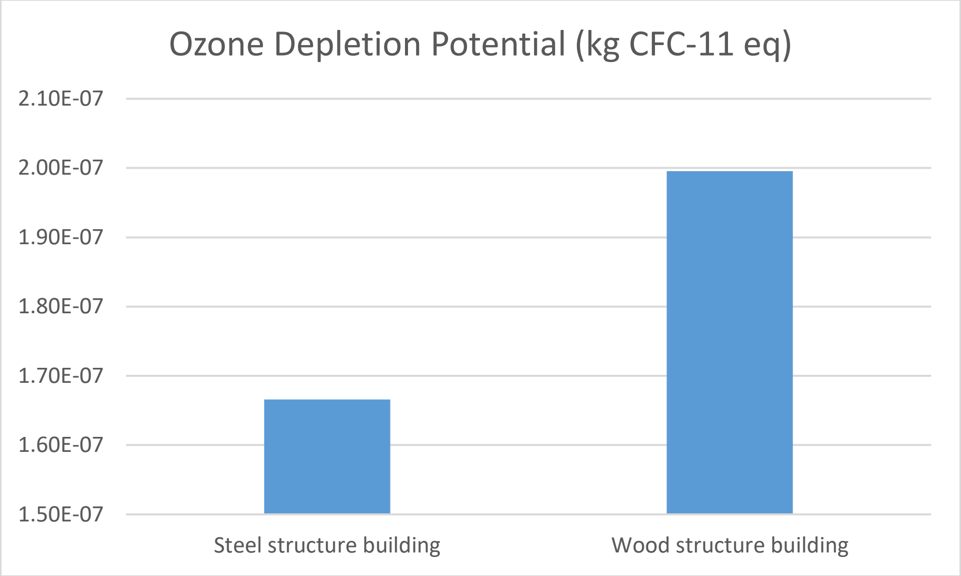

Figure 6.20. The comparison of Ozone Depletion Potential in changing the type of the columns for both buildings.

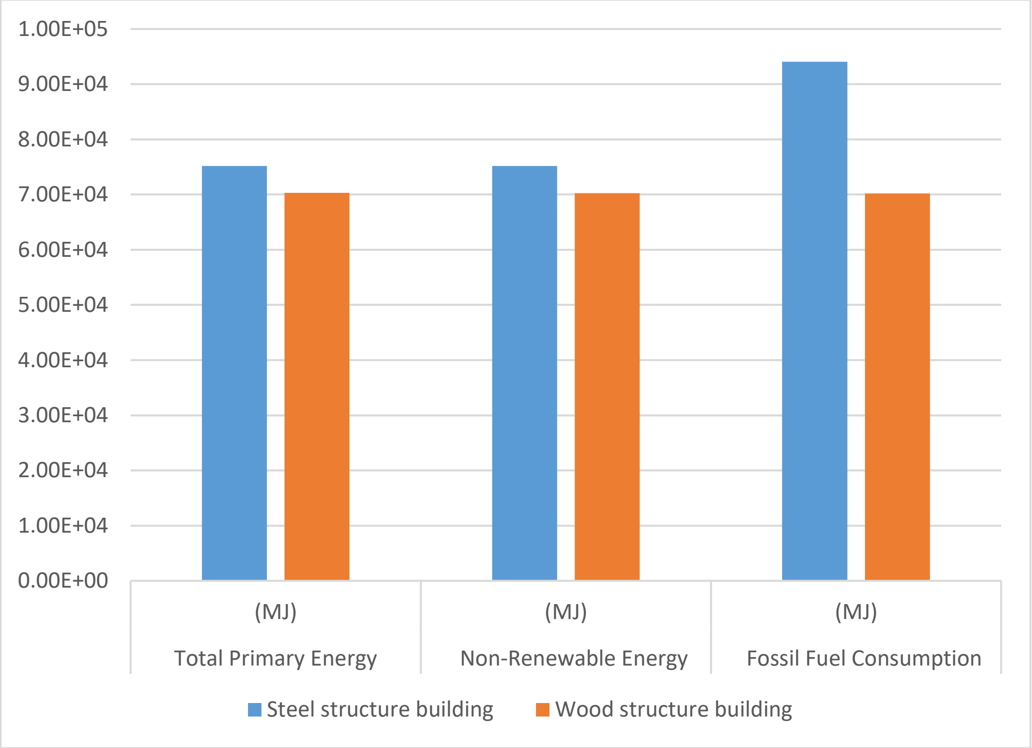

Figure 6.21. The comparison of Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption in changing the type of the columns for both buildings.

In general, this sensitivity analysis shows changing column types of either steel or wood structure buildings will change the LCIA results but will not change the comparison results between steel and wood structures.

6.2.3. Changing the building life expectancy

In this sensitivity analysis, the building life expectancy is changed, and 50, 70, 80 years are selected. The LCIA results for both buildings are shown in Tables 6.6, 6.7, and 6.8. By comparing the LCIA results of different building life expectancy, including 50, 60, 70, and 80 years, all the LCIA results are the same, as shown in Figure 6.22 to 6.29, meaning in the range of 50-80 years the building life expectancy will not change the impact of the end-of-life stage on the environment.

Table 6.6. The results of LCIA for both buildings (building life expectancy: 50 years).

LCA Measures	Unit	Type	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)	Total
Global Warming Potential	kg CO2 eq	Wood	3.87E+03	8.28E+02	-1.23E+05	-1.19E+05
		Steel	3.84E+03	2.87E+01	8.97E+03	1.28E+04
Acidification Potential	kg SO2 eq	Wood	5.54E+01	7.97E+00	0.00E+00	6.34E+01
		Steel	3.70E+01	2.76E-01	2.06E+01	5.78E+01
HH Particulate	kg PM2.5 eq	Wood	1.36E+00	4.41E-01	0.00E+00	1.80E+00
		Steel	1.23E+01	1.53E-02	9.02E+00	2.14E+01
Eutrophication Potential	kg N eq	Wood	3.46E+00	4.95E-01	0.00E+00	3.95E+00
		Steel	2.26E+00	1.72E-02	1.06E+00	3.34E+00
Ozone Depletion Potential	kg CFC-11 eq	Wood	1.69E-07	2.89E-08	0.00E+00	1.98E-07
		Steel	1.66E-07	1.00E-09	0.00E+00	1.67E-07
Smog Potential	kg O3 eq	Wood	1.84E+03	2.51E+02	0.00E+00	2.09E+03
		Steel	1.17E+03	8.72E+00	2.08E+02	1.39E+03
Total Primary Energy	MJ	Wood	5.77E+04	1.21E+04	0.00E+00	6.98E+04
		Steel	5.59E+04	4.19E+02	4.12E+04	9.74E+04
Non-Renewable Energy	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.97E+04
		Steel	5.58E+04	4.18E+02	4.12E+04	9.74E+04
Fossil Fuel Consumption	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.96E+04
		Steel	5.58E+04	4.18E+02	8.26E+04	1.39E+05

Table 6.7. The results of LCIA for both buildings (building life expectancy: 70 years).

LCA Measures	Unit	Type	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)	Total
Global Warming Potential	kg CO2 eq	Wood	3.87E+03	8.28E+02	-1.23E+05	-1.19E+05
		Steel	3.84E+03	2.87E+01	8.97E+03	1.28E+04
Acidification Potential	kg SO2 eq	Wood	5.54E+01	7.97E+00	0.00E+00	6.34E+01
		Steel	3.70E+01	2.76E-01	2.06E+01	5.78E+01
HH Particulate	kg PM2.5 eq	Wood	1.36E+00	4.41E-01	0.00E+00	1.80E+00
		Steel	1.23E+01	1.53E-02	9.02E+00	2.14E+01
Eutrophication Potential	kg N eq	Wood	3.46E+00	4.95E-01	0.00E+00	3.95E+00
		Steel	2.26E+00	1.72E-02	1.06E+00	3.34E+00
Ozone Depletion Potential	kg CFC-11 eq	Wood	1.69E-07	2.89E-08	0.00E+00	1.98E-07
		Steel	1.66E-07	1.00E-09	0.00E+00	1.67E-07
Smog Potential	kg O3 eq	Wood	1.84E+03	2.51E+02	0.00E+00	2.09E+03
		Steel	1.17E+03	8.72E+00	2.08E+02	1.39E+03
Total Primary Energy	MJ	Wood	5.77E+04	1.21E+04	0.00E+00	6.98E+04
		Steel	5.59E+04	4.19E+02	4.12E+04	9.74E+04
Non-Renewable Energy	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.97E+04
		Steel	5.58E+04	4.18E+02	4.12E+04	9.74E+04
Fossil Fuel Consumption	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.96E+04
		Steel	5.58E+04	4.18E+02	8.26E+04	1.39E+05

Table 6.8. The results of LCIA for both buildings (building life expectancy: 80 years).

LCA Measures	Unit	Type	De-construction, Demolition, Disposal (C1 & C4)	Transport (C2)	BBL (D)	Total
Global Warming Potential	kg CO2 eq	Wood	3.87E+03	8.28E+02	-1.23E+05	-1.19E+05
		Steel	3.84E+03	2.87E+01	8.97E+03	1.28E+04
Acidification Potential	kg SO2 eq	Wood	5.54E+01	7.97E+00	0.00E+00	6.34E+01
		Steel	3.70E+01	2.76E-01	2.06E+01	5.78E+01
HH Particulate	kg PM2.5 eq	Wood	1.36E+00	4.41E-01	0.00E+00	1.80E+00
		Steel	1.23E+01	1.53E-02	9.02E+00	2.14E+01
Eutrophication Potential	kg N eq	Wood	3.46E+00	4.95E-01	0.00E+00	3.95E+00
		Steel	2.26E+00	1.72E-02	1.06E+00	3.34E+00
Ozone Depletion Potential	kg CFC-11 eq	Wood	1.69E-07	2.89E-08	0.00E+00	1.98E-07
		Steel	1.66E-07	1.00E-09	0.00E+00	1.67E-07
Smog Potential	kg O3 eq	Wood	1.84E+03	2.51E+02	0.00E+00	2.09E+03
		Steel	1.17E+03	8.72E+00	2.08E+02	1.39E+03
Total Primary Energy	MJ	Wood	5.77E+04	1.21E+04	0.00E+00	6.98E+04
		Steel	5.59E+04	4.19E+02	4.12E+04	9.74E+04
Non-Renewable Energy	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.97E+04
		Steel	5.58E+04	4.18E+02	4.12E+04	9.74E+04
Fossil Fuel Consumption	MJ	Wood	5.76E+04	1.21E+04	0.00E+00	6.96E+04
		Steel	5.58E+04	4.18E+02	8.26E+04	1.39E+05

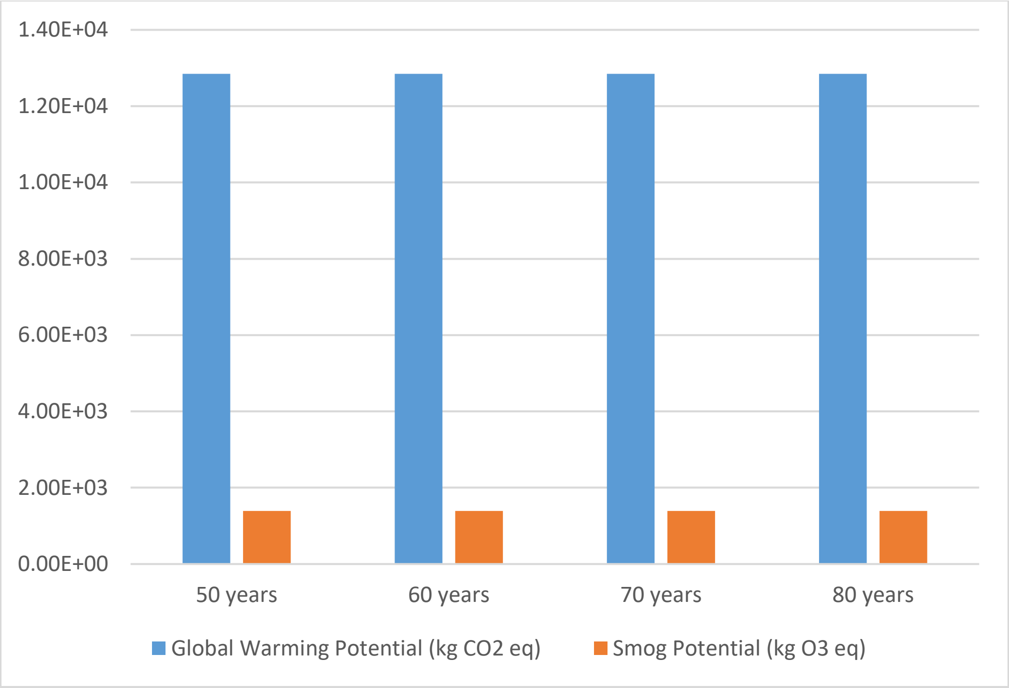

Figure 6.22. The comparison of Global Warming Potential and Smog potential in different building life expectancy for steel structure building.

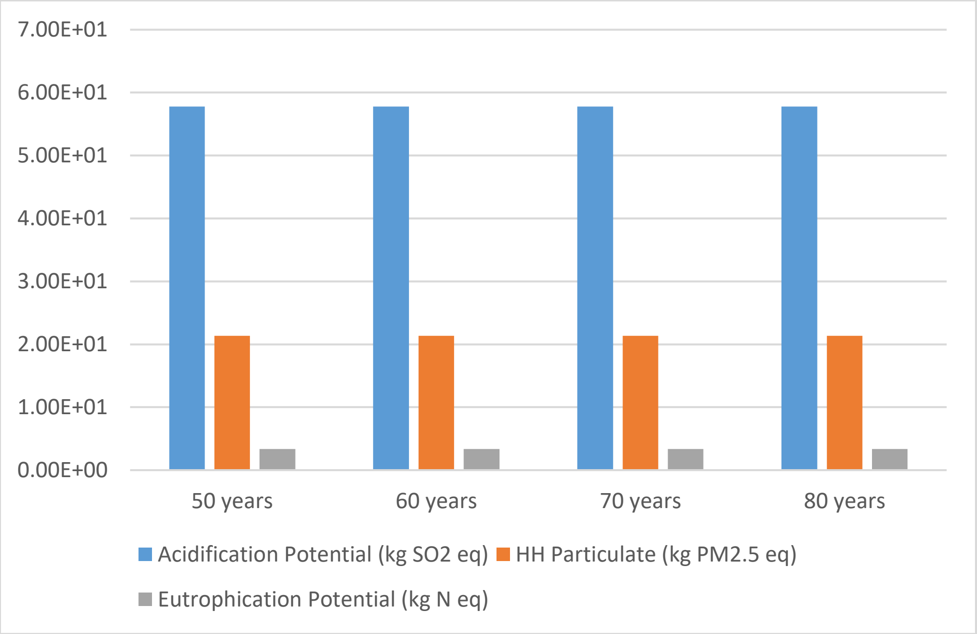

Figure 6.23. The comparison of Acidification Potential, Human Health potential, and Eutrophication Potential, in different building life expectancy for steel structure building.

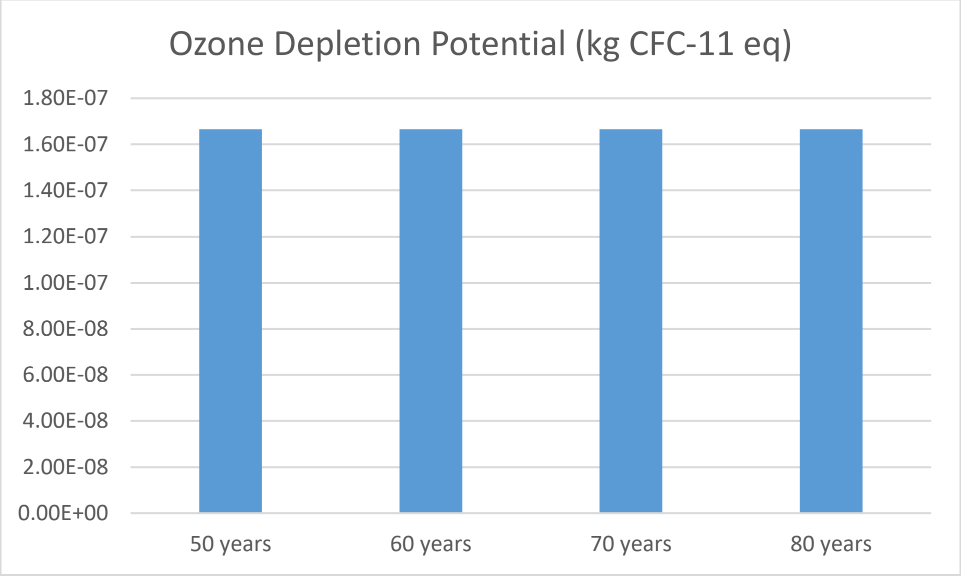

Figure 6.24. The comparison of Ozone Depletion Potential in different building life expectancy for steel structure building.

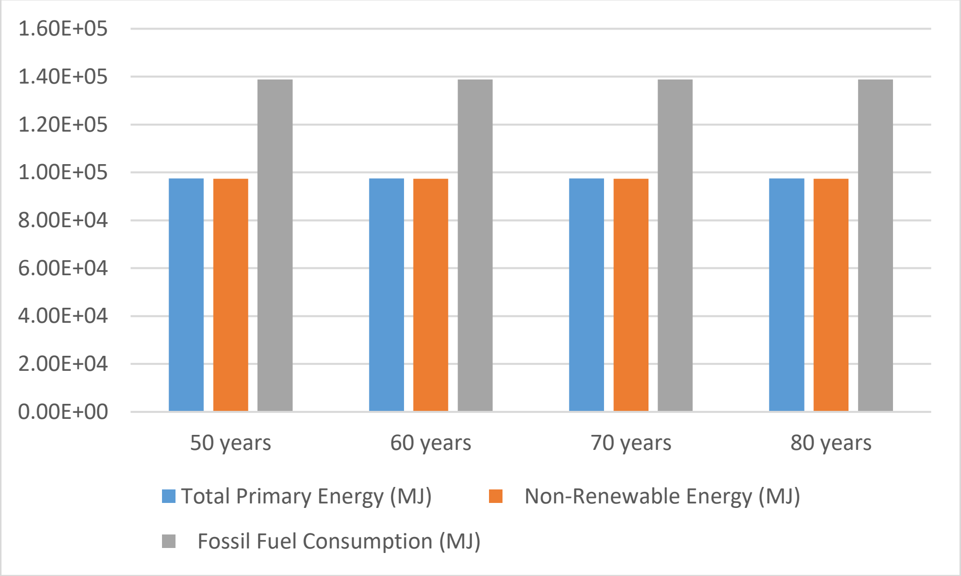

Figure 6.25. The comparison of Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption different building life expectancy for steel structure building.

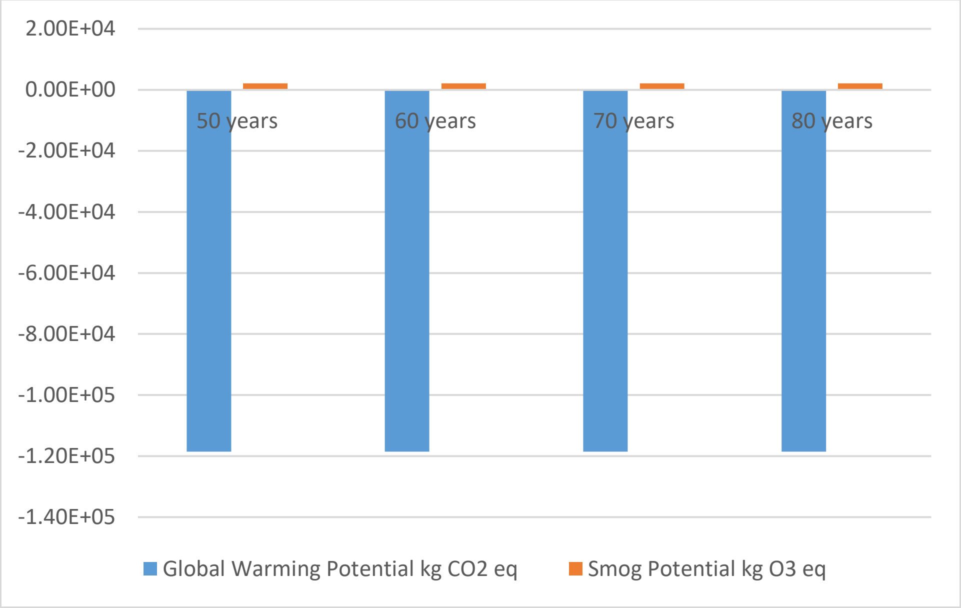

Figure 6.26. The comparison of Global Warming Potential and Smog potential in different building life expectancy for wood structure building.

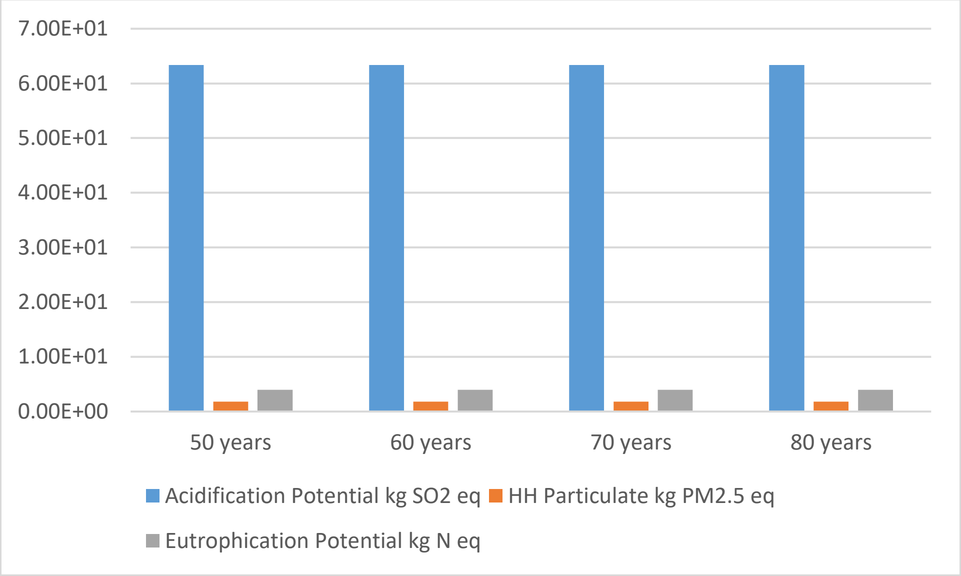

Figure 6.27. The comparison of Acidification Potential, Human Health potential, and Eutrophication Potential, in different building life expectancy for wood structure building.

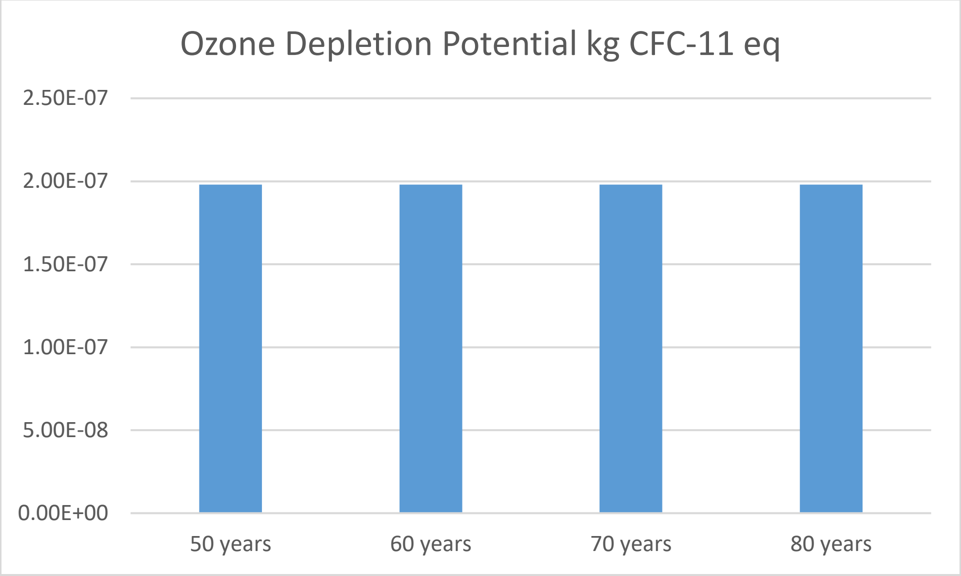

Figure 6.28. The comparison of Ozone Depletion Potential in different building life expectancy for wood structure building.

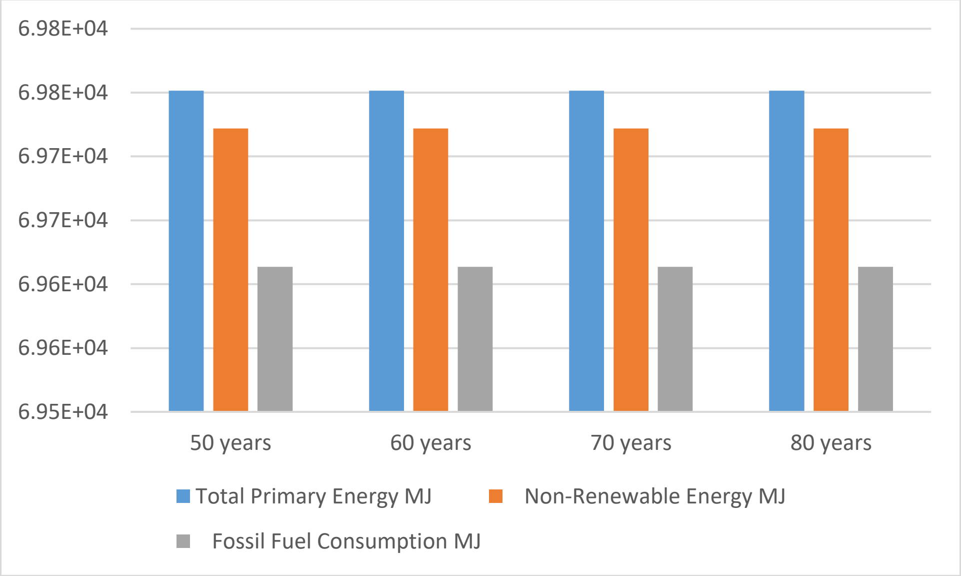

Figure 6.29. The comparison of Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption different building life expectancy for wood structure building.

6.3. Summary of analysis

This 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.

In the three sensitivity analyses, 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.

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.

CHAPTER SEVEN: CONCLUSION AND FUTURE WORK

7.1. Conclusion

Significant amount of construction and demolition wastes are produced nationwide every year, and the process of generation and disposal of those wastes impose serious environmental impacts. Especially, the end-of-life stage waste is lacking separation and comparison of different material types. This study is focused on the environmental impact at the end-of-life stage between wood structure building and steel structure building, using Life cycle assessment and Athena Impact Estimator for Building software. Through the LCIA analysis the following conclusions can be reached:

- The analysis results show 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.
- The wood structure building has less impact on environment than the steel structure building at the end-of-life stage in all other five categories of (1) Global Warming Potential (GWP), (2) Human Health Particulate, (3) Total Primary Energy Consumption, (4) Non-Renewable Energy Consumption, and (5) Fossil Fuel Consumption.
- The wood structure building at the end-of-life stage has a positive environmental impact in the GWP category.

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.

7.2. Limitations and future work

Due to the difficulty caused by COVID-19 pandemic, although the analysis in this study is relatively thorough, some limitations still exist and are listed here as well as some recommendations for future work. The limitations include: (1) There was only one type of frame design for each type of materials in this study, 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) During the use of Athena impact estimator of buildings, some deficiencies have been found. First, there are too few locations to choose from. In this study, the project location of Fargo is not provided in the database; therefore, Minneapolis was used as the project location 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. Additionally, for the sensitivity analysis of changing project location at the end-of-life stage, the average data of the United States was used. It is hoped that future researchers could expand the data of different regions to make the final results more accurate. Second, the result of LCIA at the end-of-life stage from the software did not include the waste process (C3). It is suggested that future researchers should add this part to the end-of-life stage research. Finally, if Athena Impact Estimator for Buildings can cooperate with AutoCAD or Revit in the future, the input materials will become more accurate and simpler. (3) In the LCIA results for steel structure building as shown in Table 6.1, There is something wrong with the value of the Total Primary Energy in BBL. 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. Then Athena's staff was consulted for this problem. The Athena's staff verified that some steels made in blast furnaces will produce a negative value in BBL. It means that Total Primary Energy may have a negative value, but the negative value is not in the Fossil Fuel Consumption, so that the value of Total Primary Energy is smaller than Fossil Fuel Consumption. Although the Athena's staff's explanation was sufficient for this study future detailed research will need for this problem. (4) This study did not involve the ultimate direction of material structure in recycling and reuse (module D), for example, steel after recycling is made into nails, screws. It is suggested that more detailed study of this area will be conducted in the future research.

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APPENDIX A. WOODHAVEN OFFICE COMPLEX STRUCTURE DRAWINGS

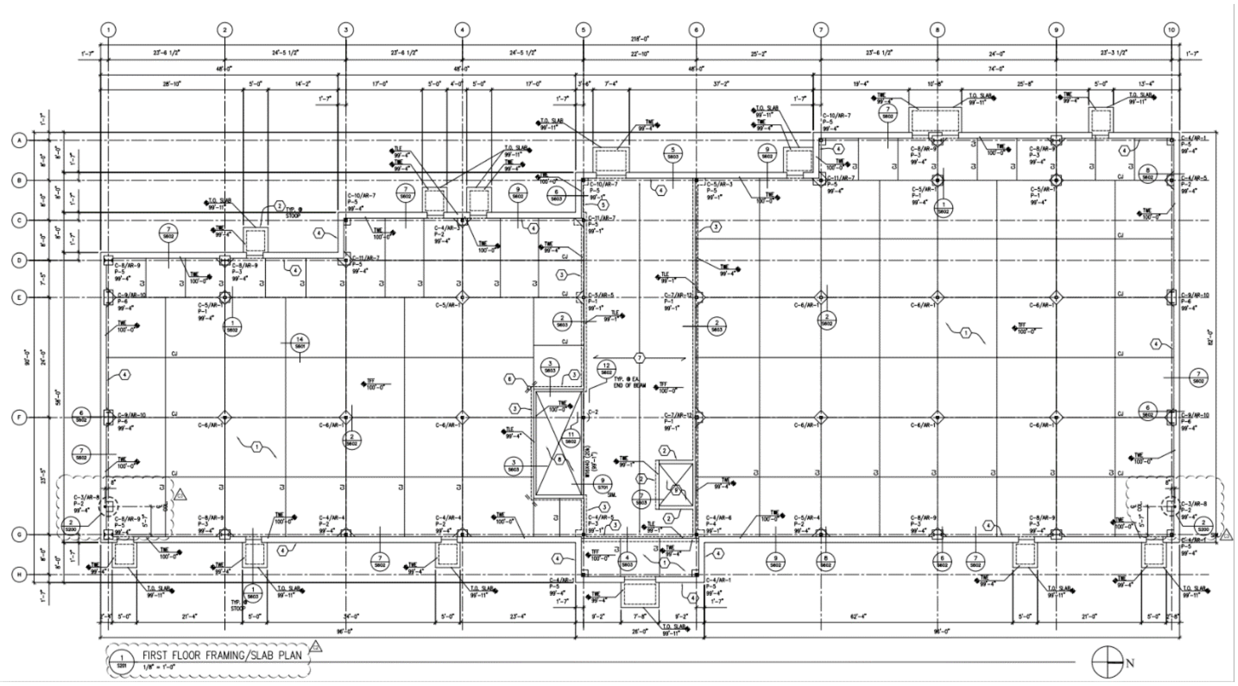


Figure A1. Office complex structure drawing (1).

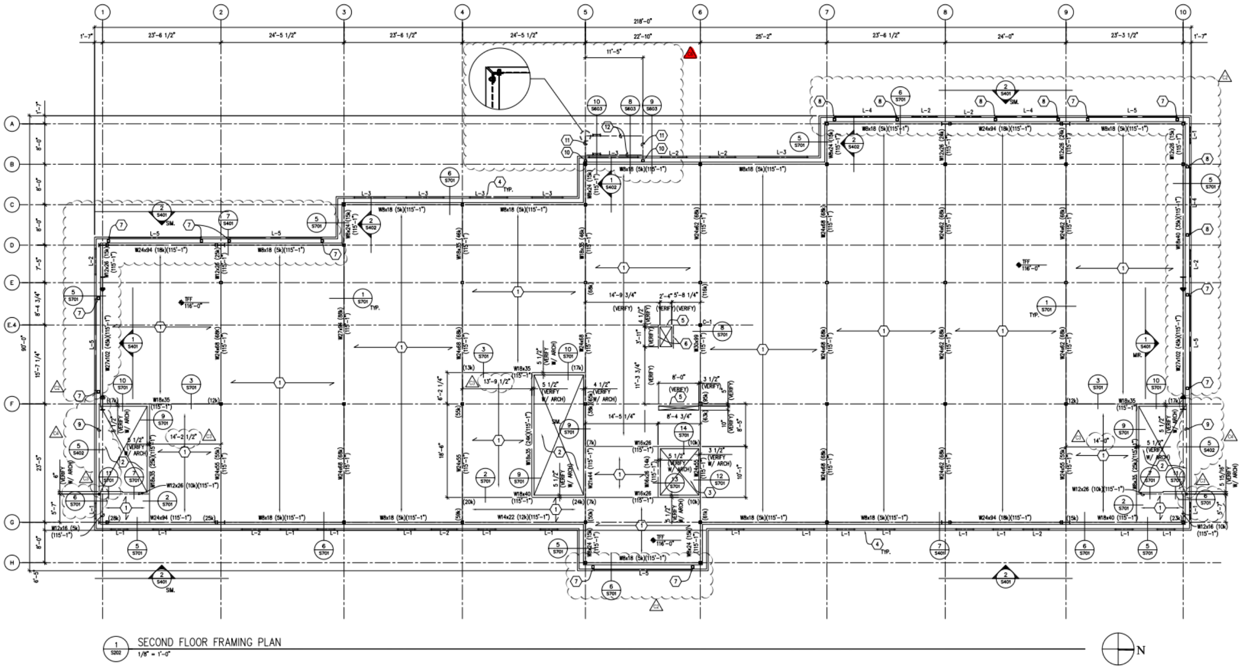


Figure A2. Office complex structure drawing (2).

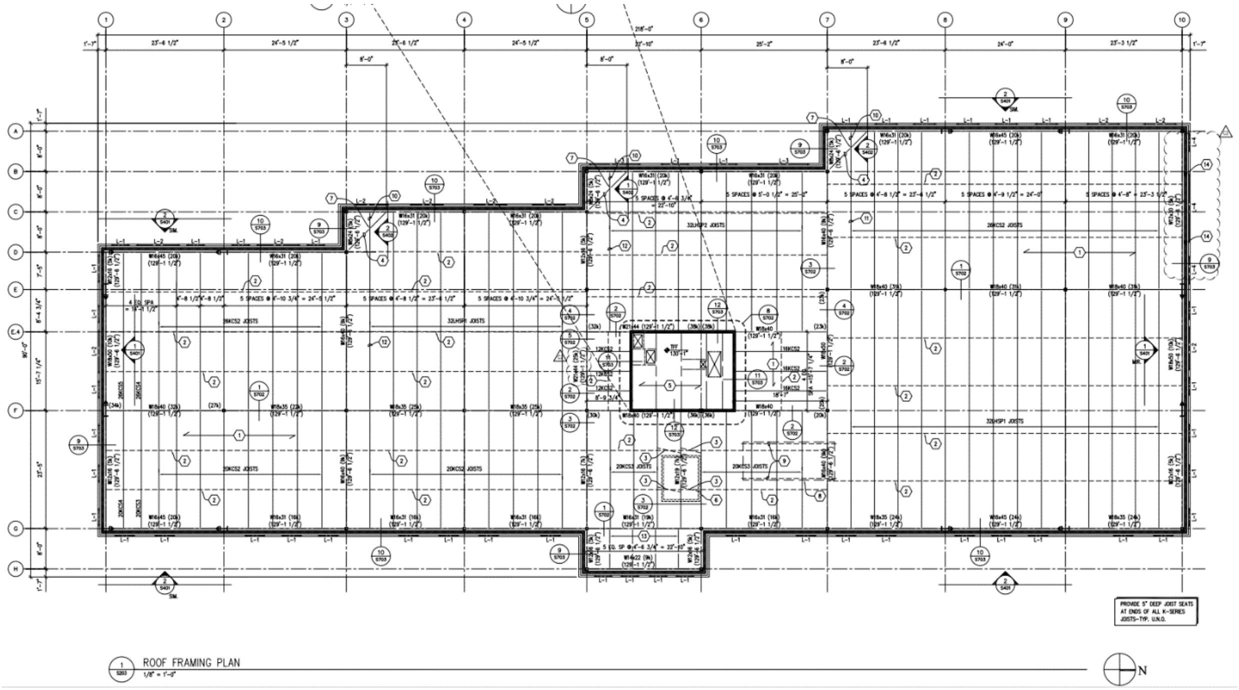


Figure A3. Office complex structure drawing (3).

APPENDIX B. THE TABLE OF LCI RESULTS AT THE END-OF-LIFE STAGE

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
1,4-Butanediol	g	0.00E+00	0.00E+00	0.00E+00
1-Butanol	g	0.00E+00	0.00E+00	0.00E+00
1-Pentanol	g	0.00E+00	0.00E+00	0.00E+00
1-Pentene	g	0.00E+00	0.00E+00	0.00E+00
1-Propanol	g	0.00E+00	0.00E+00	0.00E+00
2-Butene, 2-methyl-	g	0.00E+00	0.00E+00	0.00E+00
2-Chloroacetophenone	g	7.89E-09	0.00E+00	0.00E+00
2-Methyl-1-propanol	g	0.00E+00	0.00E+00	0.00E+00
2-Propanol	g	0.00E+00	0.00E+00	0.00E+00
4-Methyl-2-pentanone	g	0.00E+00	0.00E+00	0.00E+00
5-methyl Chrysene	g	5.17E-08	1.14E-09	0.00E+00
Acenaphthene	g	1.20E-06	2.65E-08	0.00E+00
Acenaphthylene	g	5.88E-07	1.30E-08	0.00E+00
Acetaldehyde	g	1.06E+01	0.00E+00	0.00E+00
Acetic acid	g	0.00E+00	0.00E+00	0.00E+00
Acetone	g	0.00E+00	0.00E+00	0.00E+00
Acetophenone	g	1.69E-08	0.00E+00	0.00E+00
Acrolein	g	1.28E+00	1.51E-05	0.00E+00
Acrylic acid	g	0.00E+00	0.00E+00	0.00E+00
Aldehydes	g	2.72E-05	6.06E-07	0.00E+00
Ammonia	g	2.48E+01	4.84E-01	0.00E+00
Ammonium chloride	g	7.41E-03	1.65E-04	0.00E+00
Anthracene	g	4.94E-07	1.09E-08	0.00E+00
Antimony	g	4.23E-05	9.35E-07	0.00E+00
Arsenic	g	3.13E-02	5.63E-05	0.00E+00
Benzene	g	1.29E+01	8.65E-05	0.00E+00
Benzene, 1,2-dichloro-	g	0.00E+00	0.00E+00	0.00E+00
Benzene, chloro-	g	2.48E-08	0.00E+00	0.00E+00
Benzene, ethyl-	g	1.06E-07	0.00E+00	0.00E+00
Benzo(a)anthracene	g	1.88E-07	4.16E-09	0.00E+00
Benzo(a)pyrene	g	8.94E-08	1.97E-09	0.00E+00
Benzo(b,j,k)fluoranthene	g	2.59E-07	5.72E-09	0.00E+00
Benzo(ghi)perylene	g	6.35E-08	1.40E-09	0.00E+00
Benzyl chloride	g	7.89E-07	0.00E+00	0.00E+00
Beryllium	g	2.17E-02	2.43E-06	0.00E+00
Biphenyl	g	4.00E-06	8.83E-08	0.00E+00
Bromoform	g	4.40E-08	0.00E+00	0.00E+00

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Butadiene	g	5.39E-01	0.00E+00	0.00E+00
Butane	g	0.00E+00	0.00E+00	0.00E+00
Butyrolactone	g	0.00E+00	0.00E+00	0.00E+00
Cadmium	g	2.25E-02	2.03E-05	2.98E-01
Carbon dioxide, biogenic	kg	5.54E-05	0.00E+00	0.00E+00
Carbon dioxide, fossil	kg	3.72E+03	2.79E+01	8.34E+03
Carbon dioxide, land transformation	g	6.43E+01	1.42E+00	0.00E+00
Carbon disulfide	g	1.47E-07	0.00E+00	0.00E+00
Carbon monoxide	g	9.18E-01	4.04E+01	1.34E+05
Carbon monoxide, biogenic	g	0.00E+00	0.00E+00	0.00E+00
Carbon monoxide, fossil	g	3.15E+04	9.69E+01	0.00E+00
Chlorine	g	0.00E+00	0.00E+00	0.00E+00
Chloroform	g	6.65E-08	0.00E+00	0.00E+00
Chromium	g	2.36E-02	4.42E-05	-8.66E-01
Chromium VI	g	1.86E-04	4.10E-06	0.00E+00
Chrysene	g	2.35E-07	5.20E-09	0.00E+00
Cobalt	g	6.95E-03	1.56E-04	0.00E+00
Copper	g	4.32E-02	1.13E-06	0.00E+00
Cumene	g	5.97E-09	0.00E+00	0.00E+00
Cyanide	g	2.82E-06	0.00E+00	0.00E+00
Cyclohexane	g	0.00E+00	0.00E+00	0.00E+00
Diethyl ether	g	0.00E+00	0.00E+00	0.00E+00
Diethylene glycol	g	0.00E+00	0.00E+00	0.00E+00
Dimethyl carbonate	g	0.00E+00	0.00E+00	0.00E+00
Dimethylamine	g	0.00E+00	0.00E+00	0.00E+00
Dinitrogen monoxide	g	9.46E+00	6.05E-03	0.00E+00
Dioxins, unspecified	g	0.00E+00	0.00E+00	-6.30E-05
Ethane	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1,1-trichloro-, HCFC-140	g	1.14E-04	6.91E-07	0.00E+00
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1-difluoro-, HFC-152a	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,2-dibromo-	g	1.35E-09	0.00E+00	0.00E+00
Ethane, 1,2-dichloro-	g	4.51E-08	0.00E+00	0.00E+00
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	g	0.00E+00	0.00E+00	0.00E+00

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	g	0.00E+00	0.00E+00	0.00E+00
Ethane, chloro-	g	4.73E-08	0.00E+00	0.00E+00
Ethane, hexafluoro-, HFC-116	g	0.00E+00	0.00E+00	0.00E+00
Ethanol	g	0.00E+00	0.00E+00	0.00E+00
Ethene	g	0.00E+00	0.00E+00	0.00E+00
Ethene, chloro-	g	0.00E+00	0.00E+00	0.00E+00
Ethene, tetrachloro-	g	4.14E-03	4.09E-06	0.00E+00
Ethene, trichloro-	g	0.00E+00	0.00E+00	0.00E+00
Ethyl acetate	g	0.00E+00	0.00E+00	0.00E+00
Ethylamine	g	0.00E+00	0.00E+00	0.00E+00
Ethylene oxide	g	0.00E+00	0.00E+00	0.00E+00
Ethyne	g	0.00E+00	0.00E+00	0.00E+00
Fluoranthene	g	1.67E-06	3.69E-08	0.00E+00
Fluorene	g	2.14E-06	4.73E-08	0.00E+00
Fluoride	g	2.17E-04	3.70E-06	0.00E+00
Formaldehyde	g	1.63E+01	1.32E-03	0.00E+00
Formic acid	g	0.00E+00	0.00E+00	0.00E+00
Furan	g	1.18E-08	2.60E-10	0.00E+00
Heptane	g	0.00E+00	0.00E+00	0.00E+00
Hexane	g	7.55E-08	0.00E+00	0.00E+00
Hydrazine, methyl-	g	1.92E-07	0.00E+00	0.00E+00
Hydrocarbons, unspecified	g	1.63E-01	7.79E+00	0.00E+00
Hydrogen chloride	g	3.99E+01	8.07E-02	1.86E+02
Hydrogen fluoride	g	3.53E-01	7.79E-03	0.00E+00
Hydrogen sulfide	g	0.00E+00	0.00E+00	2.20E+03
Indeno(1,2,3-cd)pyrene	g	1.43E-07	3.17E-09	0.00E+00
Isophorone	g	6.54E-07	0.00E+00	0.00E+00
Isoprene	g	0.00E+00	0.00E+00	0.00E+00
Isopropylamine	g	0.00E+00	0.00E+00	0.00E+00
Kerosene	g	3.55E-03	7.90E-05	0.00E+00
Lead	g	6.77E-02	6.44E-05	1.07E+01
m-Xylene	g	0.00E+00	0.00E+00	0.00E+00
Magnesium	g	2.59E-02	5.72E-04	0.00E+00
Manganese	g	4.78E-02	1.04E-04	0.00E+00
Mercaptans, unspecified	g	2.45E-04	0.00E+00	0.00E+00
Mercury	g	2.20E-02	9.38E-06	-5.82E-02
Methacrylic acid, methyl ester	g	2.25E-08	0.00E+00	0.00E+00

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Methane	g	1.93E+02	4.30E+00	2.54E+04
Methane, bromo-, Halon 1001	g	1.80E-07	0.00E+00	0.00E+00
Methane, biogenic	g	0.00E+00	0.00E+00	0.00E+00
Methane, bromochlorodifluoro-, Halon 1211	g	0.00E+00	0.00E+00	0.00E+00
Methane, bromotrifluoro-, Halon 1301	g	0.00E+00	0.00E+00	0.00E+00
Methane, chlorodifluoro-, HCFC-22	g	0.00E+00	0.00E+00	0.00E+00
Methane, chlorotrifluoro-, CFC-13	g	0.00E+00	0.00E+00	0.00E+00
Methane, dichloro-, HCC-30	g	2.38E-01	1.41E-04	0.00E+00
Methane, dichlorodifluoro-, CFC-12	g	1.41E-04	8.55E-07	0.00E+00
Methane, dichlorofluoro-, HCFC-21	g	0.00E+00	0.00E+00	0.00E+00
Methane, fossil	g	4.57E+03	2.71E+01	0.00E+00
Methane, monochloro-, R-40	g	5.97E-07	0.00E+00	0.00E+00
Methane, tetrachloro-, CFC-10	g	1.41E-05	8.75E-08	0.00E+00
Methane, tetrafluoro-, CFC-14	g	0.00E+00	0.00E+00	0.00E+00
Methane, trichlorofluoro-, CFC-11	g	0.00E+00	0.00E+00	0.00E+00
Methane, trifluoro-, HFC-23	g	0.00E+00	0.00E+00	0.00E+00
Methanol	g	0.00E+00	0.00E+00	0.00E+00
Methyl acetate	g	0.00E+00	0.00E+00	0.00E+00
Methyl acrylate	g	0.00E+00	0.00E+00	0.00E+00
Methyl amine	g	0.00E+00	0.00E+00	0.00E+00
Methyl ethyl ketone	g	4.40E-07	0.00E+00	0.00E+00
Methyl formate	g	0.00E+00	0.00E+00	0.00E+00
Methyl lactate	g	0.00E+00	0.00E+00	0.00E+00
Monoethanolamine	g	0.00E+00	0.00E+00	0.00E+00
Naphthalene	g	1.47E-03	3.28E-05	0.00E+00
Nickel	g	1.17E-01	2.14E-03	0.00E+00
Nitrate	g	0.00E+00	0.00E+00	0.00E+00
Nitric oxide	g	0.00E+00	0.00E+00	0.00E+00
Nitrobenzene	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen dioxide	g	2.19E-01	1.41E+01	8.47E+01
Nitrogen fluoride	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen oxides	g	4.69E+04	3.40E+02	8.01E+03
Nitrous oxides	g	4.27E-04	2.75E-02	3.12E+01

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
NMVOC, non-methane volatile organic compounds, unspecified origin	g	7.34E-08	0.00E+00	9.43E+02
o-Xylene	g	0.00E+00	0.00E+00	0.00E+00
Organic acids	g	2.72E-05	6.06E-07	0.00E+00
Organic substances, unspecified	g	1.42E-02	3.15E-04	0.00E+00
Ozone	g	0.00E+00	0.00E+00	0.00E+00
PAH, polycyclic aromatic hydrocarbons	g	2.32E+00	0.00E+00	0.00E+00
Particulates, < 2.5 um	g	1.16E+04	9.92E+00	8.27E+03
Particulates, > 2.5 um, and < 10um	g	1.43E+03	9.49E+00	0.00E+00
Pentane	g	0.00E+00	0.00E+00	0.00E+00
Pentane, 2,2,4-trimethyl-	g	0.00E+00	0.00E+00	0.00E+00
Pentane, 2-methyl-	g	0.00E+00	0.00E+00	0.00E+00
Phenanthrene	g	6.35E-06	1.40E-07	0.00E+00
Phenol	g	1.80E-08	0.00E+00	0.00E+00
Phenols, unspecified	g	1.79E-01	9.59E-05	0.00E+00
Phosphoric acid	g	0.00E+00	0.00E+00	0.00E+00
Phosphorus	g	2.06E-10	0.00E+00	0.00E+00
Phthalate, dioctyl-	g	8.23E-08	0.00E+00	0.00E+00
Propanal	g	4.28E-07	0.00E+00	0.00E+00
Propane	g	0.00E+00	0.00E+00	0.00E+00
Propene	g	3.56E+01	0.00E+00	0.00E+00
Propionic acid	g	0.00E+00	0.00E+00	0.00E+00
Propylene oxide	g	0.00E+00	0.00E+00	0.00E+00
Pyrene	g	7.76E-07	1.71E-08	0.00E+00
Radioactive species, unspecified	MBq	1.81E-01	2.96E-03	0.00E+00
Radionuclides (Including Radon)	g	1.98E-01	4.42E-03	0.00E+00
Selenium	g	1.12E-01	8.76E-05	0.00E+00
Styrene	g	2.82E-08	0.00E+00	0.00E+00
Sulfur dioxide	g	4.16E+02	9.26E+00	1.06E+04
Sulfur hexafluoride	g	0.00E+00	0.00E+00	0.00E+00
Sulfur trioxide	g	0.00E+00	0.00E+00	0.00E+00
Sulfuric acid	g	0.00E+00	0.00E+00	0.00E+00
Sulfuric acid, dimethyl ester	g	5.41E-08	0.00E+00	0.00E+00
Sulfur oxides	g	3.62E+03	1.79E+01	0.00E+00
t-Butyl methyl ether	g	3.95E-08	0.00E+00	0.00E+00
Terpenes	g	0.00E+00	0.00E+00	0.00E+00

Table B1. Emission to air LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Toluene	g	5.64E+00	0.00E+00	0.00E+00
Toluene, 2,4-dinitro-	g	3.16E-10	0.00E+00	0.00E+00
Toluene, 2-chloro-	g	0.00E+00	0.00E+00	0.00E+00
Trimethylamine	g	0.00E+00	0.00E+00	0.00E+00
Vinyl acetate	g	8.57E-09	0.00E+00	0.00E+00
VOC, volatile organic compounds	g	1.44E+03	8.84E+00	0.00E+00
Xylene	g	3.93E+00	0.00E+00	0.00E+00
Zinc	g	2.88E-02	7.52E-07	0.00E+00

Table B2. Emission to land LCI results of steel structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Other Solid Waste	kg	4.01E+01	3.29E-01	0.00E+00
Solid Waste to Landfill	kg	3.55E+03	0.00E+00	0.00E+00
Steel Waste	kg	0.00E+00	0.00E+00	0.00E+00

Table B3. Emission to water LCI results of steel structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
2-Hexanone	mg	2.87E+01	2.23E-01	0.00E+00
Acetone	mg	4.39E+01	3.42E-01	0.00E+00
Acids, unspecified	mg	0.00E+00	0.00E+00	0.00E+00
Aluminum	mg	3.90E+05	2.97E+03	0.00E+00
Ammonia	mg	8.33E+04	6.43E+02	1.38E+04
Ammonium, ion	mg	1.44E+00	0.00E+00	0.00E+00
Antimony	mg	2.43E+02	1.86E+00	0.00E+00
Arsenic, ion	mg	1.21E+03	9.40E+00	0.00E+00
Barium	mg	5.34E+06	4.08E+04	0.00E+00
Benzene	mg	7.37E+03	5.74E+01	0.00E+00
Benzene, 1-methyl-4-(1-methylethyl)-	µg	4.39E+02	3.42E+00	0.00E+00
Benzene, ethyl-	mg	4.15E+02	3.23E+00	0.00E+00
Benzene, pentamethyl-	µg	3.29E+02	2.57E+00	0.00E+00
Benzenes, alkylated, unspecified	mg	2.14E+02	1.63E+00	0.00E+00
Benzoic acid	mg	4.46E+03	3.47E+01	0.00E+00
Beryllium	mg	6.78E+01	5.24E-01	0.00E+00
Biphenyl	µg	1.38E+04	1.06E+02	0.00E+00
BOD5, Biological Oxygen Demand	mg	8.05E+05	6.26E+03	6.46E+04
Boron	mg	1.38E+04	1.07E+02	0.00E+00
Bromide	mg	9.41E+05	7.33E+03	0.00E+00
Cadmium, ion	mg	1.79E+02	1.39E+00	1.13E+02
Calcium, ion	mg	1.41E+07	1.10E+05	0.00E+00
Chloride	mg	1.59E+08	1.24E+06	0.00E+00
Chromium	mg	1.04E+04	7.87E+01	-2.06E+02
Chromium VI	µg	4.36E+04	3.31E+02	0.00E+00
Chromium, ion	mg	7.03E+02	5.77E+00	0.00E+00
Cobalt	mg	9.73E+01	7.58E-01	0.00E+00
COD, Chemical Oxygen Demand	mg	1.54E+06	1.19E+04	-4.57E+04
Copper, ion	mg	1.27E+03	9.67E+00	0.00E+00
Cyanide	mg	3.17E-01	2.47E-03	0.00E+00
Decane	mg	1.28E+02	9.98E-01	0.00E+00
Detergent, oil	mg	3.67E+03	2.87E+01	0.00E+00
Dibenzofuran	µg	8.35E+02	6.51E+00	0.00E+00
Dibenzothiophene	µg	5.22E+01	5.26E-01	0.00E+00
Dissolved solids	mg	1.96E+08	1.52E+06	3.74E+04

Table B3. Emission to water LCI results of steel structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
DOC, Dissolved Organic Carbon	mg	3.59E+02	0.00E+00	0.00E+00
Docosane	µg	4.70E+03	3.66E+01	0.00E+00
Dodecane	mg	2.43E+02	1.89E+00	0.00E+00
Eicosane	mg	6.69E+01	5.21E-01	0.00E+00
Fluorene, 1-methyl-	µg	5.00E+02	3.90E+00	0.00E+00
Fluorenes, alkylated, unspecified	µg	1.24E+04	9.45E+01	0.00E+00
Fluoride	mg	7.47E-02	0.00E+00	0.00E+00
Fluorine	µg	6.10E+03	4.66E+01	0.00E+00
Hexadecane	mg	2.65E+02	2.07E+00	0.00E+00
Hexanoic acid	mg	9.23E+02	7.19E+00	0.00E+00
Hydrocarbons, unspecified	µg	0.00E+00	0.00E+00	0.00E+00
Hydrogen chloride	mg	0.00E+00	0.00E+00	0.00E+00
Hydrogen sulfide	mg	3.22E-02	0.00E+00	0.00E+00
Iron	mg	7.73E+05	5.92E+03	-4.46E+05
Lead	mg	2.57E+03	1.98E+01	-5.95E+02
Lead-210/kg	µg	4.57E-04	3.55E-06	0.00E+00
Lithium, ion	mg	7.17E+04	1.45E+03	0.00E+00
m-Xylene	mg	1.33E+02	1.04E+00	0.00E+00
Magnesium	mg	2.76E+06	2.15E+04	0.00E+00
Manganese	mg	4.43E+03	3.49E+01	0.00E+00
Mercury	µg	4.27E+03	3.26E+01	0.00E+00
Methane, monochloro-, R-40	µg	1.77E+02	1.38E+00	0.00E+00
Methyl ethyl ketone	µg	3.54E+02	2.76E+00	0.00E+00
Molybdenum	mg	1.01E+02	7.87E-01	0.00E+00
n-Hexacosane	µg	2.93E+03	2.28E+01	0.00E+00
Naphthalene	mg	8.01E+01	6.24E-01	0.00E+00
Naphthalene, 2-methyl-	mg	6.96E+01	5.42E-01	0.00E+00
Naphthalenes, alkylated, unspecified	µg	3.50E+03	2.67E+01	0.00E+00
Nickel	mg	1.20E+03	9.28E+00	3.61E+02
Nitrate	mg	3.77E-01	0.00E+00	0.00E+00
Nitrogen	mg	2.25E+00	0.00E+00	7.22E+05
o-Cresol	mg	1.26E+02	9.85E-01	0.00E+00
Octadecane	mg	6.55E+01	5.10E-01	0.00E+00
Oils, unspecified	mg	1.02E+05	7.90E+02	0.00E+00
p-Cresol	mg	1.36E+02	1.06E+00	0.00E+00

Table B3. Emission to water LCI results of steel structure model at the end-of-life stage (continued)

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
PAH, polycyclic aromatic hydrocarbons	µg	0.00E+00	0.00E+00	0.00E+00
Pentanone, methyl-	mg	1.85E+01	1.44E-01	0.00E+00
Phenanthrene	µg	1.24E+03	9.56E+00	0.00E+00
Phenanthrenes, alkylated, unspecified	µg	1.45E+03	1.11E+01	0.00E+00
Phenol	µg	1.93E+06	1.47E+04	0.00E+00
Phenol, 2,4-dimethyl-	mg	1.23E+02	9.59E-01	0.00E+00
Phenols, unspecified	mg	2.99E+02	2.65E+00	0.00E+00
Phosphate	mg	8.38E-03	0.00E+00	-1.04E+03
Phosphorus	mg	0.00E+00	0.00E+00	-3.15E+03
Radioactive species, Nuclides, unspecified	mg	0.00E+00	0.00E+00	0.00E+00
Radium-226/kg	µg	1.59E-01	1.24E-03	0.00E+00
Radium-228/kg	µg	8.12E-04	6.32E-06	0.00E+00
Selenium	µg	4.72E+04	3.60E+02	0.00E+00
Silver	mg	9.23E+03	7.19E+01	0.00E+00
Sodium, ion	mg	4.47E+07	3.49E+05	0.00E+00
Solids, inorganic	mg	0.00E+00	0.00E+00	0.00E+00
Strontium	mg	2.40E+05	1.87E+03	0.00E+00
Sulfate	mg	3.19E+05	2.49E+03	0.00E+00
Sulfide	mg	2.24E+02	1.70E+00	0.00E+00
Sulfur	mg	1.16E+04	9.07E+01	0.00E+00
Suspended solids, unspecified	mg	1.20E+07	9.15E+04	0.00E+00
Tetradecane	mg	1.07E+02	8.30E-01	0.00E+00
Thallium	µg	5.13E+04	3.92E+02	0.00E+00
Tin	mg	9.81E+02	7.54E+00	0.00E+00
Titanium, ion	mg	3.74E+03	2.85E+01	0.00E+00
Toluene	mg	6.96E+03	5.42E+01	0.00E+00
Vanadium	mg	1.19E+02	9.29E-01	0.00E+00
Xylene	mg	3.60E+03	2.74E+01	0.00E+00
Yttrium	mg	2.96E+01	2.31E-01	0.00E+00
Zinc	mg	8.98E+03	6.86E+01	-5.30E+03

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
1,4-Butanediol	g	0.00E+00	0.00E+00	0.00E+00
1-Butanol	g	0.00E+00	0.00E+00	0.00E+00
1-Pentanol	g	0.00E+00	0.00E+00	0.00E+00
1-Pentene	g	0.00E+00	0.00E+00	0.00E+00
1-Propanol	g	0.00E+00	0.00E+00	0.00E+00
2-Butene, 2-methyl-	g	0.00E+00	0.00E+00	0.00E+00
2-Chloroacetophenone	g	7.78E-17	0.00E+00	0.00E+00
2-Methyl-1-propanol	g	0.00E+00	0.00E+00	0.00E+00
2-Propanol	g	0.00E+00	0.00E+00	0.00E+00
4-Methyl-2-pentanone	g	0.00E+00	0.00E+00	0.00E+00
5-methyl Chrysene	g	1.46E-14	3.30E-08	0.00E+00
Acenaphthene	g	3.39E-13	7.65E-07	0.00E+00
Acenaphthylene	g	1.66E-13	3.75E-07	0.00E+00
Acetaldehyde	g	1.77E+01	0.00E+00	0.00E+00
Acetic acid	g	0.00E+00	0.00E+00	0.00E+00
Acetone	g	0.00E+00	0.00E+00	0.00E+00
Acetophenone	g	1.67E-16	0.00E+00	0.00E+00
Acrolein	g	2.14E+00	4.35E-04	0.00E+00
Acrylic acid	g	0.00E+00	0.00E+00	0.00E+00
Aldehydes	g	7.69E-12	1.75E-05	0.00E+00
Ammonia	g	2.53E+01	1.40E+01	0.00E+00
Ammonium chloride	g	2.09E-09	4.76E-03	0.00E+00
Anthracene	g	1.39E-13	3.15E-07	0.00E+00
Antimony	g	1.19E-11	2.70E-05	0.00E+00
Arsenic	g	2.66E-09	1.62E-03	0.00E+00
Benzene	g	2.15E+01	2.50E-03	0.00E+00
Benzene, 1,2-dichloro-	g	0.00E+00	0.00E+00	0.00E+00
Benzene, chloro-	g	2.45E-16	0.00E+00	0.00E+00
Benzene, ethyl-	g	1.05E-15	0.00E+00	0.00E+00
Benzo(a)anthracene	g	5.31E-14	1.20E-07	0.00E+00
Benzo(a)pyrene	g	2.52E-14	5.70E-08	0.00E+00
Benzo(b,j,k)fluoranthene	g	7.30E-14	1.65E-07	0.00E+00
Benzo(ghi)perylene	g	1.79E-14	4.05E-08	0.00E+00
Benzyl chloride	g	7.78E-15	0.00E+00	0.00E+00
Beryllium	g	2.44E-10	7.00E-05	0.00E+00
Biphenyl	g	1.13E-12	2.55E-06	0.00E+00
Bromoform	g	4.34E-16	0.00E+00	0.00E+00
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene),	g	0.00E+00	0.00E+00	0.00E+00

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Butadiene	g	9.03E-01	0.00E+00	0.00E+00
Butane	g	0.00E+00	0.00E+00	0.00E+00
Butyrolactone	g	0.00E+00	0.00E+00	0.00E+00
Cadmium	g	8.35E-10	5.85E-04	0.00E+00
Carbon dioxide, biogenic	kg	0.00E+00	0.00E+00	0.00E+00
Carbon dioxide, biogenic, landfill	kg	0.00E+00	0.00E+00	-1.51E+05
Carbon dioxide, fossil	kg	3.75E+03	8.06E+02	0.00E+00
Carbon dioxide, land transformation	g	1.81E-05	4.10E+01	0.00E+00
Carbon disulfide	g	1.45E-15	0.00E+00	0.00E+00
Carbon monoxide	g	1.21E-04	1.17E+03	0.00E+00
Carbon monoxide, biogenic	g	0.00E+00	0.00E+00	0.00E+00
Carbon monoxide, fossil	g	3.55E+04	2.79E+03	0.00E+00
Chloride	g	0.00E+00	0.00E+00	0.00E+00
Chlorine	g	0.00E+00	0.00E+00	0.00E+00
Chloroform	g	6.56E-16	0.00E+00	0.00E+00
Chromium	g	7.80E-10	1.28E-03	0.00E+00
Chromium VI	g	5.24E-11	1.18E-04	0.00E+00
Chrysene	g	6.64E-14	1.50E-07	0.00E+00
Cobalt	g	2.00E-09	4.50E-03	0.00E+00
Copper	g	4.49E-10	3.25E-05	0.00E+00
Cumene	g	5.89E-17	0.00E+00	0.00E+00
Cyanide	g	9.52E-08	0.00E+00	0.00E+00
Cyclohexane	g	0.00E+00	0.00E+00	0.00E+00
Diethyl ether	g	0.00E+00	0.00E+00	0.00E+00
Diethylene glycol	g	0.00E+00	0.00E+00	0.00E+00
Dimethyl carbonate	g	0.00E+00	0.00E+00	0.00E+00
Dimethyl ether	g	0.00E+00	0.00E+00	0.00E+00
Dimethylamine	g	0.00E+00	0.00E+00	0.00E+00
Dinitrogen monoxide	g	9.40E-06	1.64E-01	0.00E+00
Dioxins, unspecified	g	0.00E+00	0.00E+00	0.00E+00
Dipropylthiocarbamic acid S-ethyl ester	g	0.00E+00	0.00E+00	0.00E+00
Ethane	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1,1-trichloro-, HCFC-140	g	1.17E-04	1.99E-05	0.00E+00

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,1-difluoro-, HFC-152a	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 1,2-dibromo-	g	1.33E-17	0.00E+00	0.00E+00
Ethane, 1,2-dichloro-	g	4.45E-16	0.00E+00	0.00E+00
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	g	0.00E+00	0.00E+00	0.00E+00
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	g	0.00E+00	0.00E+00	0.00E+00
Ethane, chloro-	g	4.67E-16	0.00E+00	0.00E+00
Ethane, hexafluoro-, HFC-116	g	0.00E+00	0.00E+00	0.00E+00
Ethanol	g	0.00E+00	0.00E+00	0.00E+00
Ethene	g	0.00E+00	0.00E+00	0.00E+00
Ethene, chloro-	g	0.00E+00	0.00E+00	0.00E+00
Ethene, tetrachloro-	g	9.12E-11	1.18E-04	0.00E+00
Ethene, trichloro-	g	0.00E+00	0.00E+00	0.00E+00
Ethyl acetate	g	0.00E+00	0.00E+00	0.00E+00
Ethylamine	g	0.00E+00	0.00E+00	0.00E+00
Ethylene oxide	g	0.00E+00	0.00E+00	0.00E+00
Ethyne	g	0.00E+00	0.00E+00	0.00E+00
Fluoranthene	g	4.71E-13	1.06E-06	0.00E+00
Fluorene	g	6.04E-13	1.36E-06	0.00E+00
Fluoride	g	4.75E-11	1.07E-04	0.00E+00
Formaldehyde	g	2.72E+01	3.82E-02	0.00E+00
Formic acid	g	0.00E+00	0.00E+00	0.00E+00
Furan	g	3.32E-15	7.50E-09	0.00E+00
Heptane	g	0.00E+00	0.00E+00	0.00E+00
Hexane	g	7.45E-16	0.00E+00	0.00E+00
Hydrazine, methyl-	g	1.89E-15	0.00E+00	0.00E+00
Hydrocarbons, unspecified	g	2.72E-08	2.25E+02	0.00E+00
Hydrogen chloride	g	1.98E-05	2.33E+00	0.00E+00
Hydrogen fluoride	g	1.30E-05	2.25E-01	0.00E+00
Hydrogen sulfide	g	0.00E+00	0.00E+00	0.00E+00
Indeno(1,2,3-cd)pyrene	g	4.05E-14	9.15E-08	0.00E+00
Isophorone	g	6.45E-15	0.00E+00	0.00E+00
Isoprene	g	0.00E+00	0.00E+00	0.00E+00
Isopropylamine	g	0.00E+00	0.00E+00	0.00E+00
Kerosene	g	1.00E-09	2.28E-03	0.00E+00

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Lead	g	1.55E-09	1.86E-03	0.00E+00
m-Xylene	g	0.00E+00	0.00E+00	0.00E+00
Magnesium	g	7.95E-08	1.65E-02	0.00E+00
Manganese	g	2.51E-08	3.00E-03	0.00E+00
Mercaptans, unspecified	g	2.41E-12	0.00E+00	0.00E+00
Mercury	g	1.38E-08	2.71E-04	0.00E+00
Metals, unspecified	g	0.00E+00	0.00E+00	0.00E+00
Methacrylic acid, methyl ester	g	2.22E-16	0.00E+00	0.00E+00
Methane	g	5.22E-05	1.24E+02	0.00E+00
Methane, bromo-, Halon 1001	g	1.78E-15	0.00E+00	0.00E+00
Methane, biogenic	g	0.00E+00	0.00E+00	0.00E+00
Methane, bromochlorodifluoro-, Halon 1211	g	0.00E+00	0.00E+00	0.00E+00
Methane, biogenic, landfill	g	0.00E+00	0.00E+00	1.27E+06
Methane, bromotrifluoro-, Halon 1301	g	0.00E+00	0.00E+00	0.00E+00
Methane, chlorodifluoro-, HCFC-22	g	0.00E+00	0.00E+00	0.00E+00
Methane, dichloro-, HCC-30	g	4.09E-09	4.08E-03	0.00E+00
Methane, dichlorodifluoro-, CFC-12	g	1.44E-04	2.47E-05	0.00E+00
Methane, dichlorofluoro-, HCFC-21	g	0.00E+00	0.00E+00	0.00E+00
Methane, fossil	g	4.67E+03	7.82E+02	0.00E+00
Methane, monochloro-, R-40	g	5.89E-15	0.00E+00	0.00E+00
Methane, tetrachloro-, CFC-10	g	1.44E-05	2.53E-06	0.00E+00
Methane, tetrafluoro-, CFC-14	g	0.00E+00	0.00E+00	0.00E+00
Methane, trichlorofluoro-, CFC-11	g	0.00E+00	0.00E+00	0.00E+00
Methane, trifluoro-, HFC-23	g	0.00E+00	0.00E+00	0.00E+00
Methanol	g	0.00E+00	0.00E+00	0.00E+00
Methyl acetate	g	0.00E+00	0.00E+00	0.00E+00
Methyl acrylate	g	0.00E+00	0.00E+00	0.00E+00
Methyl amine	g	0.00E+00	0.00E+00	0.00E+00
Methyl ethyl ketone	g	4.34E-15	0.00E+00	0.00E+00
Methyl formate	g	0.00E+00	0.00E+00	0.00E+00
Methyl lactate	g	0.00E+00	0.00E+00	0.00E+00

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Methyl methacrylate	g	0.00E+00	0.00E+00	0.00E+00
Monoethanolamine	g	0.00E+00	0.00E+00	0.00E+00
Naphthalene	g	4.18E-10	9.47E-04	0.00E+00
Nickel	g	2.74E-08	6.17E-02	0.00E+00
Nitrate	g	0.00E+00	0.00E+00	0.00E+00
Nitric oxide	g	0.00E+00	0.00E+00	0.00E+00
Nitrobenzene	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen dioxide	g	2.74E-08	4.07E+02	0.00E+00
Nitrogen fluoride	g	0.00E+00	0.00E+00	0.00E+00
Nitrogen oxides	g	7.39E+04	9.82E+03	0.00E+00
Nitrous oxides	g	5.35E-11	7.94E-01	0.00E+00
NMVOC, non-methane volatile organic compounds, unspecified origin	g	2.12E-06	0.00E+00	0.00E+00
o-Xylene	g	0.00E+00	0.00E+00	0.00E+00
Organic acids	g	7.69E-12	1.75E-05	0.00E+00
Organic substances, unspecified	g	4.02E-09	9.08E-03	0.00E+00
Ozone	g	0.00E+00	0.00E+00	0.00E+00
PAH, polycyclic aromatic hydrocarbons	g	3.88E+00	0.00E+00	0.00E+00
Particulates, < 2.5 um	g	2.89E+02	2.86E+02	0.00E+00
Particulates, > 2.5 um, and < 10um	g	2.29E+03	2.74E+02	0.00E+00
Pentane	g	0.00E+00	0.00E+00	0.00E+00
Pentane, 2,2,4-trimethyl-	g	0.00E+00	0.00E+00	0.00E+00
Pentane, 2-methyl-	g	0.00E+00	0.00E+00	0.00E+00
Phenanthrene	g	1.79E-12	4.05E-06	0.00E+00
Phenol	g	1.78E-16	0.00E+00	0.00E+00
Phenols, unspecified	g	2.95E-09	2.77E-03	0.00E+00
Phosphate	g	0.00E+00	0.00E+00	0.00E+00
Phosphoric acid	g	0.00E+00	0.00E+00	0.00E+00
Phosphorus	g	5.95E-09	0.00E+00	0.00E+00
Phthalate, dioctyl-	g	8.12E-16	0.00E+00	0.00E+00
Propanal	g	4.23E-15	0.00E+00	0.00E+00
Propane	g	0.00E+00	0.00E+00	0.00E+00
Propene	g	5.96E+01	0.00E+00	0.00E+00
Propionic acid	g	0.00E+00	0.00E+00	0.00E+00

Table B4. Emission to air LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Propylene oxide	g	0.00E+00	0.00E+00	0.00E+00
Pyrene	g	2.19E-13	4.95E-07	0.00E+00
Radioactive species, unspecified	MBq	3.83E-08	8.55E-02	0.00E+00
Radionuclides (Including Radon)	g	5.60E-08	1.27E-01	0.00E+00
Selenium	g	2.18E-09	2.53E-03	0.00E+00
Styrene	g	2.78E-16	0.00E+00	0.00E+00
Sulfur dioxide	g	1.38E-04	2.67E+02	0.00E+00
Sulfur hexafluoride	g	0.00E+00	0.00E+00	0.00E+00
Sulfur trioxide	g	0.00E+00	0.00E+00	0.00E+00
Sulfuric acid	g	0.00E+00	0.00E+00	0.00E+00
Sulfuric acid, dimethyl ester	g	5.34E-16	0.00E+00	0.00E+00
Sulfur oxides	g	3.66E+03	5.16E+02	0.00E+00
t-Butyl methyl ether	g	3.89E-16	0.00E+00	0.00E+00
Tar	g	0.00E+00	0.00E+00	0.00E+00
Terpenes	g	0.00E+00	0.00E+00	0.00E+00
TOC, Total Organic Carbon	g	0.00E+00	0.00E+00	0.00E+00
Toluene	g	9.44E+00	0.00E+00	0.00E+00
Toluene, 2,4-dinitro-	g	3.11E-18	0.00E+00	0.00E+00
Toluene, 2-chloro-	g	0.00E+00	0.00E+00	0.00E+00
Trimethylamine	g	0.00E+00	0.00E+00	0.00E+00
Vinyl acetate	g	8.45E-17	0.00E+00	0.00E+00
VOC, volatile organic compounds	g	1.88E+03	2.55E+02	0.00E+00
Xylene	g	6.58E+00	0.00E+00	0.00E+00
Zinc	g	5.96E-10	2.17E-05	0.00E+00

Table B5. Emission to land LCI results of wood structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Other Solid Waste	kg	3.92E+01	9.48E+00	0.00E+00
Solid Waste to Landfill	kg	1.03E+05	0.00E+00	0.00E+00

Table B6. Emission to water LCI results of wood structure model at the end-of-life stage.

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
2-Hexanone	mg	2.89E+01	6.45E+00	0.00E+00
Acetone	mg	4.43E+01	9.88E+00	0.00E+00
Acids, unspecified	mg	0.00E+00	0.00E+00	0.00E+00
Aluminum	mg	3.97E+05	8.59E+04	0.00E+00
Ammonia	mg	8.43E+04	1.86E+04	0.00E+00
Ammonia, as N	mg	0.00E+00	0.00E+00	0.00E+00
Ammonium, ion	mg	4.15E+01	0.00E+00	0.00E+00
Antimony	mg	2.48E+02	5.36E+01	0.00E+00
Arsenic, ion	mg	1.22E+03	2.71E+02	0.00E+00
Barium	mg	5.43E+06	1.18E+06	0.00E+00
Benzene	mg	7.42E+03	1.66E+03	0.00E+00
Benzene, 1-methyl-4-(1-methylethyl)-	µg	4.42E+02	9.87E+01	0.00E+00
Benzene, ethyl-	mg	4.18E+02	9.32E+01	0.00E+00
Benzene, pentamethyl-	µg	3.32E+02	7.40E+01	0.00E+00
Benzenes, alkylated, unspecified	mg	2.18E+02	4.71E+01	0.00E+00
Benzoic acid	mg	4.49E+03	1.00E+03	0.00E+00
Beryllium	mg	6.87E+01	1.51E+01	0.00E+00
Biphenyl	µg	1.41E+04	3.05E+03	0.00E+00
BOD5, Biological Oxygen Demand	mg	8.14E+05	1.81E+05	0.00E+00
Boron	mg	1.39E+04	3.10E+03	0.00E+00
Bromide	mg	9.48E+05	2.12E+05	0.00E+00
Cadmium, ion	mg	1.81E+02	4.00E+01	0.00E+00
Calcium, ion	mg	1.42E+07	3.17E+06	0.00E+00
Chloride	mg	1.60E+08	3.57E+07	0.00E+00
Chromium	mg	1.06E+04	2.27E+03	0.00E+00
Chromium VI	µg	4.45E+04	9.56E+03	0.00E+00
Chromium, ion	mg	6.86E+02	1.67E+02	0.00E+00
Cobalt	mg	9.81E+01	2.19E+01	0.00E+00
COD, Chemical Oxygen Demand	mg	1.56E+06	3.44E+05	0.00E+00
Copper, ion	mg	1.27E+03	2.79E+02	0.00E+00
Cyanide	mg	3.19E-01	7.13E-02	0.00E+00
Decane	mg	1.29E+02	2.88E+01	0.00E+00
Detergent, oil	mg	3.69E+03	8.29E+02	0.00E+00
Dibenzofuran	µg	8.41E+02	1.88E+02	0.00E+00
Dibenzothiophene	µg	4.35E+01	1.52E+01	0.00E+00

Table B6. Emission to water LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Dissolved solids	mg	1.97E+08	4.40E+07	0.00E+00
DOC, Dissolved Organic Carbon	mg	1.04E+04	0.00E+00	0.00E+00
Docosane	µg	4.74E+03	1.06E+03	0.00E+00
Dodecane	mg	2.45E+02	5.46E+01	0.00E+00
Eicosane	mg	6.74E+01	1.50E+01	0.00E+00
Fluorene, 1-methyl-	µg	5.04E+02	1.12E+02	0.00E+00
Fluorenes, alkylated, unspecified	µg	1.26E+04	2.73E+03	0.00E+00
Fluoride	mg	2.16E+00	0.00E+00	0.00E+00
Fluorine	µg	6.21E+03	1.35E+03	0.00E+00
Hexadecane	mg	2.67E+02	5.96E+01	0.00E+00
Hexanoic acid	mg	9.30E+02	2.08E+02	0.00E+00
Hydrocarbons, unspecified	µg	0.00E+00	0.00E+00	0.00E+00
Hydrogen chloride	mg	0.00E+00	0.00E+00	0.00E+00
Hydrogen sulfide	mg	9.31E-01	0.00E+00	0.00E+00
Iron	mg	7.86E+05	1.71E+05	0.00E+00
Lead	mg	2.61E+03	5.71E+02	0.00E+00
Lead-210/kg	µg	4.60E-04	1.03E-04	0.00E+00
Lithium, ion	mg	4.75E+03	4.18E+04	0.00E+00
m-Xylene	mg	1.34E+02	2.99E+01	0.00E+00
Magnesium	mg	2.78E+06	6.20E+05	0.00E+00
Manganese	mg	4.43E+03	1.01E+03	0.00E+00
Mercury	µg	4.38E+03	9.40E+02	0.00E+00
Metallic ions, unspecified	mg	0.00E+00	0.00E+00	0.00E+00
Methane, monochloro-, R-40	µg	1.78E+02	3.98E+01	0.00E+00
Methyl ethyl ketone	µg	3.56E+02	7.95E+01	0.00E+00
Molybdenum	mg	1.02E+02	2.27E+01	0.00E+00
n-Hexacosane	µg	2.95E+03	6.59E+02	0.00E+00
Naphthalene	mg	8.06E+01	1.80E+01	0.00E+00
Naphthalene, 2-methyl-	mg	7.01E+01	1.56E+01	0.00E+00
Naphthalenes, alkylated, unspecified	µg	3.56E+03	7.71E+02	0.00E+00
Nickel	mg	1.22E+03	2.68E+02	0.00E+00
Nitrate	mg	1.09E+01	0.00E+00	0.00E+00
Nitrate compounds	mg	0.00E+00	0.00E+00	0.00E+00
Nitric acid	mg	0.00E+00	0.00E+00	0.00E+00
Nitrogen	mg	6.50E+01	0.00E+00	0.00E+00

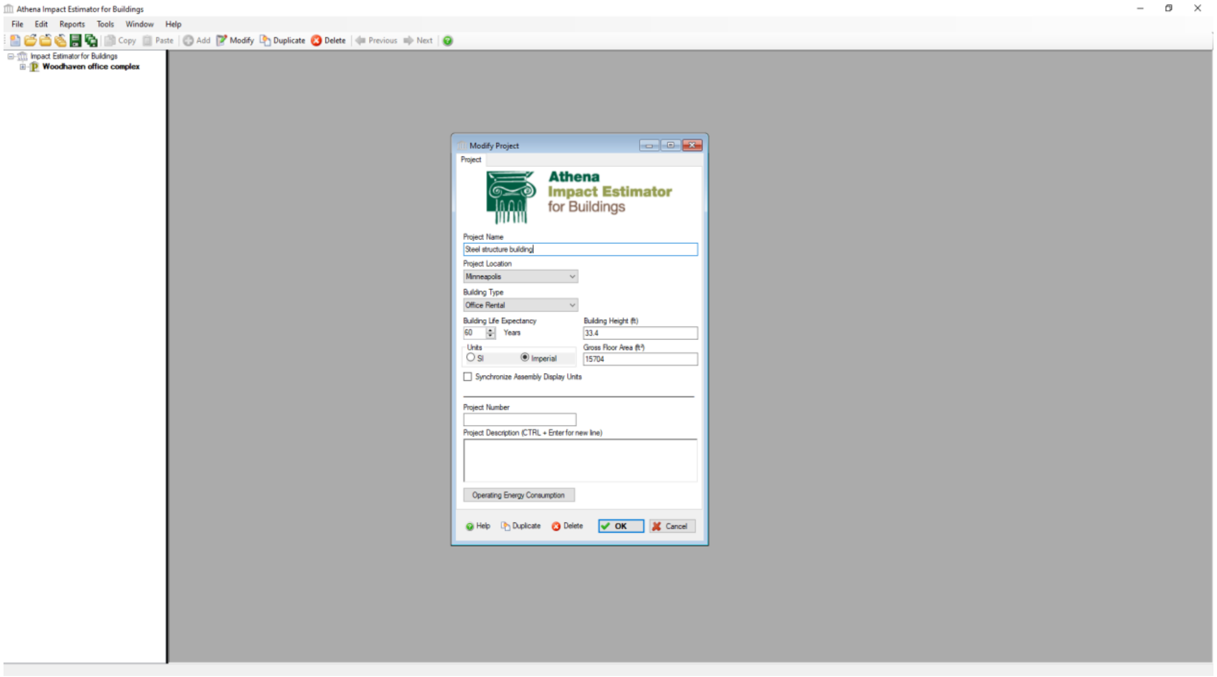
Table B6. Emission to water LCI results of wood structure model at the end-of-life stage (continued).

Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
o-Cresol	mg	1.27E+02	2.84E+01	0.00E+00
Octadecane	mg	6.60E+01	1.47E+01	0.00E+00
Oils, unspecified	mg	1.03E+05	2.28E+04	0.00E+00
p-Cresol	mg	1.37E+02	3.07E+01	0.00E+00
PAH, polycyclic aromatic hydrocarbons	µg	0.00E+00	0.00E+00	0.00E+00
Pentanone, methyl-	mg	1.86E+01	4.15E+00	0.00E+00
Phenanthrene	µg	1.26E+03	2.76E+02	0.00E+00
Phenanthrenes, alkylated, unspecified	µg	1.48E+03	3.20E+02	0.00E+00
Phenol	µg	1.97E+06	4.23E+05	0.00E+00
Phenol, 2,4-dimethyl-	mg	1.24E+02	2.77E+01	0.00E+00
Phenols, unspecified	mg	2.77E+02	7.64E+01	0.00E+00
Phosphate	mg	2.42E-01	0.00E+00	0.00E+00
Phosphorus	mg	0.00E+00	0.00E+00	0.00E+00
Radioactive species, Nuclides, unspecified	mg	0.00E+00	0.00E+00	0.00E+00
Radium-226/kg	µg	1.60E-01	3.57E-02	0.00E+00
Radium-228/kg	µg	8.18E-04	1.82E-04	0.00E+00
Selenium	µg	4.81E+04	1.04E+04	0.00E+00
Silver	mg	9.30E+03	2.07E+03	0.00E+00
Sodium, ion	mg	4.51E+07	1.01E+07	0.00E+00
Solids, inorganic	mg	0.00E+00	0.00E+00	0.00E+00
Strontium	mg	2.41E+05	5.39E+04	0.00E+00
Sulfate	mg	3.22E+05	7.18E+04	0.00E+00
Sulfide	mg	2.29E+02	4.91E+01	0.00E+00
Sulfur	mg	1.17E+04	2.62E+03	0.00E+00
Sulfuric acid	mg	0.00E+00	0.00E+00	0.00E+00
Suspended solids, unspecified	mg	1.22E+07	2.64E+06	0.00E+00
Tar	mg	0.00E+00	0.00E+00	0.00E+00
Tetradecane	mg	1.07E+02	2.39E+01	0.00E+00
Thallium	µg	5.22E+04	1.13E+04	0.00E+00
Tin	mg	9.95E+02	2.18E+02	0.00E+00
Titanium, ion	mg	3.81E+03	8.24E+02	0.00E+00
Toluene	mg	7.01E+03	1.57E+03	0.00E+00
Vanadium	mg	1.20E+02	2.68E+01	0.00E+00
Xylene	mg	3.68E+03	7.90E+02	0.00E+00

Table B6. Emission to water LCI results of wood structure model at the end-of-life stage (continued).

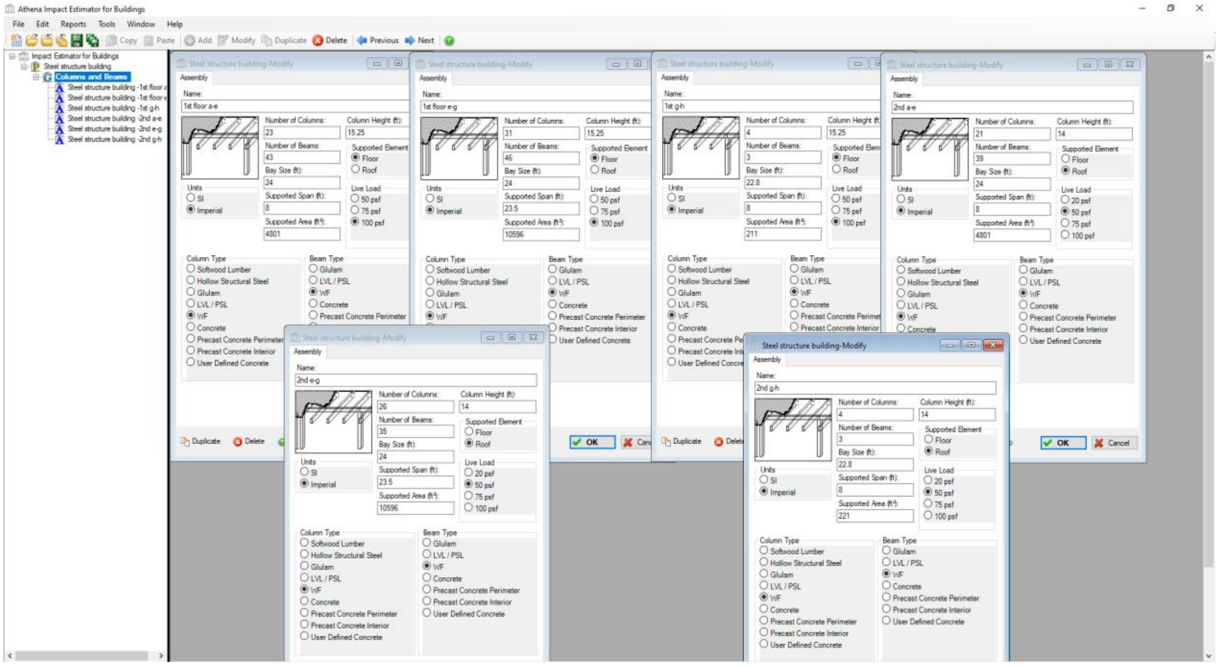
Emission	Unit	De-construction, Demolition, Disposal	Transport	BBL Material
Yttrium	mg	2.98E+01	6.66E+00	0.00E+00
Zinc	mg	9.14E+03	1.98E+03	0.00E+00

APPENDIX C. THE RUNNING PROCESS OF THE SOFTWARE



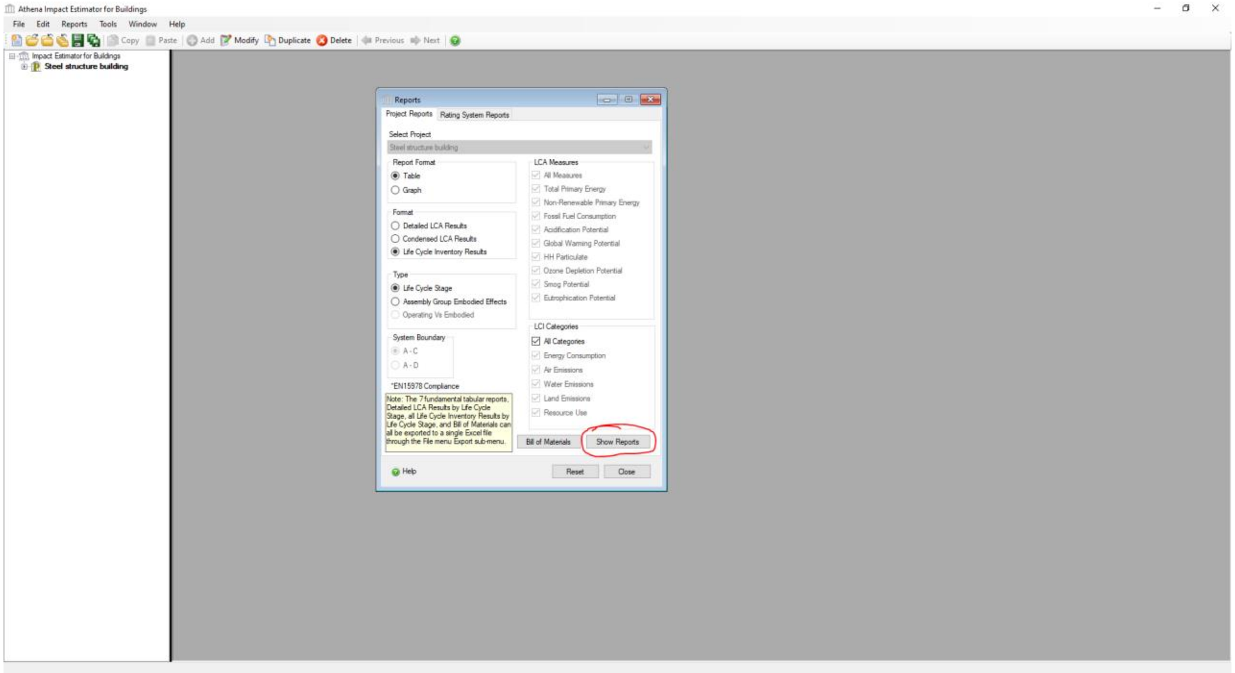
Project Name: Steel structure building
Project Location: Minneapolis
Building Type: Office Rental
Building Life Expectancy: 60 Years
Building Height (ft): 33.4
Units: ○ SI ● Imperial
Gross Floor Area (ft²): 15704
☐ Synchronize Assembly Display Units
Project Number:
Project Description (CTRL + Enter for new line):

Figure C1. Step 1 Input the basic information of building to the software.



Name:	1st floor a-e	1st floor e-g	1st g-h	2nd a-e	2nd e-g	2nd g-h
Number of Columns:	23	31	4	21	26	4
Column Height (ft):	15.25	15.25	15.25	14	14	14
Number of Beams:	43	46	3	39	35	3
Bay Size (ft):	24	24	22.8	24	24	22.8
Supported Span (ft):	8	23.5	8	8	23.5	8
Supported Area (ft²):	4801	10596	211	4801	10596	221
Supported Element	● Floor	● Floor	● Floor	● Roof	● Roof	● Roof
Live Load	● 100 psf	● 100 psf	● 100 psf	● 50 psf	● 50 psf	● 50 psf
Units	● Imperial	● Imperial	● Imperial	● Imperial	● Imperial	● Imperial
Column Type	● WF	● WF	● WF	● WF	● WF	● WF
Beam Type	● WF	● WF	● WF	● WF	● WF	● WF

Figure C2. Step 2 Input the information of beams and columns to the software.



Select Project: Steel structure building

Report Format
● Table
○ Graph

Format
○ Detailed LCA Results
○ Condensed LCA Results
● Life Cycle Inventory Results

Type
● Life Cycle Stage
○ Assembly Group Embodied Effects
○ Operating Vs Embodied

System Boundary
● A - C
○ A - D

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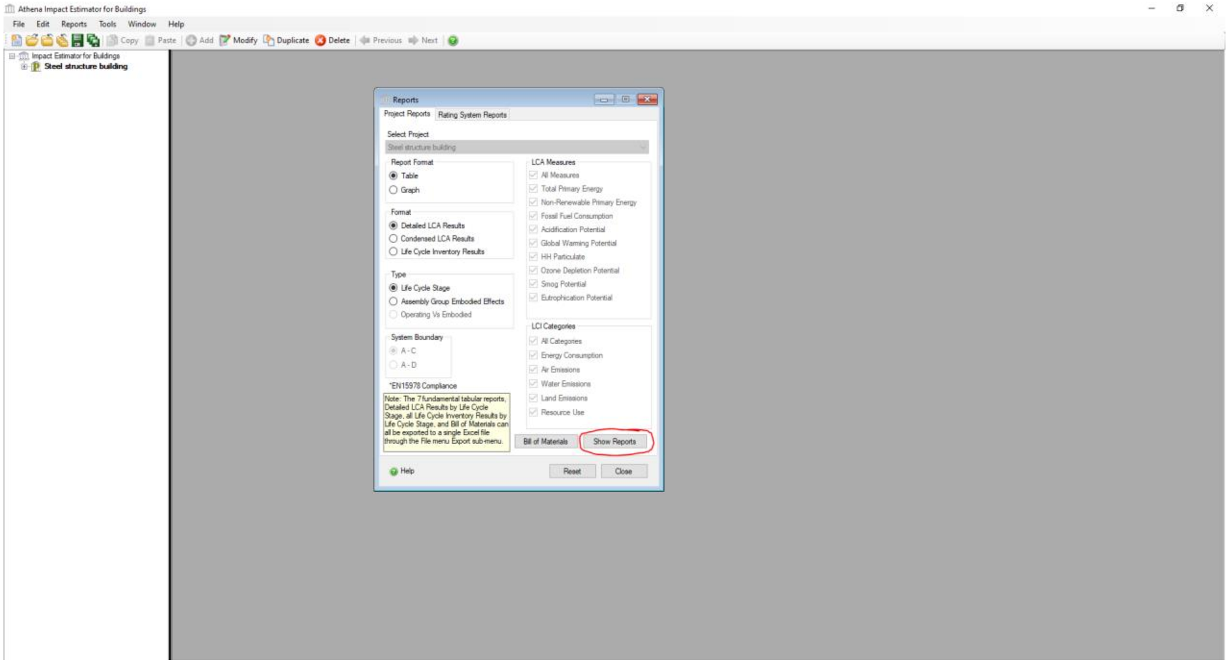
Note: The 7 fundamental tabular reports, Detailed LCA Results by Life Cycle Stage, all Life Cycle Inventory Results by Life Cycle Stage, and Bill of Materials can all be exported to a single Excel file through the File menu Export sub-menu.

LCA Measures
☑ All Measures
☑ Total Primary Energy
☑ Non-Renewable Primary Energy
☑ Fossil Fuel Consumption
☑ Acidification Potential
☑ Global Warming Potential
☑ HH Particulate
☑ Ozone Depletion Potential
☑ Smog Potential
☑ Eutrophication Potential

LCI Categories
☑ All Categories
☑ Energy Consumption
☑ Air Emissions
☑ Water Emissions
☑ Land Emissions
☑ Resource Use

Figure C3. Step 3 Click Show Reports will get the results of LCI.



Select Project: Steel structure building

Report Format
● Table
○ Graph

Format
● Detailed LCA Results
○ Condensed LCA Results
○ Life Cycle Inventory Results

Type
● Life Cycle Stage
○ Assembly Group Embodied Effects
○ Operating Vs Embodied

System Boundary
● A - C
○ A - D

*EN15978 Compliance

Note: The 7 fundamental tabular reports, Detailed LCA Results by Life Cycle Stage, all Life Cycle Inventory Results by Life Cycle Stage, and Bill of Materials can all be exported to a single Excel file through the File menu Export sub-menu.

LCA Measures
☑ All Measures
☑ Total Primary Energy
☑ Non-Renewable Primary Energy
☑ Fossil Fuel Consumption
☑ Acidification Potential
☑ Global Warming Potential
☑ HH Particulate
☑ Ozone Depletion Potential
☑ Smog Potential
☑ Eutrophication Potential

LCI Categories
☑ All Categories
☑ Energy Consumption
☑ Air Emissions
☑ Water Emissions
☑ Land Emissions
☑ Resource Use

Figure C4. Step 4 Click Show Reports will get the results of LCIA.