Embodied Energy Assessment of Building Structural Systems using Building Information Modeling

by

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Author's Declaration

I hereby declare that I am the sole author of the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

As the population of the world increases, the need to develop sustainable housing has gained worldwide attention. Although buildings contribute to socio-economic development, they are also among the biggest consumers of energy and contributors to the greenhouse gas emissions. Building construction projects are typically recognized for substantial consumption of natural resources and energy consumption. The most common structural materials used in the Canadian construction industry are steel, reinforced concrete, and engineered wood. Cost, the speed of construction, and the mechanical performance have been usually the main criteria when selecting a building's structural system, with the environmental impact of the structural material typically ignored. Environmental impact is overlooked mainly because the industry lacks a documented framework, similar to cost estimation and scheduling, for assessment. Although there are several studies that have studied energy consumption of buildings, they mostly focused on the operational energy, since it has the highest energy consumption in a building life cycle. This research project introduces a framework for the environmental assessment of structural materials, in which it calculates the embodied energy of the material production and construction as the main parameter for comparison. This assessment tool is implemented using a building information modelling platform to automate the process. This method considers all the main factors in estimation of the embodied energy, including production, transportation, installation/construction, and wastage of the material. A case study on two typical residential buildings with a similar layout but different structural systems were carried out to assess the practical use of this approach in the design stage. This system demonstrated an easy-to-use process to estimate embodied energy of the structural material using the building information model of the structure. The results indicate that the manufacturing stage has the most significant

impact on the embodied energy and GHG emissions of the building structures. In addition, integration of the building information modeling to the assessment system could facilitate the embodied energy assessment process for decision makers.

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List of Abbreviations

BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Method
CFA	Conditioned Floor Area
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
ECF	Energy consumption factor
EC	Embodied Carbon
EE	Embodied Energy
EPD	Environmental Product Declaration
FU	Functional Unit
GHG	Greenhouse Gas
GHP	Gross engine Horsepower
GWP	Global Warming Potential
IFC	Industry Foundation Classes
KPL	Weight of fuel
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LF	Load Factor
LMPH	Liters used per Machine Hour
N_2O	Nitrous Oxide
OE	Operational Energy
PED	Primary Energy Demand
QTO	Quantity Take-Offs

List of Symbols

D_i – Transportation distance of material i

E_C – Energy consumption in construction phase

E_i – Energy usage of equipment i

E_{IP} – Energy consumed in installation process

E_{LP} – Energy consumed in lifting process

E_M – Energy consumption in manufacturing phase

E_T – Energy consumption in transportation stage

EC_i – Embodied carbon coefficient of material i

EC^t_i – Energy consumption per kilometer per ton of material i

EC_{LP} – Emissions in lifting process

ECF_i – Energy consumption factor of selected equipment i

EE_i – Embodied energy coefficient of material i

EF^t_i – Greenhouse gas emissions per kilometer per ton of material i

GHG_M – Greenhouse gas emissions during manufacturing phase

GHG_T - Greenhouse gas emissions during Transportation stage

m_i – Quantity of material i required

T_i – Equipment working hour

T_{IP} – Equipment working time in installation process

T_{LP} – Equipment working time in lifting process

T_P – Working hour of concrete placement

P^c_i – Labor productivity of placing concrete for component i

V_i – Volume of component i

CHAPTER 1 – Introduction

The importance of sustainable building development is gaining widespread attention worldwide. Building projects have significant impacts on the environment as they consume resources and energy in one form or another throughout their entire life cycle. One major concern for engineers has been the design of more energy-efficient houses that produce less greenhouse gas emissions. Buildings use energy either directly or indirectly throughout their entire lifecycle. The direct uses of energy occur in the construction, habitation/operation, maintenance and renovations, and subsequent demolition throughout the end of the building life. Figure 1 demonstrates different stages of the lifecycle of a building project.

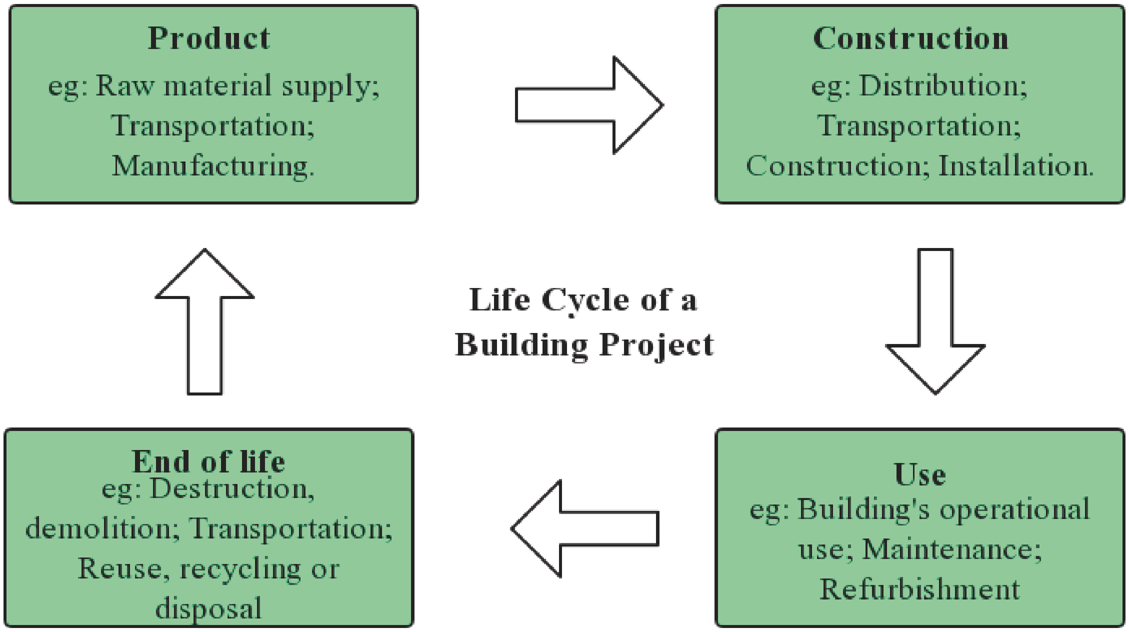


Figure 1: The life cycle stages of a building

Energy is also indirectly used by buildings through the production of the construction materials and other embodied energy (Sartori and Hestnes, 2007). Every aspect of built environment systems has environmental consequences, and it is reported that 70%-80% of resources that are produced in the world are directly or indirectly linked to buildings (Baccini, 1997). The production, transportation, and utilization of the items used in buildings emit greenhouse gasses and contribute to global warming. A study conducted in the United States in 2009 indicated that 20% of the total U.S. energy-related GHG emissions are associated with the construction and operation of commercial buildings (Stadel et al., 2012). This is an important finding considering the fact that the United States is one of the top producers of greenhouse gasses in the world, and the race to prevent the two-degree Celsius temperature rise threshold is gaining attention (Nanda, 2012). The construction industry constitutes 40% of the global economy, which translates to 40-50% of total greenhouse gas emissions (CIWMB, 2000).

Structural performance, cost, and the speed of construction have generally been the main criteria for the selection of a structural system for a building project, and the environmental impact of the structural material is usually ignored. This is mainly due to the lack of a documented system, similar to cost estimation and scheduling (such as Critical Path Method), to assess such impacts. Research attempts to study the environmental impact of buildings are limited, and there are two practical issues in the existing assessment methods: (1) The process of assessment is performed manually by engineers/researchers. This approach is time-consuming and fallible for construction projects because it includes a considerable data collection task and a large number of manual calculations; (2) Current sustainability assessment of buildings primarily focuses on energy usage and emissions in the operation and maintenance stages, which account for the majority of total energy consumption and emissions during the entire life cycle of buildings. However, the assessment for the construction phase is usually incomplete.

1.1. Research Objectives

The main objective of this research is to develop a building information modeling (BIM) based framework that automates calculation of the embodied energy and greenhouse gas emission of the structural construction of a building project. The second objective is to provide building designers a tool to make decision among different structural systems based on environment impacts of each system. To achieve these objectives, the framework should:

- Include an inventory of the carbon and energy database of common building materials;
- Identify the category and attributes of the material used in structural building elements, and collect corresponding carbon and energy data from the database;
- Calculate energy consumption and emissions during different stages of structural building construction, including manufacturing, transportation, and construction;
- Apply appropriate computing methods according to different structural systems.

1.2. Research Methods

The following steps will be followed to achieve the objectives:

- Assess the current state of environmental impact assessment methods in building construction projects and identify shortcomings and areas for improvement;
- Collect the required data from existing literature and create database for the proposed framework;
- Develop a framework to automatically identify structural material, extract energy and emission data, and calculate energy consumption using proper approach;
- Assess the framework in two different building structural samples (steel-framed and reinforced concrete-framed);
- Compare total embodied energy and greenhouse gas emissions of the sample buildings

during three main stages (material manufacture, transportation, and structural assemblies) to assess environmental impacts of the test cases;

- Identify the limitations of the system and propose future research directions.

The research methodology for this study is portrayed in Figure 2. First, it defines the problem statement, research objectives and the scope of the project. Next, the literature review is carried out to assess current state of embodied energy and environmental impacts assessment methods in different stages of building life cycle. In addition, the required data to calculate embodied energy and greenhouse gas (GHG) emissions are collected. Next, three modules are developed to assess energy consumption and GHG emissions for each stage, and the modules are integrated to develop the BIM-based embodied energy assessment framework. This framework is used to compare energy usage and GHG emissions among two different structural systems (steel frame and concrete frame). Finally, the findings, advantages, and limitations of this study were discussed and future research directions are highlighted.

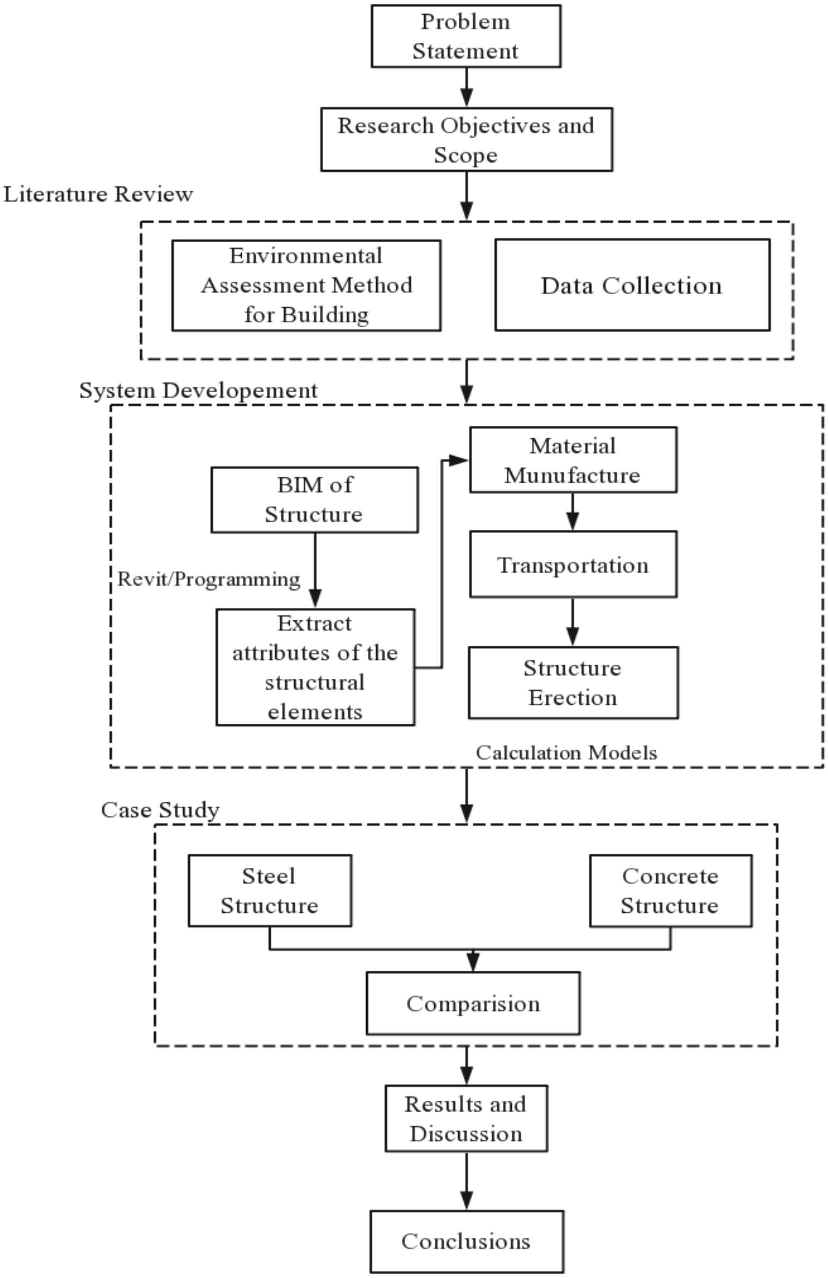


Figure 2: Methodology of research

1.3. Research Scope

The life cycle of a building includes a number of stages, namely design and planning, manufacturing, construction, operation/rehabilitation, and demolition. Planning is crucial in building projects especially considering sustainability within the stages of the life cycle. Stakeholders such as owners and designers hold regular meetings during the planning process to exchange ideas and compare notes to optimize building performance and sustainability. For instance, decision makers can identify different ways of reducing building costs. The design phase takes place after understanding the necessary requirements needed for sustainable construction. During the design stage, layout, elements, materials, and electrical and mechanical systems for the building are defined. Engineers and architectures develop a design detailing how the building will look and function. The importance of the design phase is to find out if the structure will meet technical and functional requirements. Engineers are supposed to produce conceptual ideas that contribute to high performance.

The manufacturing phase consists of the required activities in manufacturing of building materials and components from raw material acquisition to the production of elements. The construction phase involves the transportation of materials and components from the manufacturing plant or distribution centers to the construction site, and the related handling and erection/installation processes. In the operation phase, heating, cooling, lighting, and refurbishment and maintenance services mainly contribute to the environmental impacts and energy consumption. Finally, the last phase is demolition which includes the destruction processes and transportation of dismantled materials to landfills or recycling plants. In this study, manufacturing and construction phases of the structural system of buildings are considered (Figure 3). Energy used in the operation and demolition phases will not be covered.

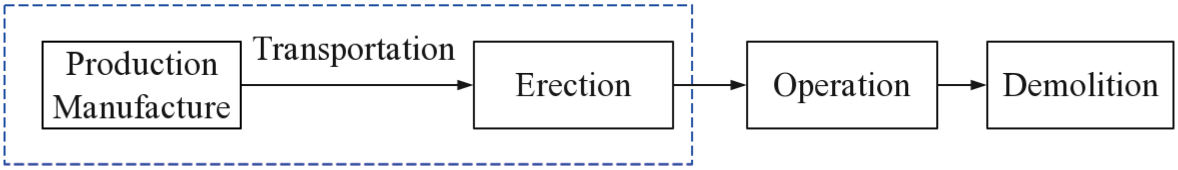


Figure 3: Research scope of thesis

The embodied energy of building structural systems can be expressed as:

$$EE = E_M + E_C \tag{1}$$

Where,

EE — Embodied energy of the new building;

E_M — Energy used in material manufacturing process;

E_C — Energy used in building construction process.

1.4. Outline of the thesis

This thesis comprises six chapters. Chapter 1 introduces the research and provides the outline of this research project. Chapter 2 presents the current state of knowledge related to building sustainability assessment. Data sources used in this study are also listed in this chapter. Chapter 3 describes the methodology for BIM-based assessment framework of building structural sustainability. Chapter 4 presents the application of the proposed methodology in two sample construction projects, in which both have the same layout but designed with different structural systems. Chapter 5 discusses the embodied energy and emission results obtained from Chapter 4 for each phase of their construction process. Chapter 6 (Conclusion and Recommendations) summarizes the research, discusses its contributions and limitations, and suggests recommendations for future research works.

CHAPTER 2: Literature Review

This chapter provides background information on the previous research for building sustainability assessment. The first section looks at the existing sustainability rating systems of building construction. Further, the second section briefly introduces the life cycle assessment (LCA), which is the most commonly used methodology to collect data and report information about the environmental impacts of buildings, and section three focuses on comparing embodied energy (EE) and operational Energy (OE) of buildings. Next, studies on the environmental assessment of different structural systems are investigated. Finally, section five discusses building information modeling and the opportunities of using BIM for building sustainability assessment.

2.1. Building sustainability assessment

The modern construction industry has been ushered into green building. It is estimated that in the United States, there were close to 80 million buildings in 2002, which consumed 36% of the country's primary energy (Kibert, 2008). Furthermore, these buildings generated large amounts of waste in construction and operation phases, indicating that they utilize energy inefficiently and emit large amounts of greenhouse gases and pollutants (USGBC, 2015). The idea of green building can be traced to 1960s. Green building is defined as "*the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's lifecycle from sitting to design, construction, operation, maintenance, renovation and deconstruction*" (EPA, 2016). Green building is also defined as the practice to increase efficiency of building in regards to consumed materials, water, and energy in order to reduce the building's impacts on environment and human health (Fischer, 2010). Green building is achieved through incorporating sustainability concepts in design, construction, maintenance, operation, and demolition processes within the building lifecycle. In other words, green building is sustainable building.

Efficiency of energy use is a mandate from some state and local energy codes for the new and renovated buildings that should comply with the established requirements. Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) are the most popular methods for the assessment of building's sustainability. LEED was established by the U.S Green Building Council (USGBC); it was meant to provide building contractors, operators and owners with a precise framework used in identifying and implementing measurable and practical green building design, construction, operations, and maintenance solutions. Between 1994 and 2015, LEED grew to a system with interrelated standards touching on aspects of both design and construction of buildings. BREEAM originated in the United Kingdom in 1988, but the initial version was launched in 1990 to assess office buildings. Each of these assessment methods has its own strength and weakness given that there are different business models and philosophies (Rezaallah et al, 2012). Some practitioners in the construction industry have argued whether LEED certified buildings are more efficient when it comes to the use of energy against regular buildings (Newsham et al., 2009; Scofield, 2009). LEED is known to help contractors in solving building problems and make improvements on building performance over a long period of time (Stefano & Sergio, 2013). The guidelines for LEED require two energy models which represent the designed building and a baseline building. The requirement of the baseline building is to model it within the same location, occupancy, and geometry requirements similar to the main building design. The ultimate goal of this method is to provide a baseline building as a reference point of comparison against the design option. Buildings with LEED certification use a modeling software for predicting future use of energy based on the intention of use.

BREEAM is used for the environmental performance assessment of both existing and new buildings (Roderik et al., 2009). This assessment method provides building scores in relation to its performance against a certain set of criteria. The assessment consists of two stages: first is the assessment of the design, leading to provisional ratings, and the second stage is a post construction assessment that leads to final ratings. Both LEED and BREEAM are assessment methods used in design, construction, and operation phases.

2.2. Life Cycle Assessment

Life-Cycle Assessment (LCA) is a methodology used in the construction industry which attempts to assess all processes involved in the life cycle of a building from raw material extraction to the last stage of demolition waste disposal. LCA can be used for the evaluation of environmental concerns in the construction industry (Kohler and Moffatt, 2003). Also, LCA is a method of evaluation for products and environmental processes within an entire building product life-cycle (Trusty, 2004). The assessment is inclusive of the whole life-cycle, systems and processes including raw material processing and extraction, manufacturing, transportation, maintenance, recycling, and disposal. LCA is a widely used method due to its nature of integrated data quality and impact assessment (Peuportier, 2001). From the point of view of ISO 14040, LCA method has distinctive analytical procedures, such as definition of scope and goals, life-cycle inventory creation, assessment of its impacts and interpretation of final results (ISO, 2006). LCA has been defined by ISO 14040 as a framework for assessment of environmental features including potential impacts related to production. In other words, the LCA evaluates environmental impacts and interprets inventory analysis results (Asif et al., 2007). The ISO 14040 standards offer procedural terms in which LCA begins with defining a functional unit for quantitative inputs and outputs inventory. The second step is to classify and assess environmental impacts of buildings under study (Bribian et al., 2009). LCA has been used to address issues such as excessive consumption of global resources, from construction and building operation to the pollution of the surrounding environment (Ahn et al., 2010).

At the same time, sustainability is also about focusing on minimizing required resources and energy, thus reducing environmental damage. LCA is therefore a framework used in comparing alternative services, components and materials in building. Different needs of users, complexity and subjectivity led to development of LCA-based tools to simplify conducting building materials environmental assessment. These tools are the same as environmental modeling software known to create and show a life cycle inventory (Bayer et al., 2010). These tools follow ISO standards and other accepted LCA guidelines. LCA tools are defined into three levels (Anastaselos et al, 2009; Ortiz et al., 2009 and Bayer et al., 2010): The first level consists of environmental performance evaluation tools for material. These tools are used to identify building materials' environmental traits and for comparison and selection of building materials. Level 2 relates to decision making tools for building design within a life cycle framework. These are software packages used for assessing environmental impacts by evaluating building assemblies and geometry input. The calculated results for the designed building are combined and presented in terms of environmental effects. This assessment includes environmental impacts of different stages of the life cycle of a building. They can compare different building design options and help engineers in the initial designing stages (Bayer et al, 2010). Level 3 tools mainly offer frameworks for assessment of buildings' environmental performance based on a set of predetermined criteria. The frameworks used in assessing building impacts on the environment, such as BREEAM and LEED, are widely used in promoting green building designs

(Ding, 2014).

2.3. Embodied Energy (EE) vs Operational Energy (OE)

In the construction industry, building embodied energy is considered in the process of life-cycle assessment. Embodied energy is the total amount of energy needed to produce a product with the assumption that the energy is incorporated within the product itself (Haynes, 2010). This concept is normally used to determine the effectiveness of energy saving methods or energy producing systems in building expenses. The general perspective is that the service operations and maintenance in the building lifecycle consume much more energy compared to construction processes (Cole, 2005). Generally, the operational energy accounts for 80%-90% of a building life cycle energy demand and the embodied energy takes 10%-20% of the total (Ramesh et al., 2010). The main reason for the larger proportion of the operational energy is the long service life of buildings, as it is estimated that the service life of a building is usually more than 76 years (O'Connor, 2004). While, the embodied energy is one-time energy consumption during the manufacturing and construction phase. The proportion of embodied energy in total lifecycle energy depends on the climate of the building location (Nebel et al. 2011). For example, in Negev desert region in Israel, the embodied energy of climatically responsive buildings is about 60% of the total lifecycle energy with a service life of 50 years (Huberman and Pearlmutter, 2008), whereas in a heating-dominated region like the United Kingdom, the embodied energy is only about 10% of the total lifecycle energy (Plank, 2008).

The main purpose of measuring the quantity of embodied energy is to determine the energy amount consumed in the production process and compare the energy savings by selection of a certain option. Embodied energy is supposed to account for the energy necessary within life-cycle of a product (Pöyry et al., 2015; Monteiro, 2015).

On the other hand, operational energy is the amount of renewable and non-renewable energy required annually to operate a building in its life cycle. This type of energy is mainly used for cooling, ventilation, heating, lighting, and hot-water production whereas embodied energy is primarily non-renewable energy needed in the extraction of raw resources and conversion into finished products. Embodied energy and operational energy are gauged on the basis of primary energy: the embodied energy is a onetime consideration, operational energy is accumulated over the building's lifetime (Canadian Wood Council, 2004). Operational energy is commonly measured based on Conditioned Floor Area (CFA) (Hammond and Jones, 2008). It is concluded that content of embodied energy of a building is smaller than its operational energy (Thormark, 2002). It is suggested that estimating embodied energy is more complex and time consuming than operational energy (Langston & Langston, 2008), and no generally accepted method is available to calculate the embodied energy accurately and consistently (Crowther, 1999; Miller, 2001).

2.3.1. Energy consumption and environmental impacts of manufacturing and construction phase

Embodied energy has been established as the energy consumed by the processes linked to manufacturing, transportation, and on-site construction activities. The manufacturing stage accounted for the largest portion of emissions and embodied energy relating to building product life-cycle (Anderson & Thornback, 2012). This phase is known to begin with delivering raw materials to the processing plant and ends with delivering the building products to retailers. It involves processes relating to the extraction or production of raw materials such as steel, wood, aluminum, and concrete, among others. This stage also entails transporting raw materials to the processing site and converting into finished products.

The construction phase could be equated as an additional step of manufacturing in which the products, sub-assemblies and components are put together to construct a whole building. This phase begins with transporting components and products to building sites from centers of distribution. The actual distance of transportation to the building sites must be covered in LCA process of the construction phase (Kohler and Moffatt, 2003; Cole, 2005; Menzies et al., 2007; Ortiz and Castells, 2009), given that there is significant energy utilization leading to environmental impacts. Activities in the construction phase involve the use of equipment, such as mixers, pumps, and cranes used for concrete work and lifting. Construction processes need energy that can be divided into gasoline and diesel fuel, electricity, and natural gas (Sharrard et al., 2007). Fuel is consumed in the process of transportation of equipment, materials, and personnel to construction sites (Cole, 1998). Diesel and gasoline are normally used in the transportation. Construction heavy equipment, such as earthmoving machineries, concrete pumps, and mobile cranes, also use fuel for their operations.

The amount of energy consumed in construction depends on certain factors such as construction method, electricity availability, type of materials, and the size of the project. Energy consumption of electricity mainly takes place in the construction phase while CO_2 emissions result from transportation and handling of materials (Cole, 1998). Energy consumption and CO_2 emission in construction can be linked together (Chenga, 2011). The importance of calculating energy consumption and CO_2 emission is highlighted in various phases of construction and production (Cole, 1998; Haapio and Viitaniemi, 2008).

During the construction process, resources are consumed and thereafter environmental impacts are witnessed. Impacts on the environment are highly associated with activities on material extraction and during construction stage (Ametepey & Ansah, 2014). Effects on the environment, such as greenhouse emissions, are key factors described in the LCA to quantify the impacts. Sometimes, material extraction for building construction may cause temporary disturbances and might even cause long term land loss resulting in habitat fragmentation. Some of the materials used in construction such as copper, steel, and aluminum are examples of products linked to most pollutants and emissions (Calkins, 2008). Concrete is also considered to be one of the main contributors to greenhouse gas emissions given the high volumes consumed during construction (Ortiz et al., 2009). The impacts experienced from construction activities usually take place in extraction and processing of materials (Todd et al., 2001). On the contrary, waste management and demolition stages are associated with fewer environmental impacts (Coelho & Brito, 2012). The waste from construction may include unused material, waste water and domestic waste. Improper disposal of waste material from construction sites may cause land and soil degradation (Arslan et al. 2012).

2.3.2. Energy consumption and environmental impacts in operation phase

The operation stage includes features, such as the lighting, cooling, water use, heating, and operation of mechanical equipment (e.g. elevators and escalators), required to operate a building facility, as well as products such as paint and interior finishing (Muthu, 2015). Apart from building products used during the operation phase, there are other factors causing environmental impacts. Maintenance methods and types, and replacement and maintenance intervals also affect the environmental performance of a building (Marine, 2002). During maintenance, some areas of the building will be changed through renovation and repair processes, but some parts may not be touched until the time of demolition of the building. Research has ascertained that the consumption of energy during the operation phase has high environmental impacts (Shoubi et al, 2015). For instance, it was estimated that the operation phase is responsible for more than 50%

of GHG emissions in the whole lifecycle of a building (Sharma et al., 2011). Therefore, reduction of operational energy becomes the center stage of construction industry, prompting to build and design green buildings. It is argued that any decisions with regards to reducing energy consumption and emission of greenhouse gases should be made before or during construction stage (Ali & Al-Nsairat, 2009). Reducing thermal energy consumption in the operation stage needs high-efficiency windows plus floors, ceiling and walls insulation to increase building efficiency (Shoubi et al., 2015). Therefore, both embodied energy and operational energy should be considered when attempting to reduce the total energy consumption of a whole building lifecycle (Waldron, 2013).

A research effort reported that the operation stage accounts for approximately 65% of the environmental impact of the building lifecycle (Ali & Al-Nsairat, 2009). It recommends that operation stage should emphasize the use of building products and materials that consume less energy and cause fewer environmental impacts. Low energy buildings can be attained by reducing the amount of energy consumed in the operation phase through use of energy management technologies (Anastaselos et al., 2009). Watson (2009) recommended LEED buildings that could use up to 25% less amount of energy compared to conventional buildings in the operation phase. To summarize, the operation phase in conventional buildings consumes more energy compared to sustainable buildings.

2.4. Environmental assessment of different structural systems

There are different structural systems in building construction, namely reinforced concrete, steel and wood framing, and each of these have several sub-classes. Reinforced concrete-framed systems are the most common type of building structure at the international level (Kibert 2008; Sarma & Adeli, 2002; Kibert, 2003). Concrete is the most popular construction material due to the low cost, general availability, and fewer environmental impacts (Meyer, 2005). In addition, the inherent fire resistance of concrete is an advantage over other building materials (Bilow & Kamara, 2008). Nevertheless, concrete walls are known to be heavy; thus, some construction works choose drywall partitions with wood or light steel frames. Steel is another material used for structural framing. Its strength is a great advantage to building since it is ductile and does not usually have a brittle failure, namely it flexes under lateral earthquake or strong wind loads (Sunira & Geetha, 2016). The downside of using steel framing is that in the case of fire, it loses strength and stiffness (Bailey et al., 1999). It is detailed that structural steel at 425 °C will start to soften, and it loses approximately 50% of its strength at 650 °C (Eagar & Musso, 2001). To protect steel from high temperatures or fire, concrete encasement, insulating board systems and spray-on fireproofing are suggested (Goode, 2004).

Several studies have been conducted to show how much energy is used and CO_2 released with using different construction materials or methods. A quantitative assessment of the environment was carried out by calculating CO_2 emissions of building materials used in construction of the concrete and steel frame buildings (Kaethner and Burridge, 2012). The results revealed that the embodied CO_2 of the concrete and steel framed buildings were similar. However, a research effort showed that a concrete-framed structure had 26% less CO_2 and energy consumption compared to the steel structure (Kim et al., 2013). The same result was found in another research project that concrete frames used about 27% less energy than steel frames in the production and construction phase (Heravi et al., 2016). Another research project studied and described changes in energy and CO_2 balance caused by varying the key parameters of the material manufacturing and operational phases in concrete- and wood-framed buildings, and the results showed that the wood-framed buildings had lower energy and CO_2 balances than the concrete-framed buildings (Gustavsson & Sathre, 2006). Wooden structures are typically considered to have less carbon intensity and less energy consumption compared to other building structural systems (Gustavsson et al. 2006; Koch, 1992). It is detailed that the manufacturing of wood frames normally requires 60-80% lower primary energy input, mainly in the form of fossil fuel, than that of concrete frames (Borjesson & Gustavsson, 2000). Wood harvest on a global ground increased to 34%, which could be associated with positive effects: 14% to 31% of global CO_2 emission could be reduced through using wood structures; and 12% to 19% of global fossil fuel would be saved per year (Oliver et al., 2014).

In some other research studies, however, the insinuation was that the concrete walls or frames would require less operational energy and emission of CO_2 compared to wooden walls on a basis of life-cycle indicators. Gajda (2001) studied operational energy in building structures to compare thermal performance and found that a concrete frame house consumes 6% less heating and cooling costs when measured against a similar wood-framed building. As well, it was stated that frames with concrete-based walls had lower operational energy than those with wood-framed walls (Marceau & VanGeem, 2006). A study done in Shanghai, China, found that in an annual lifecycle, the steel framing consumed 12% more energy and produced 14% more CO_2 than the concrete-framed structure in the operation phase (Xu et al., 2007).

2.5. BIM and embodied energy assessment

Building Information Modeling (BIM) is defined as "*a digital representation of physical and functional characteristics of a facility*," and it is a "*shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle, defined as existing from earliest conception to demolition*" (BSA, 2017). Building information models are files that often contain proprietary format and data. These files can be exchanged and extracted to support decision making in relation to a building. BIM is used beyond design and planning phase, including the construction phase and continues in the whole building lifecycle (Foxe, 2010).

The construction industry considers BIM to have made a notable improvement in the industry and have changed how the construction industry handles projects across the world (Shadram et al. 2015). BIM has provided unparalleled ability to improve the communication of design teams and coordination of operators and contractors, and it has presented the construction industry with better outcomes with low costs. It brings all parties together in connection to projects that can be designed virtually and collaboratively (Mitchell & Lambert, 2013). With BIM, construction companies can raise issues, share information, and review simulated structures. BIM has enabled engineers, architects, and surveyors to use virtual information models to engage general contractors and suppliers. Each professional in the construction industry with help of BIM can contribute their own data to the shared model. The coordination with various stakeholders in the construction industry has improved, and designing, scheduling and detection of any clashes can be done early, if BIM is accommodated (Kuehmeier, 2008).

BIM can also prevent the loss of information that might occur when new teams come into an ongoing project (Van Berlo et al., 2012; Davies et al., 2015; Baroš 2016). In addition, contractors have the ability to minimize costly misunderstandings between facility managers, construction participants, and the design teams. BIM is not limited to 3D visualization of projects, and can be extended much further: time and scheduling (also called 4D); quantity takeoff and cost information (5D); and sixth dimension for facility management (Migilinskas et al., 2013; Smith, 2014; Saleh, 2015). If more attributes and intelligence is added to BIM, more useful information can be extracted for project performance identification and monitoring. In construction, close performance tracking is important and interventions can be made at early stages of the project whenever there is an element of falling behind in the case of design specifications. Several developed countries in Europe, North America, and Asia are taking the benefits of BIM when it comes to delivery of projects and subsequent asset management (Eastman et al., 2011). However, there are other countries which are lagging behind with regards to embracing BIM and they are falling into the risk of dragging the construction industry globally (Bolpagni et al. 2013). Governmental agencies around the world have acknowledged that BIM brings cost efficiency and more coordination in building and management of assets in the lifecycle of buildings (Staub-French et al., 2011).

Construction information has undergone advancement recently to address the complex issues on building design and energy performance integration. BIM can support energy performance analysis in buildings (Eastman, 2011). It has the ability to play a role as an independent, multi-disciplinary data repository, which gives new approaches and opportunities in the integration of performance analysis and design (Schlueter & Thesseling, 2009). Wong and Fan (2013) proposed a simple energy BIM development which stated that it can generate a "sketch" of the energy performance of buildings.

Several studies have used BIM to assess the energy consumption and GHG emissions of buildings. Shrivastava and Chini (2012) studied embodied energy of three 2-story office buildings (concrete-framed, steel-framed, and wood-framed), which were designed with equivalent frame system but different materials. It proved that BIM software can be used as a decision-making tool for environmental assessment of alternative systems. In this study, Revit Architecture, a BIM software, was used to develop the models and estimate embodied energy of those frame models. Parameters associated with environmental performance on a mathematical formula to calculate the desired value were assigned to various elements of the building models. It was found that embodied energy of concrete and steel structural system is approximately double of that for wood structural system. The embodied energy in this study included energy required to extract and manufacture materials as well as the energy used to transport them to the construction site, but the energy used in on-site construction activities was not covered.

Yang & Wang (2013) developed an integrated BIM-LCA framework to assist decision makers to reduce the environmental impacts and cost of the project in China. In this research, Autodesk Revit and Microsoft Excel were used to develop the assessment framework. An integrated LCA and Life cycle cost (LCC) model was built in Microsoft Excel using Chinese data. The assembly category and material schedules derived from Revit can be linked with the Excel model. The results proved that the integrated BIM-LCA methodology based on Autodesk Revit and Excel is a useful tool to support environmental decision- making in early design stage.

A BIM-based environmental assessment framework was developed to estimate the embodied energy and CO_2 emissions of buildings using Revit and Excel programs (Shadram et al. 2014). The proposed method uses BIM framework for quantity take-off of building elements and maps the material quantities with components of Environmental Product Declaration (EPD) to assess the environmental impacts. The components and constituents of modules are noted in the EPD codes that are then transferred to a spreadsheet to calculate the environmental impacts. This study, however, only focused on energy used in the production of building material and components.

Similarly, an integrated BIM and the UK New Rules of Measurement (NRM) assessment tool was investigated to automate the cost and embodied energy computation process of building projects (Abanda et al., 2017). The assessment tool automatically extracts quantities from Revit building model and fits them into the New Rules of Measurement catalogues. The NRM ontology was mapped to XML codes and exported to spreadsheet for importing into the assessment system. The system then uses an in-built density, embodied energy and CO_2 intensities database adapted from the Bath ICE to compute the embodied energy and CO_2. As well, this assessment tool considered the material manufacturing phase and transportation stage, but the energy consumption and emissions for the onsite operations were not included.

These BIM-based frameworks focused on either manufacturing stage or operation stage during life cycle of buildings, and the impacts of the production and construction stage were not covered. Therefore, there is a need to investigate BIM based methods to assess environmental impacts of entire upstream phases, including production and construction stages of a building project. This research project explicitly studies this topic and attempts to use BIM-based models for assessing manufacturing, transportation, and installation/construction energy consumption and GHG emissions of building structural systems.

CHAPTER 3: Proposed Methodology

This chapter describes the methods used to develop environmental assessment framework using a BIM model. Figure 4 illustrates the architecture of the proposed framework. This system firstly performs the quantity take-off (QTO) of the structural components and materials using the schedules/quantities function available in most BIM platforms, such as Autodesk Revit. The constituent structural components of the building are extracted together with their main properties (i.e. type, size, volume, reference level), which are then exported to a spread sheet. The required energy inventory was created and formulas were coded in the spreadsheet model to calculate energy consumption and GHG emissions in manufacturing and construction phases of common structural systems. The quantities were linked to the embodied energy and the environmental impacts of the materials of components, and consequently the environmental footprint and embodied energy of the structural system can be computed.

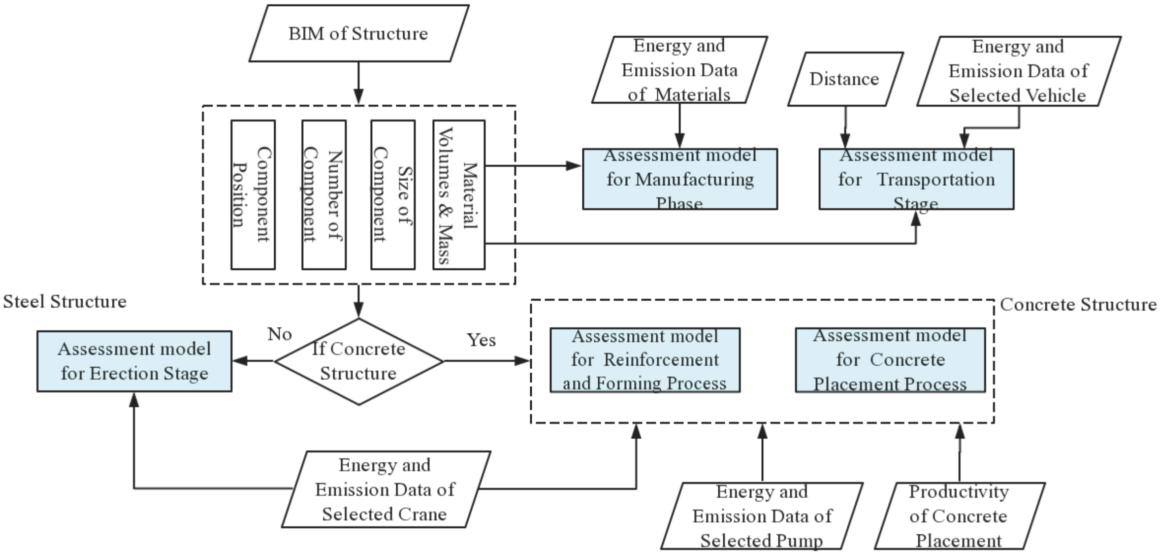


Figure 4: Method to assess embodied energy and environmental impacts using BIM application and spreadsheet

3.1. Quantity Take-Off from BIM

3.1.1. Introduction

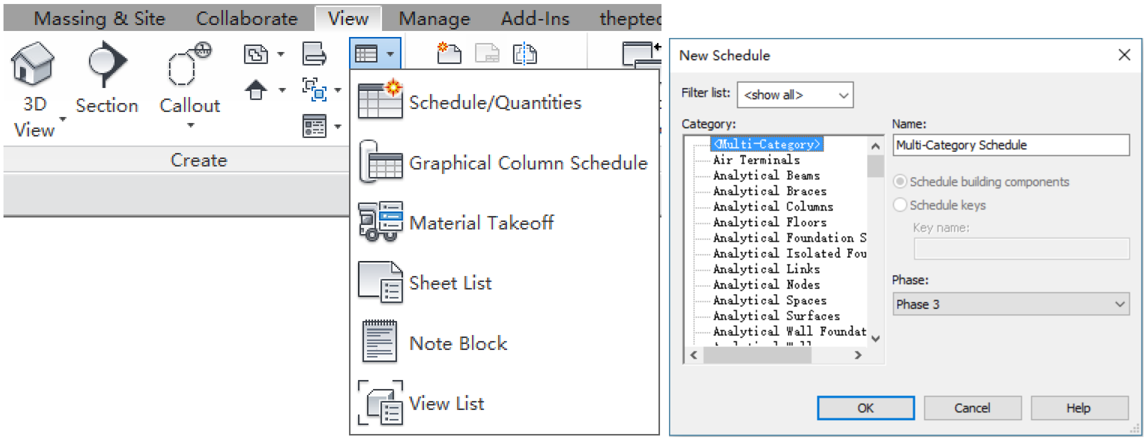
Quantity Take-Off (QTO) is a vital process in cost estimation and scheduling in the construction industry, which is also a key element for environmental impact assessment. QTO helps architects and engineers in getting accurate estimation from design data (Choi et al., 2015). Completeness and accuracy are the most important factors in QTO, which depend on detailed modelling of the building elements

Object-oriented BIM models have built-in parametric information that makes it possible to automate quantity estimation. QTO tools of BIM platforms are able to extract building components together with their corresponding type, size, volume, space area, location, and weight from BIM model and report to different schedules (Eastman et al., 2011). This also can be used to identify environmental impact during every stage of the projects. BIM specifically can provide environmentally friendly modifications and additions to save energy and time, which is beneficial in a project during early stages of design (Amor et al., 2014). Estimation workflow using model-based BIM is better than the upfront effort and time needed to start the process. This is known to be a smart and lean method since the manual and time-consuming quantity take-off processes are automated and subjective, where the required object properties for subsequent calculations are easily available. The information output is in a text file that is imported by the energy estimation algorithms in a spreadsheet.

3.1.2. QTO from Revit

In this study, Autodesk Revit was used to perform quantity take off process. Architects and designers usually use Revit Architecture™ tool to export material information such as material takeoffs and initial bill of quantities to Excel spreadsheets for further processes (Davis, 2011).

The Schedule/Quantities function produces a schedule for a selected family category. When a new schedule is created, a list of available fields is provided to select desired properties of object family tape, such as family type, volume, and length (Figure 5).



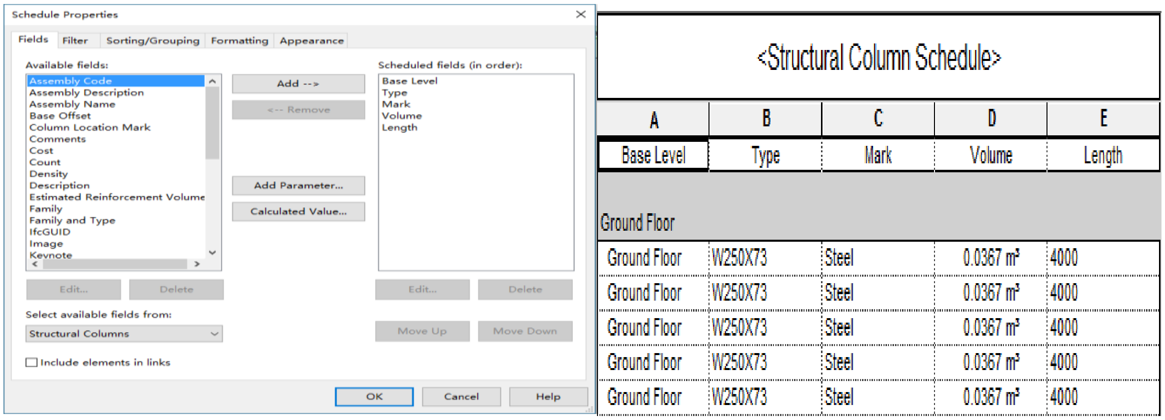
Filter list: <show all>

Name: Multi-Category Schedule

Phase: Phase 3

Figure 5: Screenshots of creating a new schedule for a family category

Figure 6 shows a schedule for structural columns of a sample steel frame, which can be exported to a spreadsheet and linked to energy inventory data to calculate the energy usage.



Scheduled fields (in order):
Base Level
Type
Mark
Volume
Length

Select available fields from: Structural Columns

☐ Include elements in links

<Structural Column Schedule>

A	B	C	D	E
Base Level	Type	Mark	Volume	Length
Ground Floor				
Ground Floor	W250X73	Steel	0.0367 m³	4000
Ground Floor	W250X73	Steel	0.0367 m³	4000
Ground Floor	W250X73	Steel	0.0367 m³	4000
Ground Floor	W250X73	Steel	0.0367 m³	4000
Ground Floor	W250X73	Steel	0.0367 m³	4000

Figure 6: Screenshot of schedule properties table and the structural column schedule of a sample steel frame

3.1.3. QTO from IFC file

In the building design stage, different BIM-enabled design tools, such as SketchUp, Revit, AECOsim Building Designer, and ArchiCAD, are used by different engineering and construction companies. One of the similarities of these software is that they can export the building design model as Industry Foundation Classes (IFC) file by their built-in function or additional plugin. The IFC is a global standard created by BIM community for data exchange between various commercial software vendors (buildingSMART, 2011). The IFC file which contains all geometry and property data of a building model can be used to share data regardless of the software application used during the design phase. It is possible to export IFC file from another application to Revit, and then perform quantity take offs as described in previous section. However, it is also possible to generate quantity take offs directly using an IFC file and programming, or use open source quantity take offs application. A sample process is presented in Figure 7. A research effort presented a framework to calculate QTO from IFC open BIM files and the results were almost the same as the results generated by Revit (Choi et al., 2015).

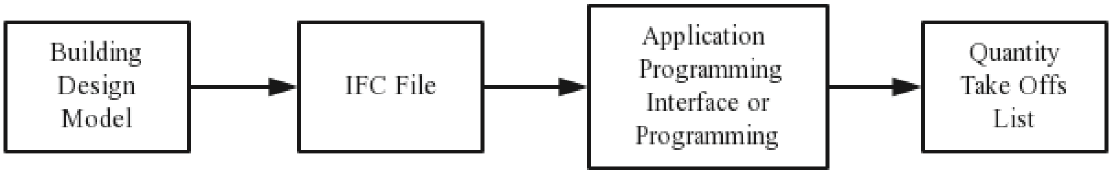
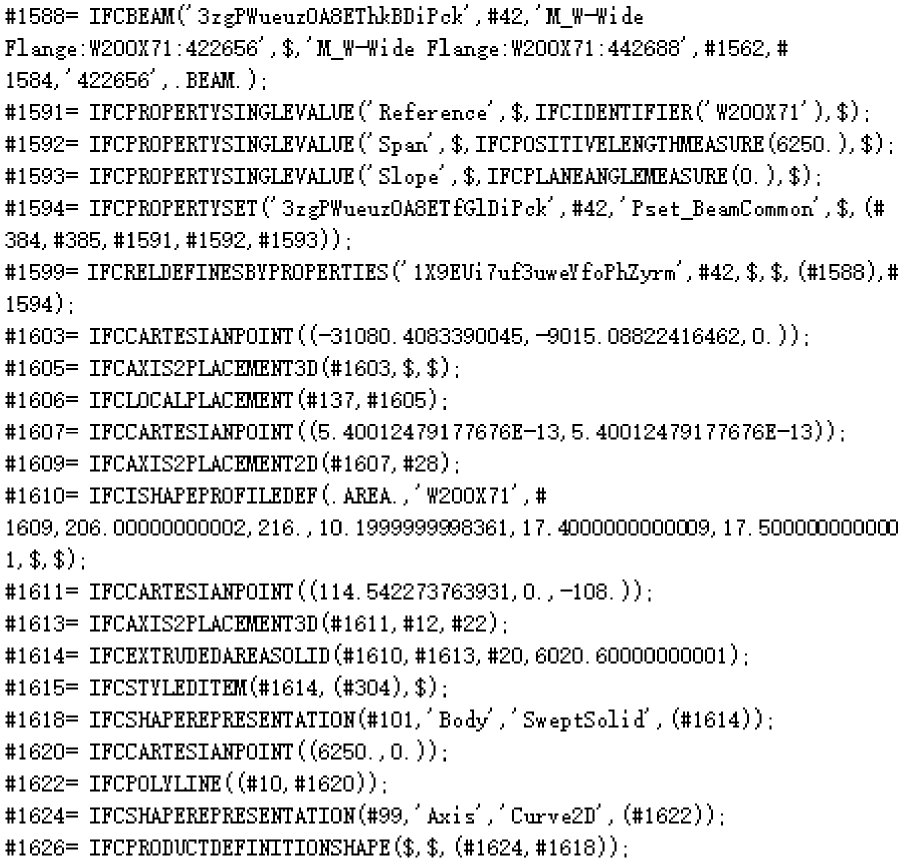


Figure 7: Overall process of QTO from IFC file

A sample IFC file for a steel beam in a plain text file is presented in Figure 8. It shows the geometry and material data of a steel beam in the IFC format. It also defines relationships between the building elements, which include the spatial structure, location, and connection. "IFCPROPERTYSINGLEVALUE" indicates a property object with a single value assigned. For example, the length value of the beam is 6250 mm in the #1592. With this value, the weight of the beam could be calculated by multiplying the length by the unit weight of this particular type of steel beam, which is indicated by IFCBEAM as W200x71. "IFCCARTESIANPOINT" is the coordinates of the object in a two or three-dimensional rectangular Cartesian coordinate system.

The explanation of other parameters can be found in the buildingSMART website (buildingSMART, 2007). With these information, the QTO of an open BIM file in IFC format could be calculated using corresponding programming or existing commercial QTO tools.



```
#1588= IFCBEAM('3zgPWueuzOA8EThkBDiPck',#42,'M_W-Wide
Flange:W200X71:422656',$,'M_W-Wide Flange:W200X71:442688',#1562,#
1584,'422656',.BEAM.);
#1591= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('W200X71'),$);
#1592= IFCPROPERTYSINGLEVALUE('Span',$,IFCPOSITIVELENGTHMEASURE(6250.),$);
#1593= IFCPROPERTYSINGLEVALUE('Slope',$,IFCPLANEANGLEMEASURE(0.),$);
#1594= IFCPROPERTYSET('3zgPWueuzOA8ETfGlDiPck',#42,'Pset_BeamCommon',$,(#
384,#385,#1591,#1592,#1593));
#1599= IFCRELDEFINESBYPROPERTIES('1X9EUi7uf3uweYfoPhZyrm',#42,$,$,(#1588),#
1594);
#1603= IFCCARTESIANPOINT((-31080.4083390045,-9015.08822416462,0.));
#1605= IFCAXIS2PLACEMENT3D(#1603,$,$);
#1606= IFCLOCALPLACEMENT(#137,#1605);
#1607= IFCCARTESIANPOINT((5.40012479177676E-13,5.40012479177676E-13));
#1609= IFCAXIS2PLACEMENT2D(#1607,#28);
#1610= IFCISHAPEPROFILEDEF(.AREA.,'W200X71',#
1609,206.00000000002,216.,10.1999999998361,17.4000000000009,17.500000000000
1,$,$);
#1611= IFCCARTESIANPOINT((114.542273763931,0.,-108.));
#1613= IFCAXIS2PLACEMENT3D(#1611,#12,#22);
#1614= IFCEXTRUDEDAREASOLID(#1610,#1613,#20,6020.60000000001);
#1615= IFCSTYLEDITEM(#1614,(#304),$);
#1618= IFCSHAPEREPRESENTATION(#101,'Body','SweptSolid',(#1614));
#1620= IFCCARTESIANPOINT((6250.,0.));
#1622= IFCPOLYLINE((#10,#1620));
#1624= IFCSHAPEREPRESENTATION(#99,'Axis','Curve2D',(#1622));
#1626= IFCPRODUCTDEFINITIONSHAPE($,$,(#1624,#1618));
```

Figure 8: Description of a sample steel beam in IFC file

3.2. Model for the Manufacturing phase

3.2.1. Introduction

A major portion of CO_2 emissions is produced in the manufacturing phase of a building lifecycle (Hong et al. 2013) and it is believed that the manufacturing phase is associated with a high level of energy consumption (Cole & Kernana, 1996). This portion of the energy is found in the materials and components that are utilized in building installations. The manufacturing phase begins with extracting and delivering raw materials to the processing plant and finishes with the processed construction material/ products, such as steel plates or fresh concrete. It has been projected that the production of building components accounts for 75% of the total embodied energy of a building (Ding et al, 2004). In the manufacturing phase, embodied energy is calculated by identifying the materials used and estimating their quantities to uncover the amount of energy content they have. The system of calculating carbon foot print and embodied energy of the manufacturing phase are well-studied which help contractors or designers to evaluate a construction plan in a proper manner.

The database of Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) assists in providing data on consumed energy in the manufacturing phase. ICE is a top-ranked database across the globe as a source of carbon and embodied energy data (Goodhew, 2016). Computer programs of LCA each has a specific database compiling embodied energy coefficients. Using Life Cycle Inventory (LCI) database makes LCA more accurate and reliable (Trusty & Meil, 2002).

A main part of the overall embodied energy occurs in the manufacturing phase. Table 1 presents the values for manufacturing energy and carbon coefficient used in this study (Hammond & Jones, 2011).

Table 1: Embodied energy and carbon coefficients

Materials	Embodied Energy(EE) (MJ/kg)	Embodied Carbon(EC) ($kgCO_2e/kg$)
Steel	20.1	1.46
Glulam	12	0.42
Concrete	0.88	0.132
Rebar	17.4	1.4
Plywood	15	0.45

It is common to have some level of material waste in the building construction process due to various reasons, such as unique shapes of building elements and the need to extract them from standard sized manufactured items, defects in products, poor handling, and damages to material during delivery. The wastage should be considered in the estimation of embodied energy. Waste factor is commonly calculated as a percentage of required amount of material. With the waste factor, wastage of specific material during construction process can be calculated in the model. The waste factor depends on the type of building materials and the common factors are provided in Table 2 (Chen et al., 2001).

Table 2: Waste factor for different types of materials in the erection of building

Materials	Waste Factor
Steel	0.05
Concrete	0.025
Timber	0.025

3.2.2. Calculation Method

The energy consumption of the manufacturing phase is equal to the total embodied energy of materials needed of a building. It can be expressed as:

$$E_M = \sum m_i EE_i \qquad (2)$$

Where,

E_M— Energy used in material manufacturing process;

m_i — mass of material i needed in a building;

EE_i — Embodied energy coefficient of material i.

Similarly, calculation of the emissions in manufacturing phase can be expressed as:

$$GHG_M = \sum m_i EC_i \qquad (3)$$

Where,

GHG_M — Greenhouse gas emissions during manufacturing phase;

m_i — mass of material i needed in a building;

EC_i — Embodied carbon coefficient of material i.

Inventory data and calculation formula were coded in a spreadsheet. The quantity take offs derived from BIM model are exported to preassigned position in an excel file, then the energy consumption and GHG emissions are estimated by excel automatically.

3.3. Model for the Construction Phase

3.3.1. Introduction

Energy consumption in the construction phase represents 7% to 10% of the total embodied energy (Cole, 1998), and it only account for a minor part of the total life cycle energy demand (Gustavsson et al. 2010). However, in order to estimate the embodied energy correctly, the energy consumption for the construction activities should be considered. Construction phase includes transportation and erection/construction stages. Transportation energy is calculated based on distance travelled for material delivery from the factory to the construction, including distribution centers. The calculation for erection/installation is based on construction equipment and methods used for various structural systems. Amount of energy consumption and carbon emission in erection stage differ in wood, steel and concrete structures. Different mobile cranes are used for erecting wood and steel frames while concrete mixer trucks, pumps, and cranes are used in construction of concrete structures.

3.3.2. Transportation Stage

Diesel and gasoline are the common types of fuel used in transportation operations of building construction projects. Consumption of energy during transportation depends on the weight of the load, distance, and size and type of the vehicle. It is estimated that steel beams are the components that consume most energy as total energy consumption amounted to about 18% in the transportation stage, and ready mixed concrete and steel shuttering each accounting for 11% of total transportation energy (Miller, 1998). These percentages are based on energy consumption during delivery process and only represent 1.5% of the building elements' embodied energy (Miller, 1998). The variance in energy consumption has been linked to the type of vehicles used in transportation, which can complicate estimating energy consumption in transportation stage. However, it is easier to predict the distance and vehicle type used in transportation by considering the materials to be transported to construction site. Several previous studies on LCA have ignored or assumed simple data, such as direct distance travelled, to calculate embodied energy portion of transportation. However, it is common that most construction material, namely steel and timber, go through some distribution centers before arriving at the construction site. Thus, energy is consumed for loading and unloading processes in each distribution center. This part of energy is also considered in this study.

Concrete materials are transported to the site with powered mixer trucks, which consume diesel to transport and also to maintain the concrete fluid and to extend the setting time of agitated concrete mixture. Fresh concrete has to be offloaded within 2-3 hours (Durbin & Hoffman, 2008).

Engineered wood and structural steel requires flat-bed trucks consuming diesel (Cole, 1998). The difference in the type of transportation vehicle result to different level of carbon emission and consumption of energy.

Recent energy consumption rates and GHG emission factors for transportation of building materials are presented in Table 3 (Hong et al 2013). To simplify the calculation process, the GHG emission factors are converted to carbon dioxide equivalent (CO2e) using the "global warming potential" ("GWP") of GHG emissions which are presented in Table 4.

Table 3: Energy consumption and GHG emission factor of transportation vehicles

Materials	Vehicle	Size	Energy consumption (MJ/t/km)	GHG emission(kg/t/km)			CO_2e (kg/t/km)
				CO_2	CH_4	N_2O	
Steel	Trailer	20 t	0.97	0.0713	0.0000029	0.00000058	0.0715
Concrete	Concrete mix truck	6 m^3	2.06	0.0982	0.0000876	0.00000028	0.1005
Timber	Trailer	20 t	0.97	0.0713	0.0000029	0.00000058	0.0715

Table 4: Global warming potential of common greenhouse gas

Greenhouse Gas	Global Warming Potential(GWP)
Carbon (CO_2)	1
Methance (CH_4)	25
Nitrous oxide (N_2O)	298

A round trip, including both haul and empty return trips, was considered for transportation of structural material from the manufacturing plant to the construction site. It is estimated that the energy consumption and emissions of empty backhauling is 66% of a full load transportation (Sheckler & Maynus, 2009). In addition, the energy used for loading/unloading in distribution centers should be accounted for transportation of steel and timber products. The energy consumed in each loading/unloading process is assumed to be equal to a lifting process in construction erection stage which is described in the next section. The calculation of energy usage and GHG emissions during the transportation stage are calculated as:

In-situ concrete:

$$E_T = 1.66 \cdot \sum m_i \cdot EE_i^t \cdot D_i \tag{4}$$

$$GHG_T = 1.66 \cdot \sum m_i \cdot EC_i^t \cdot D_i \tag{5}$$

Steel and Wood:

$$E_T = 1.66 \cdot \sum m_i \cdot EE_i^t \cdot D_i + n \cdot E_{LP} \tag{6}$$

$$GHG_T = 1.66 \cdot \sum m_i \cdot EC_i^t \cdot D_i + n \cdot EC_{LP} \tag{7}$$

Where,

E_T — Energy usage during transportation stage;

GHG_T— Greenhouse gas emissions during transportation stage;

m_i — Mass of material i required to be delivered;

EE^t_i — Energy consumption per kilometer per ton of material i;

EC^t_i — Greenhouse gas emissions per kilometer per ton of material i;

D_i — Distance between manufacture factory of material i and construction site;

n — Number of distribution center;

E_{LP} — Energy consumed in lifting process;

EC_{LP} — Emissions in lifting process.

3.3.3. Erection Stage

Special construction methods and equipment are required for different structural systems. The Energy consumption during erection stage is mainly due to the energy used by the construction equipment. Generally, mobile cranes are used for steel or wood frame building, and concrete pump trucks are used for pouring concrete in low to mid rise concrete-framed buildings. Reinforcement and form working are also required for concrete-framed structures, these two preparatory works are performed mainly by labor, but mobile cranes are also used to deliver rebar and forms from warehouse to the installation location. Thereby, both mobile cranes and concrete pumps are considered for the evaluation of the energy consumption of the concrete-framed construction. The method used to estimate energy consumption and emission in erection stage is based on the equipment working hour. It is calculated as:

$$E_i = T_i \cdot ECF_i \tag{8}$$

Where,

E_i — Energy usage of equipment i;

T_i — Equipment working hour;

ECF_i — Energy consumption factor of selected equipment, MJ/h.

Energy Consumption Factor (ECF)

To estimate the energy usage of equipment, the energy consumption factor (MJ/hour) has to be determined. First, the liters of fuel used per machine hour by the equipment is estimated by following equation adopted from a Food and Agriculture Organization paper (Sessions, 1992).

$$LMPH = \frac{K \times GHP \times LF}{KPL} \tag{9}$$

Where,

LMPH — Liters of fuel used per machine hour;
K — Weight of fuel used per brake hp/hour;
GHP — Gross engine horsepower at governed engine rpm;
LF — Load factor of the equipment in percent;
KPL — Density of fuel in kg/liter.

Given the values listed in Table 5 (Sessions, 1992), and the value of gross engine horsepower (GHP) of selected equipment provided by equipment manufacturer, the liters used per machine hour (LMPH) can be estimated. Then, according to the energy and emission conversion factors in Table 6 (Ministry of Environment, B.C., 2016), the energy consumption factor (MJ/hour) can be calculated as:

Energy consumption factor (ECF) = LMPH * Energy conversion factor; (10)

Emission factor (EF) = LMPH * Emission conversion factor. (11)

Table 5: Weight, fuel consumption rates, and load factors for diesel and gasoline engines

Engine	Weight (KPL)	Fuel Consumption(K)	Load Factor(LF)		
	kg/liter	kg/brake hp-hour	Low	Med	High
Gasoline	0.72	0.21	0.38	0.54	0.7
Diesel	0.84	0.17	0.38	0.54	0.7

Table 6: Energy and emission conversion factor of diesel and gasoline

Fuel Type	Energy Conversion Factor (MJ/L)	Emission Conversion Factor (Off-Road Equipment) (kgCO_2e/L)
Diesel	38.3	2.914
Gasoline	35	2.283

Steel Structure

Equipment working time (T)

As mentioned in the previous section, mobile cranes are typically used to complete the erection task. It can be separated into two processes: (1) Lifting process; (2) Installation process.

a) Time for lifting process (T_{LP})

The lifting process is divided into five motions, as presented in Figure 9. T_{LP} is the total time of these five motions. First, the crane adjusts the height hoist to load building component, followed by lifting the component to a safe position, then it rotates to deliver the component to the installation position. After the component is fixed, the crane rotates to its initial position. One piece of column or beam is delivered in each cycle.

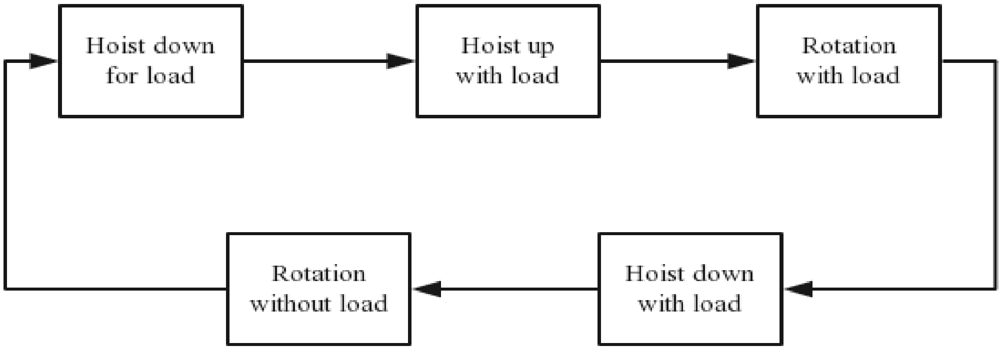


Figure 9: The cycle of delivering material using crane

A method by Hammond and Jones (2008) was used to determine the values of motion times:

$$V_{\max}({}^{o}/\min) = (P_{\max} \times 0.01) \times S \times 360^{o}\, and V_{\max}(m/\min) = (P_{\max} \times 0.01) \times S \tag{12}$$

$$V_{\min}({}^{o}/\min) = (P_{\min} \times 0.01) \times 360^{o}\, and V_{\min}(m/\min) = (P_{\min} \times 0.01) \times S \tag{13}$$

$$y = \frac{V_{\min} - V_{\max}}{F_{\min} - F_{\max}} x + V_{\max}({}^{o}/\min, m/\min) \tag{14}$$

$$T_{motion} = \frac{L_{angle}, L_{height}}{y} + T_{penalty} \tag{15}$$

Where V_{max} and V_{min} are the allowable maximum and minimum speeds of slewing and hoisting; P_{max} and P_{min} are the acceptable maximum and minimum percentage of hoisting and slewing speeds; S is the rotation speed in (rmp) or hoist speed (m/min) provided by crane manufactures; y represents the speed of a motion; F_{min} and F_{max} are minimum and maximum safety factor, which are 0% and 100%, respectively; x is a safety factor in a motion; T_{motion} is the cycle time of a motion; L_{angle} and L_{height} are the lifting angle and lifting height for a motion; and T_{penaty} is time penalty for a crane movement change from a precedent motion to a subsequent motion.

Then, energy consumption in lifting process (E_{LP}) is estimated as:

$$E_{LP} = T_{LP} * ECF_{Crane}. \qquad (16)$$

b) Time for installation process (T_{IP})

Once a building component is lifted to the installation position, a group of workers will connect it to other installed objects. When the component is fixed, the crane will move to the next motion. The time required to install a structural element by the group of crew is the working time for the crane in the installation process. Therefore, it is critical to confirm the productivity of labor for structure installations.

The productivity information were provided by RS Means Building Construction Cost Data (R.S. mean, 2017). The daily outputs presented in RS Means are the average production rates by one work team for 8 hours per day under normal conditions. Table 7 lists the daily outputs of W10 series steel beams installation, which have been convert to hourly productivity based on eight hours working time.

Energy consumption in installation process (E_{IP}) is estimated as:

$$E_{IP} = T_{IP} * ECF_{Crane}. \qquad (17)$$

Table 7: Productivity of steel beam installation

Structural Steel Beam	Daily Output (linear feet/day)	Productivity (m/hour)
W 10 x 12	600	23
W 10 x 15	600	23
W 10 x 22	600	23
W 10 x 26	600	23
W 10 x 33	550	21
W 10 x 49	550	21

Concrete structure

Construction of concrete-framed structures requires additional temporary settings and materials (particularly formwork). Before placing concrete, the formwork preparation of structural assemblies and reinforcement should be done. All formworks were assumed to be 0.018 thick plywood in this study (Engineered Wood Association, 2012). The amount of formwork and rebar for the cast-in-place concrete varies with the type of structural assembly (column, wall, floor plate etc.), the size of the element, complexity of its design, and the type of concrete and rate of pour. The volume of reinforcement can be provided according to the design drawing of project. The formwork area for each component can be estimated as "calculated parameter" in Revit schedule and exported together with the quantity take offs of building model.

Equipment working hour (T)

Construction of a concrete structure can be also divided into two processes: (1) Lifting process; (2) Concrete placement.

a) Time for lifting process (T_{LP})

In the lifting process, a mobile crane is used to deliver rebar and concrete forms to the element position. Delivery of concrete forms and rebar is considered the same as the delivery of steel component. One set of forms or rebar for each element is delivered in a lifting cycle.

b) Concrete placement (T_P)

Concrete pump truck is used to pour concrete. The energy usage of the pump truck for concrete placement was calculated to assess the energy consumption of this process.

Working hours of a concrete pump was calculated using the following equation:

$$T_P = \sum \frac{V_i}{P_i^c} \tag{18}$$

Where,

T_P — the working hour of concrete pump truck;

V_i — the volume of component i;

P^c_i — labor productivity of placing concrete for component i.

As described before, volume of each element in structure is included in quantity take-offs derived from a BIM model, and a database for labor productivity data (extracted from RS Means) was encoded in the spreadsheet model.

Energy consumption in installation process (E_P) is estimated as:

$$E_P = T_P * ECF_{Pump}. \tag{19}$$

CHAPTER 4: Case Study

In this chapter, the embodied energy and emissions of two residential buildings with rather similar layout, but designed with different structural systems are assessed based on the proposed framework. The case study building is a four-story structure (ground plus three) located in Thunder Bay. The concrete structure has the total gross floor area of 5,490.69 square meter, while, the steel structure has a total gross floor area of 4,934.60 square meter.

4.1. Building Model Description

Model 1

The concrete-framed building has seventy-six square reinforced concrete columns (400 x 400mm) distributed on foundation; and three hundred and one square reinforced concrete columns (300 x 300mm) distributed on ground, level 1, 2, and 3 in total. Structural beams are designed by using 400 x 500mm, and 500 x 600mm regular concrete girders.

Model 2

The same 4-story residential building was designed with a steel frame system. There are two hundred and fifty-two steel columns distributed on ground, level 1, 2, and 3 in total. Structural beams & joists are designed by using W310 x 74 girders and W200 x 71 beams for level 1, 2, and 3; using W250 x 89 girders and W200 x 52 beams for the roof.

Figure 10 and Figure 11 show a 3D view and floor plan of the concrete-framed residential building, respectively. Figure 12 and Figure 13 illustrate a 3D view and structural plan of the building design with a steel frame.

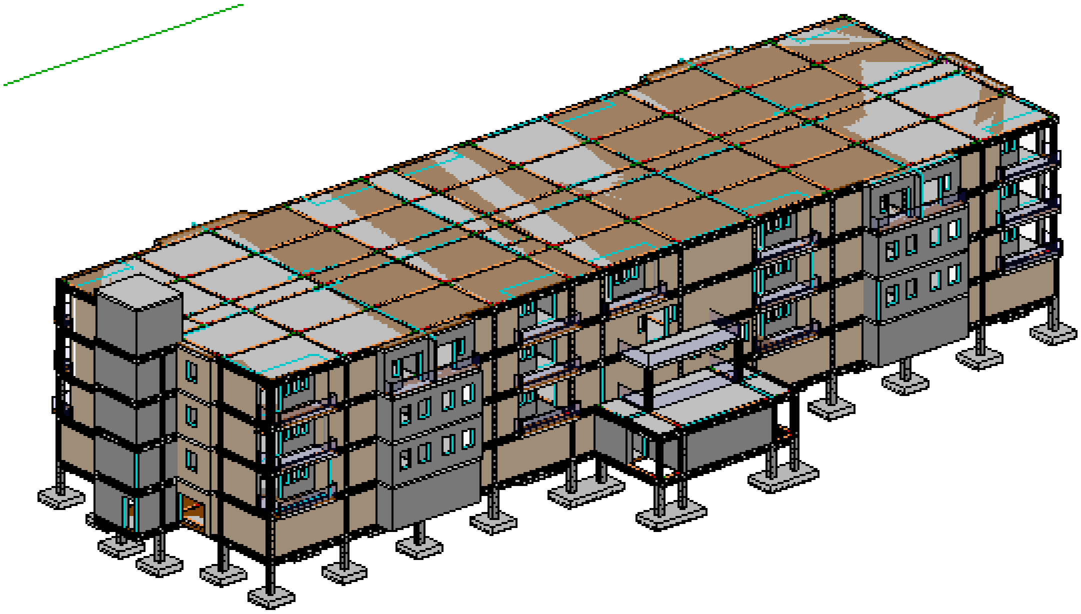


Figure 10: 3D view of concrete residential design

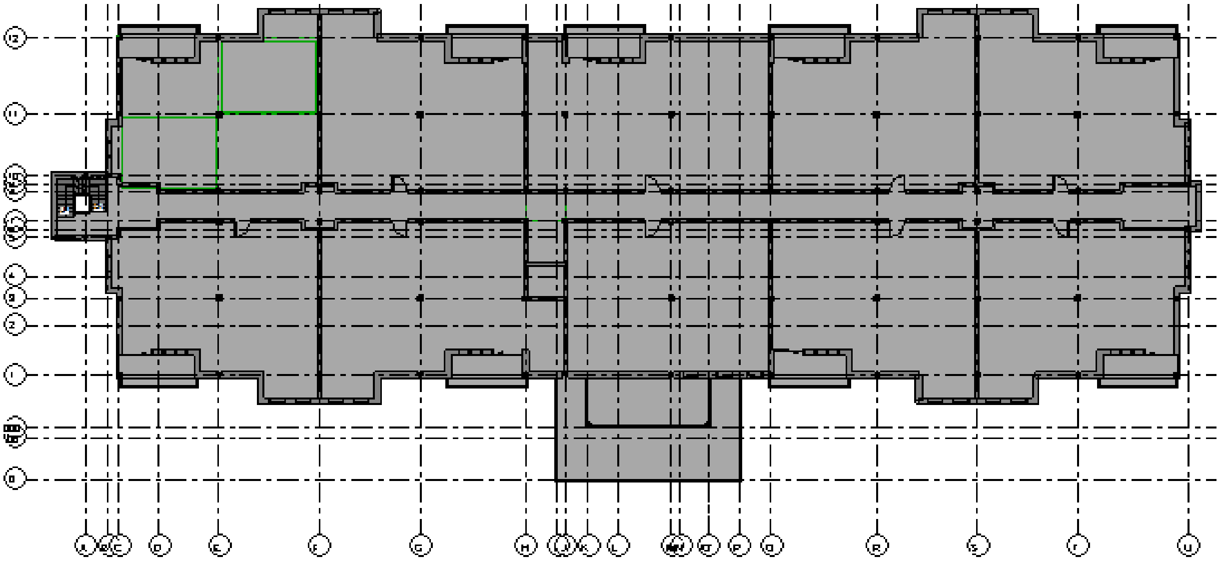


Figure 11: Floor plan of concrete residential design

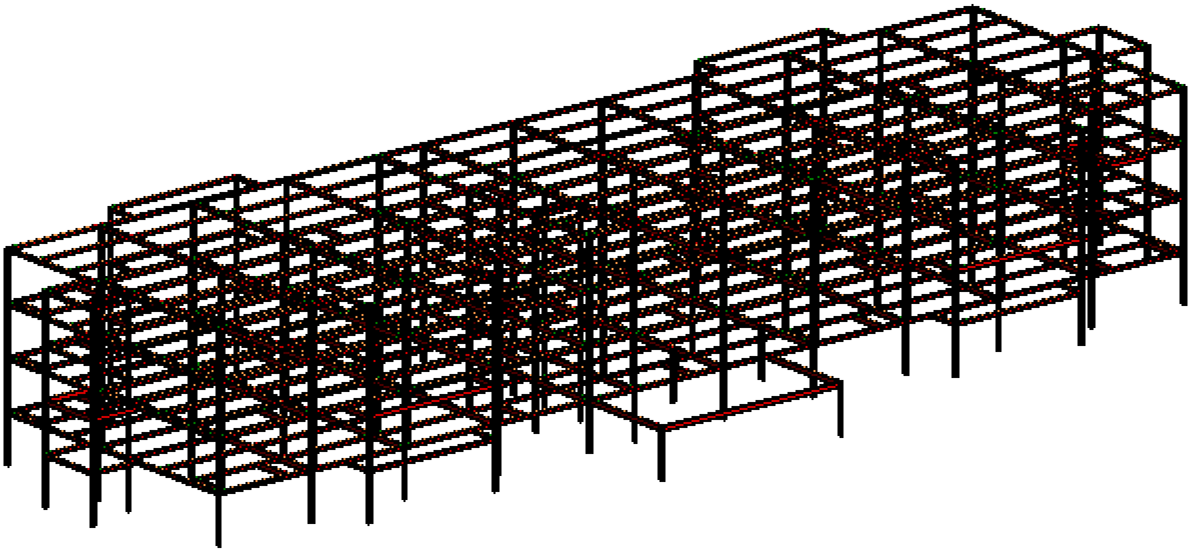


Figure 12: 3D view of steel residential design

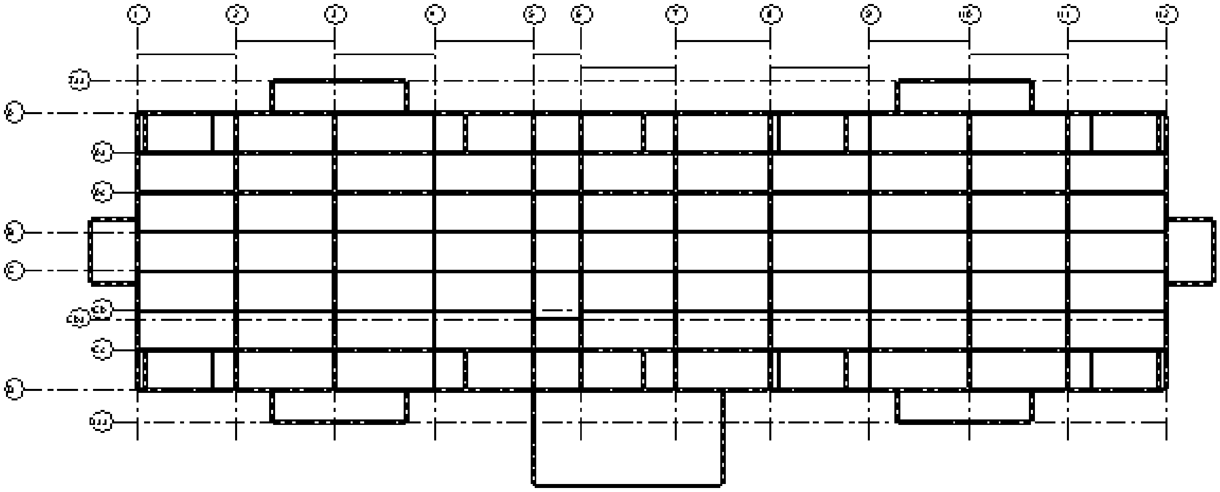


Figure 13: Structural plan of steel residential design

4.2. Perform Proposed Methodology

This case study estimates the embodied energy and emissions of the buildings' structural framing system using the methodology presented in Chapter 3. First, QTO of the structural components (columns, beams, and slabs) of these two building models were generated in the BIM platform. Then, the QTO were exported to spreadsheets to estimate the energy consumption and emissions. The results are discussed in chapter 5.

4.2.1. Quantity take off

Model 1- Concrete structure

In Revit, a shared parameter is a user defined variable that could be assigned to various families under different categories of Revit model, and is accessible in a schedule of the model. The following shared parameters are added to column and beam components to estimate the formwork area of the concrete model: (1) height; (2) width; and (3) perimeter. Figure 14 indicates the formwork area estimation of beams. Figure 15 and Figure 16 present the shared parameters assigned to concrete columns and beam assemblies. Figure 17 and Figure 18 show parameters added to columns and beams schedule. Additional build-in parameter "Area" which indicates the surface area of the floors is added to floor schedule. Formwork area is added to schedule as a calculated value using following equations:

- For column:

  Formwork Area = Perimeter *Length; (20)

- For beam assemblies:

  Formwork Area = Perimeter * Length – width * length; (see Figure 14) (21)

Where, Length is a built-in field in the Revit.

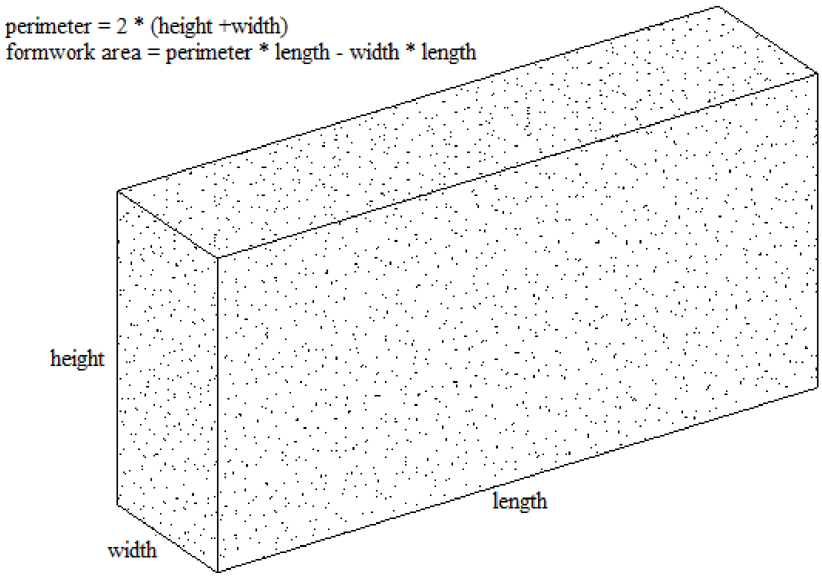
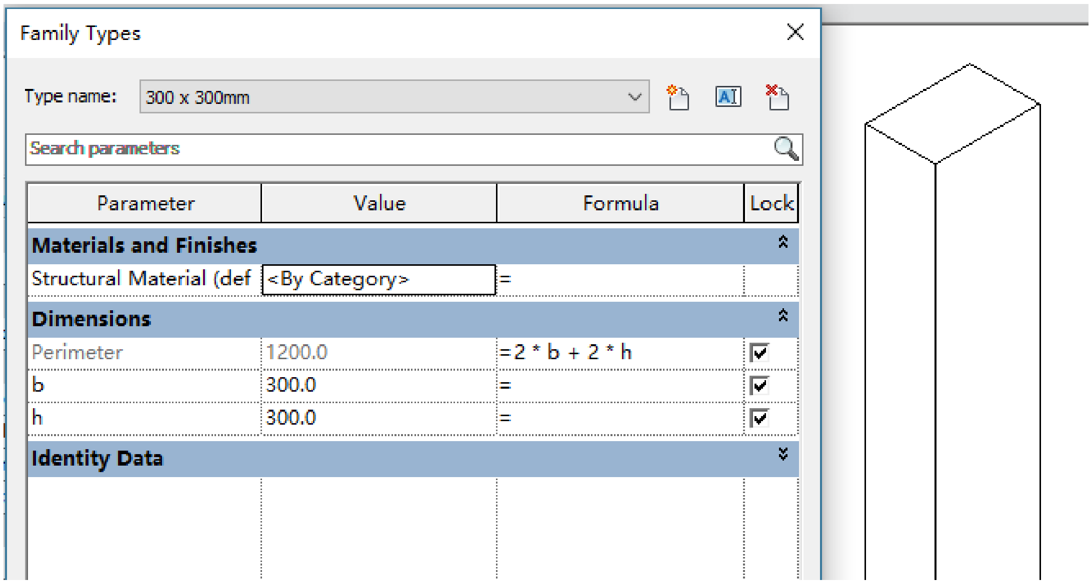


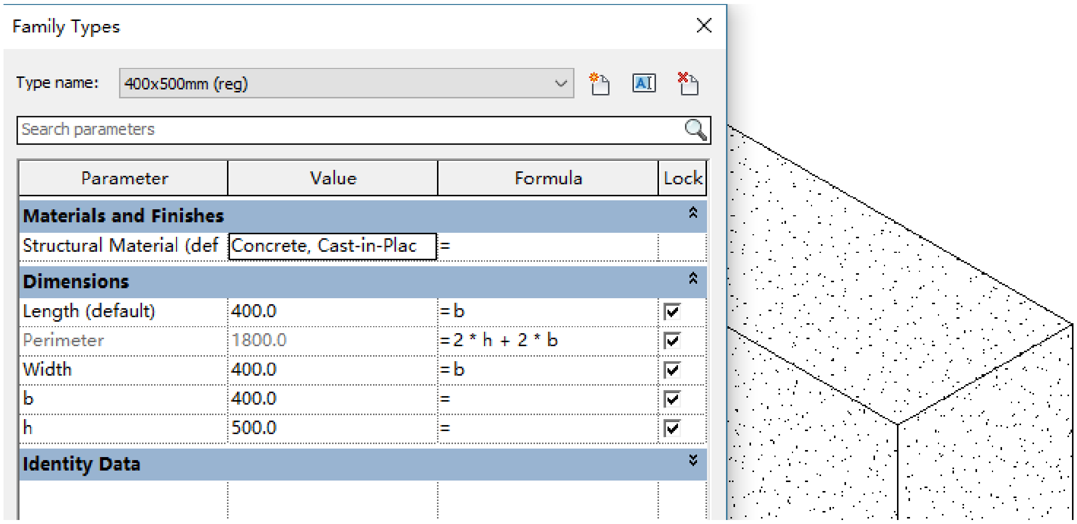
Figure 14: formwork area calculation of beams



Type name: 300 x 300mm

Parameter	Value	Formula	Lock
Materials and Finishes			
Structural Material (def	<By Category>	=	
Dimensions			
Perimeter	1200.0	=2 * b + 2 * h	☑
b	300.0	=	☑
h	300.0	=	☑
Identity Data			

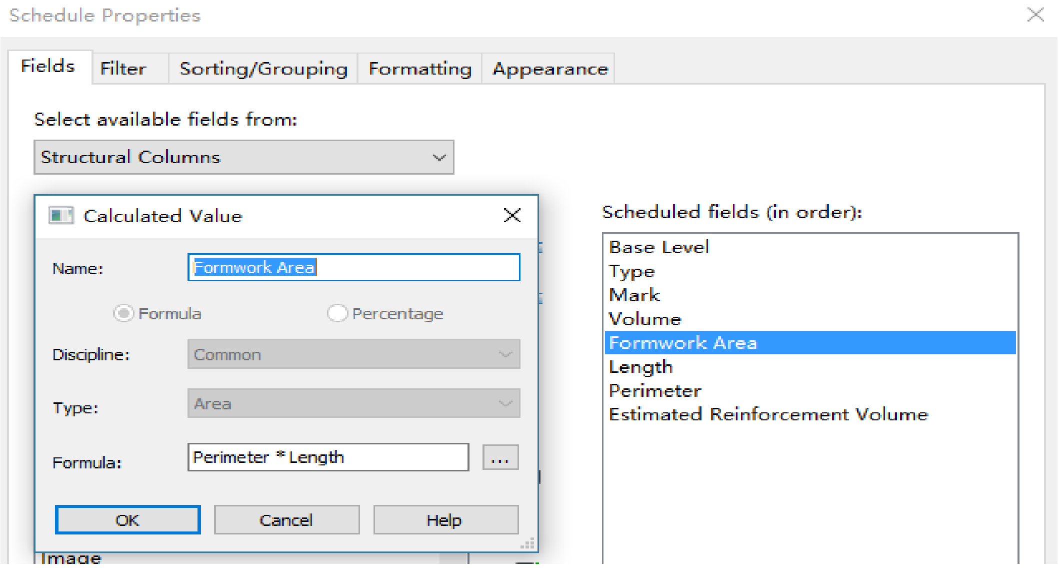
Figure 15: Parameters associated to concrete columns



Type name: 400x500mm (reg)

Parameter	Value	Formula	Lock
Materials and Finishes			
Structural Material (def	Concrete, Cast-in-Plac	=	
Dimensions			
Length (default)	400.0	= b	☑
Perimeter	1800.0	= 2 * h + 2 * b	☑
Width	400.0	= b	☑
b	400.0	=	☑
h	500.0	=	☑
Identity Data			

Figure 16: Parameters associated to concrete beam components



Select available fields from: Structural Columns

Name: Formwork Area

● Formula ○ Percentage

Discipline: Common

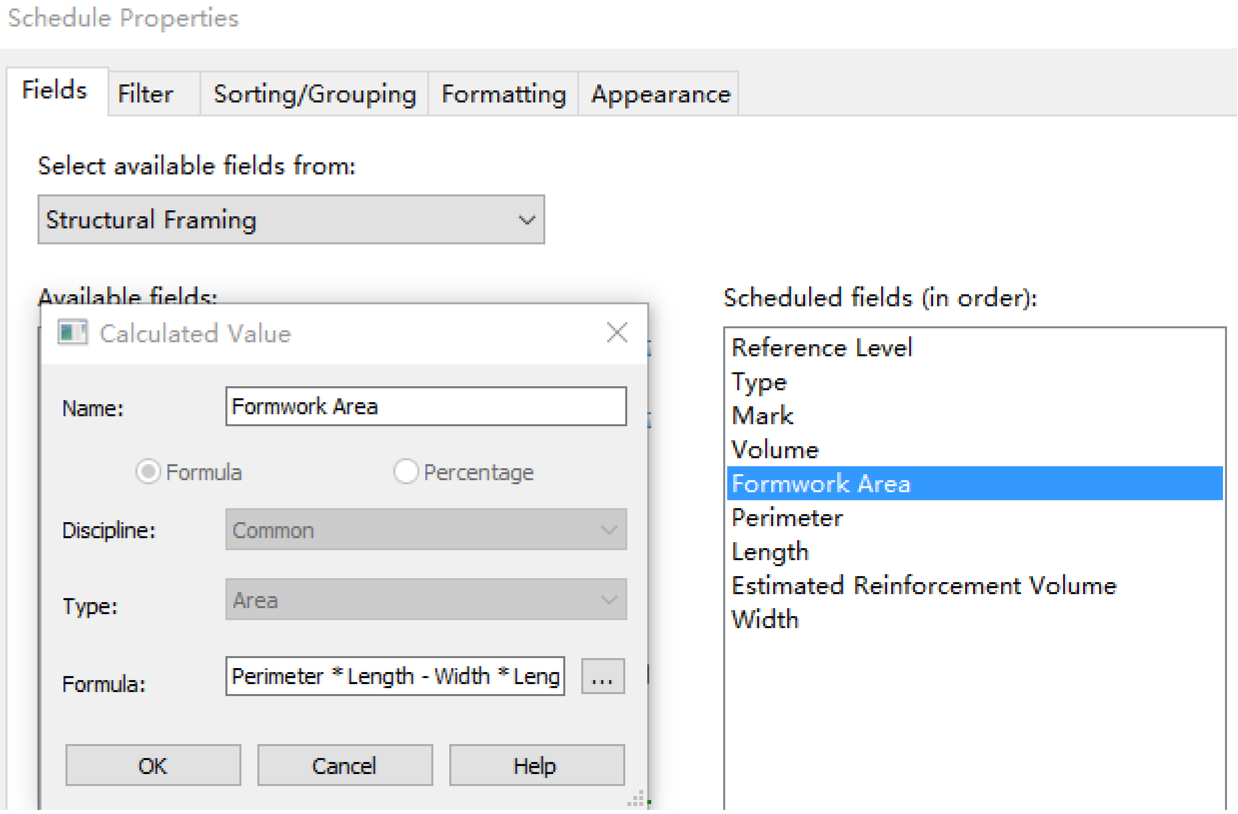
Type: Area

Formula: Perimeter * Length

Scheduled fields (in order):

- Base Level
- Type
- Mark
- Volume
- Formwork Area
- Length
- Perimeter
- Estimated Reinforcement Volume

Figure 17: Parameters added to concrete structural columns schedule



Select available fields from: Structural Framing

Available fields:

Calculated Value

Name: Formwork Area

● Formula ○ Percentage

Discipline: Common

Type: Area

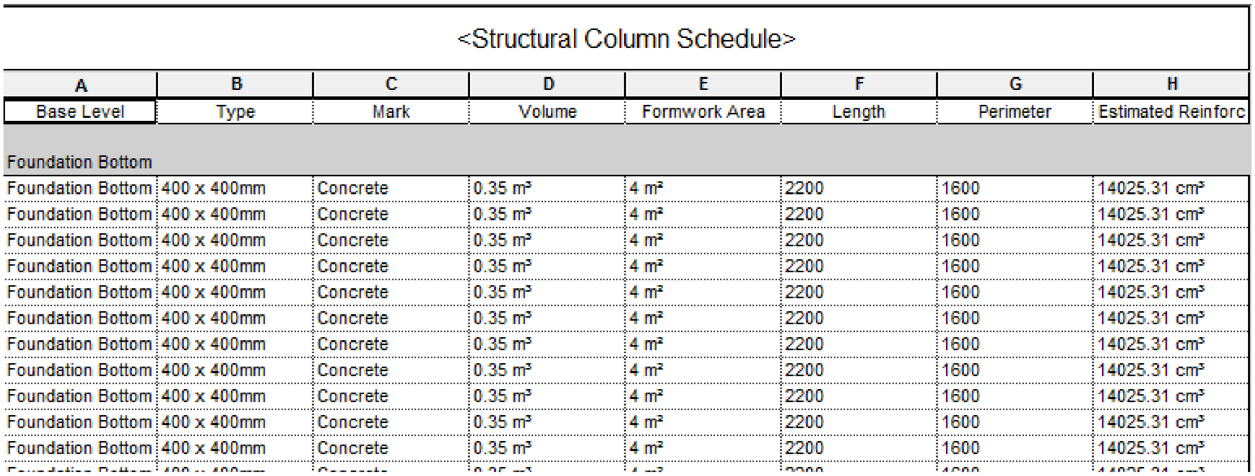
Formula: Perimeter * Length - Width * Leng

Scheduled fields (in order):

- Reference Level
- Type
- Mark
- Volume
- Formwork Area
- Perimeter
- Length
- Estimated Reinforcement Volume
- Width

Figure 18: Parameters added to concrete structural beam schedule

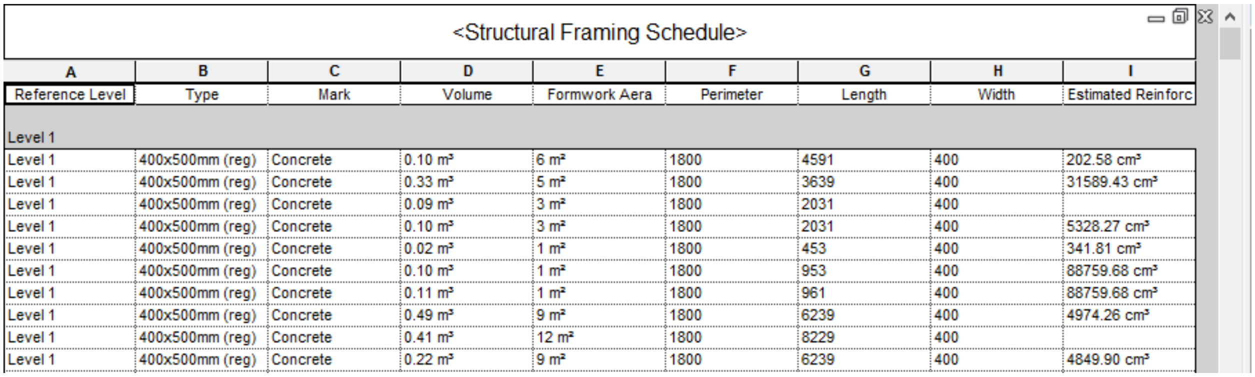
Figure 19 and Figure 20 show a sample schedule of columns and beams.



<Structural Column Schedule>

A	B	C	D	E	F	G	H
Base Level	Type	Mark	Volume	Formwork Area	Length	Perimeter	Estimated Reinforc
Foundation Bottom							
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³
Foundation Bottom	400 x 400mm	Concrete	0.35 m³	4 m²	2200	1600	14025.31 cm³

Figure 19: Screenshot of concrete structural column schedule in Revit



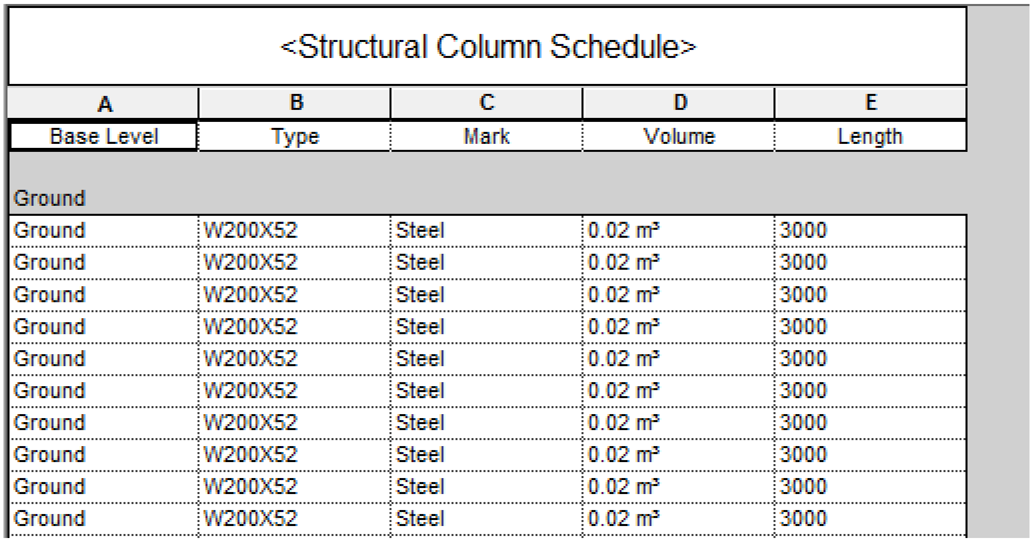
<Structural Framing Schedule>

A	B	C	D	E	F	G	H	I
Reference Level	Type	Mark	Volume	Formwork Aera	Perimeter	Length	Width	Estimated Reinforc
Level 1								
Level 1	400x500mm (reg)	Concrete	0.10 m^3	6 m^2	1800	4591	400	202.58 cm^3
Level 1	400x500mm (reg)	Concrete	0.33 m^3	5 m^2	1800	3639	400	31589.43 cm^3
Level 1	400x500mm (reg)	Concrete	0.09 m^3	3 m^2	1800	2031	400	
Level 1	400x500mm (reg)	Concrete	0.10 m^3	3 m^2	1800	2031	400	5328.27 cm^3
Level 1	400x500mm (reg)	Concrete	0.02 m^3	1 m^2	1800	453	400	341.81 cm^3
Level 1	400x500mm (reg)	Concrete	0.10 m^3	1 m^2	1800	953	400	88759.68 cm^3
Level 1	400x500mm (reg)	Concrete	0.11 m^3	1 m^2	1800	961	400	88759.68 cm^3
Level 1	400x500mm (reg)	Concrete	0.49 m^3	9 m^2	1800	6239	400	4974.26 cm^3
Level 1	400x500mm (reg)	Concrete	0.41 m^3	12 m^2	1800	8229	400	
Level 1	400x500mm (reg)	Concrete	0.22 m^3	9 m^2	1800	6239	400	4849.90 cm^3

Figure 20: Screenshot of concrete structural beams schedule in Revit

Model 2 – Steel structure

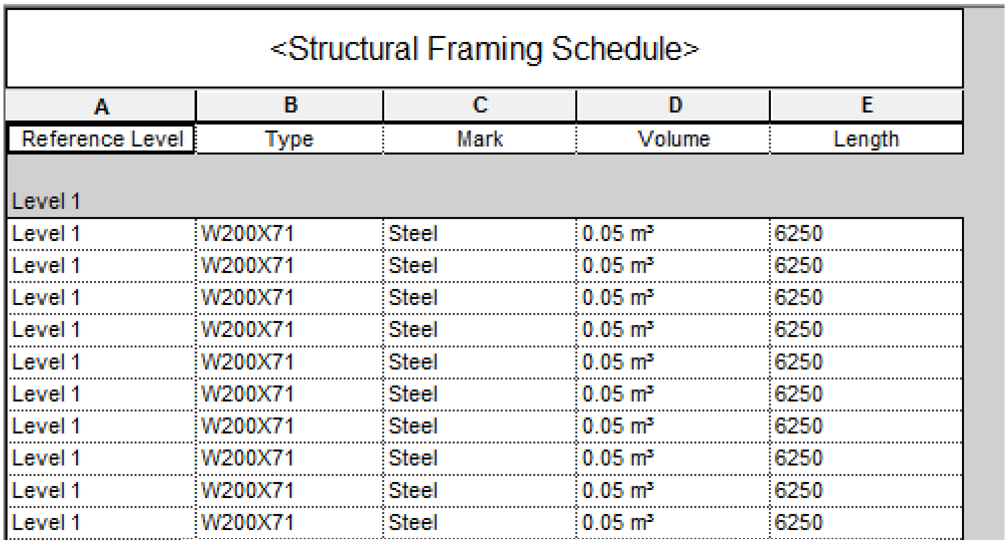
The quantity take-off process for the steel-framed model is more straightforward than for the one used for concrete-framed buildings, because all the parameters needed for structural columns and beams are built-in. However, it is required to add additional parameter, "Area", for the floor schedule to estimate the concrete volume and formwork area. Figure 21 and Figure 22 show samples of structural columns and beams schedules.



<Structural Column Schedule>

A	B	C	D	E
Base Level	Type	Mark	Volume	Length
Ground				
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000
Ground	W200X52	Steel	0.02 m^3	3000

Figure 21: Screenshot of steel structural column schedule from Revit



<Structural Framing Schedule>

A	B	C	D	E
Reference Level	Type	Mark	Volume	Length
Level 1				
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250
Level 1	W200X71	Steel	0.05 m^3	6250

Figure 22: Screenshot of steel structural beams & joists schedule from Revit

4.2.2. Manufacturing phase calculation

As mentioned in Chapter 3, the embodied energy and emissions for the manufacturing phase is calculated by multiplying the quantities of materials provided and corresponding embodied energy and carbon coefficient. The formulas are presented as Equation (2) and Equation (3) in chapter 3. The wastage of each type of material during the construction stage is accounted in this phase.

Model 1- Concrete Structure

Table 8, Table 9, and Table 10 display the embodied energy and carbon for concrete, rebar, and plywood used for the concrete beams. Table 11, Table 12, and Table 13 show the embodied energy and carbon for concrete, rebar, and plywood used for the concrete columns. Table 14, Table 15, and Table 16 indicate the embodied energy and carbon for concrete, rebar, and plywood used for the concrete slabs.

Table 8: Embodied energy and carbon for concrete used in beam system

Reference Lever	Number of Component	Volume (m3)	Mass[a] (kg)	EE (MJ)	EC (kgCO$_2$e)
Ground	141	80.69	198497.4	174677.71	26201.66
Level 1	149	54.56	134217.6	118111.49	17716.72
Level 2	143	50.44	124082.4	109192.51	16378.88
Level 3	140	52.88	130084.8	114474.62	17171.20
Roof	139	51.8	127428	112136.64	16820.50
Total	712	290.35	714310.2	628592.97	94288.96

Table 9: Embodied energy and carbon for rebar used in beam system

Reference Lever	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC (kgCO$_2$e)
Ground	2.04	16689.33	290394.41	23365.07
Level 1	1.91	15662.10	27252.50	21926.94
Level 2	1.76	14377.09	250161.3	20127.92
Level 3	1.83	14951.77	260160.80	20932.48
Roof	1.44	11761.42	204648.77	16465.99
Total	8.97	73441.71	1277885.78	102818.40

Table 10: Embodied energy and carbon for plywood used in beam system

Reference Lever	Formwork Area(m^2)	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC (kgCO$_2$e)
Ground	896	16.13	9870.34	37013.76	1110.41
Level 1	934	16.81	10288.94	38583.54	1157.51
Level 2	880	15.84	9694.08	36352.80	1090.59
Level 3	872	15.70	9605.95	36022.32	1080.67
Roof	870	15.66	9583.92	35939.70	1078.19
Total	4452	80.14	12260.81	183912.12	5517.36

Table 11: Embodied energy and carbon for concrete used in column system

Base Level	Number of Component	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC (kgCO$_2$e)
Foundation	76	26.60	65436	57583.68	8637.55
Ground	78	19.44	47822.40	42083.71	6312.56
Level 1	75	18.55	45633	40157.04	6023.56
Level 2	74	18.50	45510	40048.80	6007.32
Level 3	74	17.96	44181.60	38879.81	5831.97
Total	377	101.05	248583	218752.04	32812.96

Table 12: Embodied energy and carbon for rebar used in column system

Base Level	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Foundation	1.00	8198.99	142662.47	11478.59
Ground	0.56	4600.08	80041.41	6440.11
Level 1	0.57	4677.13	81382.01	6547.98
Level 2	0.59	4845.90	84318.73	6784.27
Level 3	0.55	4512.81	78522.96	6317.94
Total	3.28	26834.92	466927.57	37568.89

Table 13: Embodied energy and carbon for plywood used in column system

Base Level	Formwork Area(m^2)	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Foundation	304	5.47	3348.86	12558.24	376.75
Ground	312	5.62	3436.99	12888.72	386.66
Level 1	300	5.40	3304.80	12393.00	371.79
Level 2	296	5.33	3260.74	12227.76	366.83
Level 3	296	5.33	3260.74	12227.76	366.83
Total	1508	27.14	4153.03	62295.48	1868.86

Table 14: Embodied energy and carbon for concrete used in slabs

Reference Lever	Volume (m3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Ground	288.28	709168.80	624068.54	93610.28
Level 1	302.52	744199.20	654895.30	98234.29
Level 2	292.79	720263.40	633831.79	95074.77
Level 3	299.99	737975.40	649418.35	97412.75
Roof	283.99	697459.20	613764.10	92064.61
Total	1467.10	3609066.00	3175978.08	476396.712

Table 15: Embodied energy and carbon for rebar used in slabs

Reference Lever	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Level 1	0.58	4750.20	82653.48	6650.28
Level 2	0.57	4668.30	81228.42	6535.62
Level 3	0.57	4668.30	81228.42	6535.62
Roof	0.57	4668.30	81228.42	6535.62
Total	2.29	18755.1	326338.74	26257.14

Table 16: Embodied energy and carbon for plywood used in slabs

Base Level	Formwork Area(m^2)	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Ground	1372.77	24.71	3780.61	56709.13	1701.27
Level 1	1440.56	25.93	3967.30	59509.53	1785.29
Level 2	1350.01	24.30	3717.93	55768.91	1673.07
Level 3	1350.01	24.30	3717.93	55768.91	1673.07
Roof	1350.01	24.30	3717.93	55768.91	1673.07
Total	6863.36	123.54	4725.42	70881.35	2126.44

Note: [a] wastage of each material during erection process is accounted, Mass = Volume * Density * (1+ waste factor) and concrete forms are reused for 4 times.

Model 2 – Steel Structure

In contrast to the concrete-framed structure, steel is the only material used in beams & joists and columns in the steel frame structure. Concrete and forms, however, are used in the composite slabs. Table 17 and Table 18 show the embodied energy and carbon in steel beams & joists and columns, respectively. Table 19 and Table 20 display the embodied energy and carbon in the slabs of the steel structure.

Table 17: Embodied energy and carbon for steel used in beam & joist system

Reference Level	Number of Component	Volume (m3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Level 1	161	7.19	58886.10	1183610.61	85973.71
Level 2	160	7.14	58476.6	1175379.66	85375.84
Level 3	158	6.98	57166.20	1149040.62	83462.65
Roof	142	6.16	50450.40	1014053.04	73657.58
Total	621	27.47	224979.30	4522083.93	328469.78

Table 18: Embodied energy and carbon for steel used in columns

Base Level	Number of Component	Volume (m3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Ground	64	1.28	10483.20	210712.32	15305.47
Level 1	64	1.28	10483.20	210712.32	15305.47
Level 2	62	1.24	10155.60	204127.56	14827.18
Level 3	62	1.24	10155.60	204127.56	14827.18
Total	252	5.04	41277.6	829679.76	60265.30

Table 19: Embodied energy and carbon for concrete used in slabs

Reference Lever	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Ground	74.51	183285.38	161291.13	24193.67
Level 1	84.97	209029.28	183945.76	27591.86
Level 2	80.49	197996.18	174236.63	26135.50
Level 3	80.49	197996.18	174236.63	26135.50
Roof	80.49	197996.18	174236.63	26135.50
Total	400.94	986303.18	867946.79	130192.02

Table 20: Embodied energy and carbon for plywood used in slabs

Reference Lever	Formwork Area(m^2)	Volume (m^3)	Mass[a] (kg)	EE (MJ)	EC ($kgCO_2e$)
Level 1	1307.25	23.53	3600.17	54002.50	1620.07
Level 2	1238.25	22.29	3410.14	51152.11	1534.56
Level 3	1238.25	22.29	3410.14	51152.11	1534.56
Roof	1238.25	22.29	3410.14	51152.11	1534.56
Total	5022.00	90.40	3457.65	51864.71	1555.94

4.2.3. Construction phase calculation

4.2.3.1. Transportation stage

Transportation distance for concrete was assumed to be 25 km, because fresh concrete is a locally-sourced material. In order to analyze impacts of transportation distance and number of distribution centers on the energy usage in transportation stage, 1000 km, 2000 km, and 3000 km were assumed as transportation distances with variable distribution centers from 0 to 3 for both steel and timber products. Table 21, Table 22, and Table 23 show the embodied energy and carbon of different materials in the transportation stage for the concrete structure. Table 24 and Table 25 present the embodied energy and carbon in the transportation stage for the steel frame.

Model 1 – Concrete structure

Table 21: Embodied energy and carbon of forms in transportation stage for concrete structure

Distance(km)		1000		2000		3000	
		EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)
Number of Distribution Center	0	23511.09	2509.02	41766.56	4457.18	60022.03	6405.34
	1	77695.03	6631.53	95950.50	8579.68	114205.97	10527.84
	2	131878.96	10754.03	150134.44	12702.19	168389.91	14650.35
	3	186062.90	14876.54	204318.38	16824.70	222573.85	18772.86

Table 22: Embodied energy and carbon of rebar in transportation stage for concrete structure

Distance(km)		1000		2000		3000	
		EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)
Number of Distribution Center	0	132387.09	14127.88	264774.18	28255.75	397161.27	42383.63
	1	186776.46	18266.01	319163.55	32393.89	451550.64	46553.02
	2	241165.83	22404.15	373552.92	36532.02	505940.01	50722.42
	3	295555.20	26542.29	427942.29	40670.16	560329.38	54891.82

Table 23: Embodied energy and carbon of concrete in transportation stage for concrete structure

Distance(km)	EE(MJ)	EC($kgCO_2e$)
25	390856.79	19068.50

Model 2 – Steel structure

Table 24: Embodied energy and carbon of steel components in transportation stage for steel structure

Distance(km)		1000		2000		3000	
		EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)	EE (MJ)	EC ($kgCO_2e$)
Number of Distribution Center	0	296130.92	31602.03	592261.85	63204.06	888392.77	94806.09
	1	340277.18	34960.84	636408.10	66562.87	932539.03	98164.90
	2	384423.43	38319.64	680554.35	69921.67	976685.28	101523.70
	3	428569.68	41678.44	724700.61	73280.47	1020831.53	104882.51

Table 25: Embodied energy and carbon of concrete in transportation stage for steel structure

Distance(km)	EE(MJ)	EC($kgCO_2e$)
25	84319.06	4113.62

4.2.3.2. Erection stage

The energy consumption and emissions associated with the erection stage are calculated by multiplying the working hours of the equipment by its energy consumption factors (ECF).

GROVE RT530E-2 mobile crane with a capacity of 30 ton was selected for the rebar, forms, and steel components lifting process, and Alliance 38 Meter LZ-Fold Boom Pump with the MACK chassis was selected to complete the concrete placement task. The engine of MACK series provides 395hp for the 30- and 40-meter class pump model. Table 26 indicates the properties of selected mobile crane.

Table 26: Properties of Grove RT530E-2 mobile crane

Maximum slewing speed	Maximum hoist speed	Gross House Power
2.0 RPM	136 m/min	163.6 hp

In Equation (12) and Equation (13), 60% and 40% were defined as the acceptable maximum and minimum percentages for hoisting and slewing speeds. To maintain operation safety, 85% was defined as the safety factor(x) for each motion in Equation (14). 105^{o} is assumed as the average angle between the warehouse and installation position in Equation (15).

Following Equation (9) and Table 6, the energy consumption factor for the mobile crane and concrete pump are estimated, 684.77 MJ/h for mobile crane and 1653.33 MJ/h for concrete pump. The crane working hour is calculated using Equation (12) to Equation (15). The concrete pump working hour is calculated using Equation (18), in which the labor productivities of concrete placement (P_i) for columns and beams are provided by RS Means Building Construction Cost Data. The embodied energy and carbon for erection stage of concrete frame and steel frame are presented in Table 27 to Table 30.

Model 1 – Concrete structure

Table 27: Embodied energy and carbon of Lifting Rebar and forms for concrete structure

	Energy Consumption Factor = 684.77 MJ/h		
Material	Lifting Time TLP (h)	EE(MJ)	EC(kgCO$_2$e)
Rebar	79.43	54389.37	4138.14
Forms	79.13	54183.94	4122.51
Total	158.56	108573.31	8260.64

Table 28: Embodied energy and carbon of concrete placement for concrete structure

	Energy Consumption Factor = 1653.33 MJ/h			
Assembly	Volume(m3)	Working Hour(h)	EE(MJ)	EC(kgCO$_2$e)
Beam	290.35	50.68	83783.09	6374.52
Column	101.05	11.68	19316.08	1469.64
Slabs	1467.10	85.30	141023.28	10729.45
Total	1858.80	147.66	244122.45	18573.61

Model 2 – Steel structure

Table 29: Embodied energy and carbon of erection stage for steel structure

	Energy Consumption Factor = 684.77 MJ/h				
Assembly	Lifting Time (h)	Installation Time(h)	Working Hour (h)	EE (MJ)	EC (kgCO$_2$e)
Beam	46.72	150.40	197.12	134982.74	10269.97
Column	18.89	18.73	37.26	25517.36	1941.45
Total	65.61	169.13	234.38	160500.10	12211.42

Table 30: Embodied energy and carbon of concrete placement for steel structure

	Energy Consumption Factor = 1653.33 MJ/h			
Assembly	Volume(m3)	Working Hour(h)	EE(MJ)	EC(kgCO$_2$e)
Slabs	400.94	29.97	49543.06	3769.38

CHAPTER 5: Results Discussion

This chapter discusses the results from Chapter 4, where the estimated embodied energy and emissions values of the two building structures are analyzed. The embodied energy and emissions are expressed in MJ/m^2 (embodied energy per unit of indoor space area) and in kgCO$_2$e/m^2 (equivalent carbon emission per unit of indoor space area), respectively. In particular, the results are separately discussed for manufacturing and construction phases.

5.1. Manufacturing Phase Results

Figure 23 and Figure 24 illustrate the embodied energy and emission values of the different materials used in the two structures.

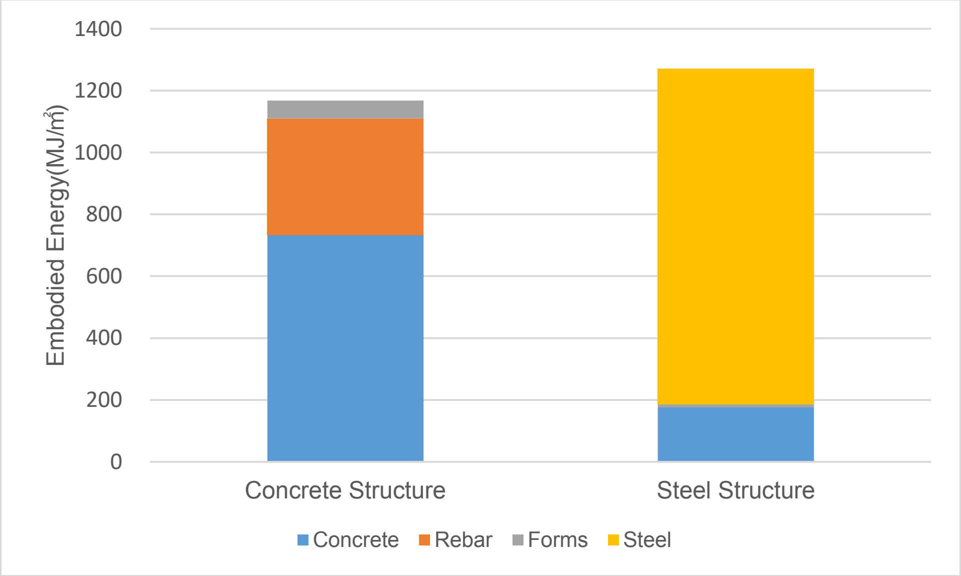


Figure 23: Embodied energy of materials in the building structures during the manufacturing phase

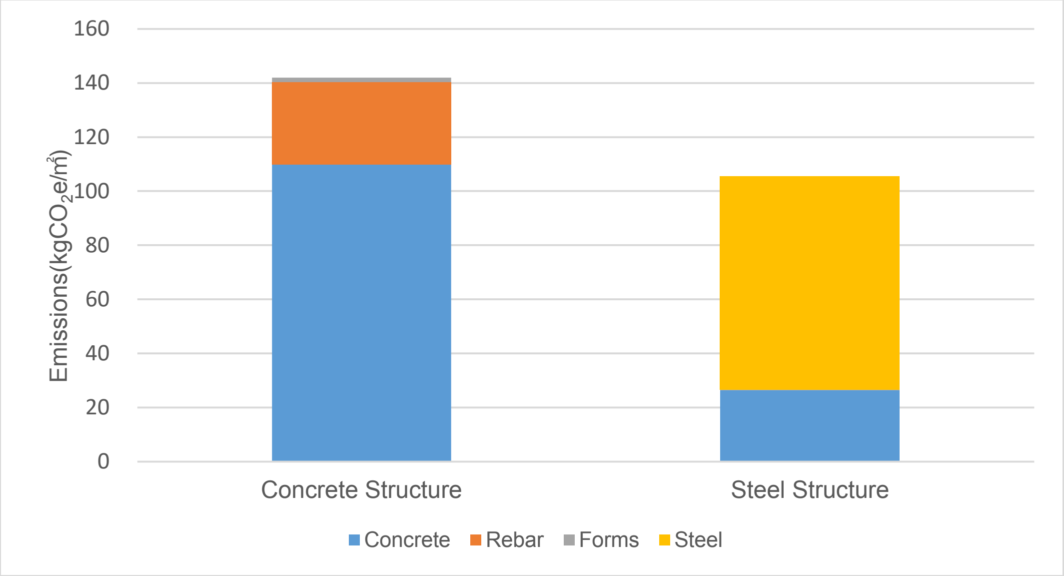


Figure 24: Emissions of materials in the building structures during the manufacturing phase

From the two graphs, it is evident that the energy consumption of the steel structure is larger than the concrete structure during the manufacturing phase, which is consistent with some other research findings (Heravi et al. 2016). However, the concrete structure produces more GHG emissions. This is due to higher ratio of embodied carbon of concrete production compared to its embodied energy (see Table 1). Production embodied energy of concrete is 4.4% of the steel, but the ratio for the embodied carbon is about 9%. This higher ratio is due to large level of CO_2 release during production of cement (Kosmatka et al. 2011).

The most energy used in the production phase of reinforced concrete-framed structure is for fresh concrete, which accounts for 732.75 MJ/m^2, followed by the rebar production, 377.21 MJ/m^2. The least energy consumption, 57.75 MJ/m^2, is due to the plywood production of forms, considering that they are reused four times. A similar tendency happens in emissions: the most CO_2e is emitted by concrete production, followed by rebar and forms. The emissions of concrete, rebar, and plywood forms are 109.91 $kgCO_2e/m^2$, 30.35 $kgCO_2e/m^2$, and 1.73 $kgCO_2e/m^2$, respectively. Overall, the energy consumption of the production phase of the sample concrete structure was 1167.72 MJ/m^2, and the carbon emission was 142.00 $kgCO_2e/m^2$.

For the steel structure, the amount of energy used to produce steel columns and beams was 1084.54 MJ/m^2, because steel has a high energy consumption factor, 20.1 MJ/kg (see Table 1), which is much greater than the other structural materials used in the concrete building. The energy used to produce concrete slabs and plywood forms were 175.89 MJ/m^2 and 10.51 MJ/m^2, respectively. The carbon emissions of the steel structure during the manufacturing phase was 105.48 kgCO$_2$e/m^2, less than the concrete-framed sample.

5.2. Construction Phase Results

This section examines the embodied energy and carbon emission results for the transportation and construction activities, and discusses the impact of some major factors, such as transportation distance and number of distribution centers on the results.

5.2.1 Transportation Stage

Figure 25, Figure 26, Figure 27 show the embodied energy and emissions of the concrete and steel structures during the transportation stage with different transportation distances. It is important to mention that the transportation distances for steel and wood products were the same, and it was altered from 1000 km to 3000 km. For the concrete, the transportation distance was assumed 25 km.

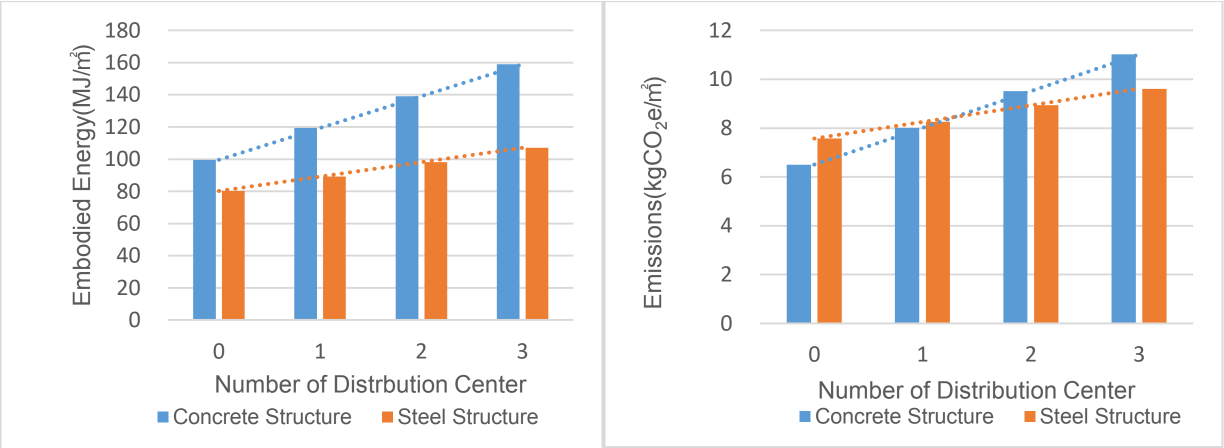


Figure 25: Embodied energy and emissions in the building structures during transportation stage (1000 km)

Figure 25 displays the embodied energy and emissions in the concrete and steel structures during the transportation stage with a distance of 1000 km, and the number of distribution centers vary from 0 to 3. It is clear that the growth rates of embodied energy and emissions of the concrete structure are both higher than that of the steel structure, which means that the impact of the number of distribution centers on the concrete structure is greater than it is on the steel structure. Because there are two types of materials (plywood forms and steel products) require to be delivered for the concrete operation for a long distance. However, in each distribution center, those materials for the concrete structure consumed more energy in the loading/unloading process than that of the steel structure. To be specific, each distribution center consumes 19.78 MJ/m^2 for concrete structure, which is double than for steel structure, 8.95 MJ/m^2.

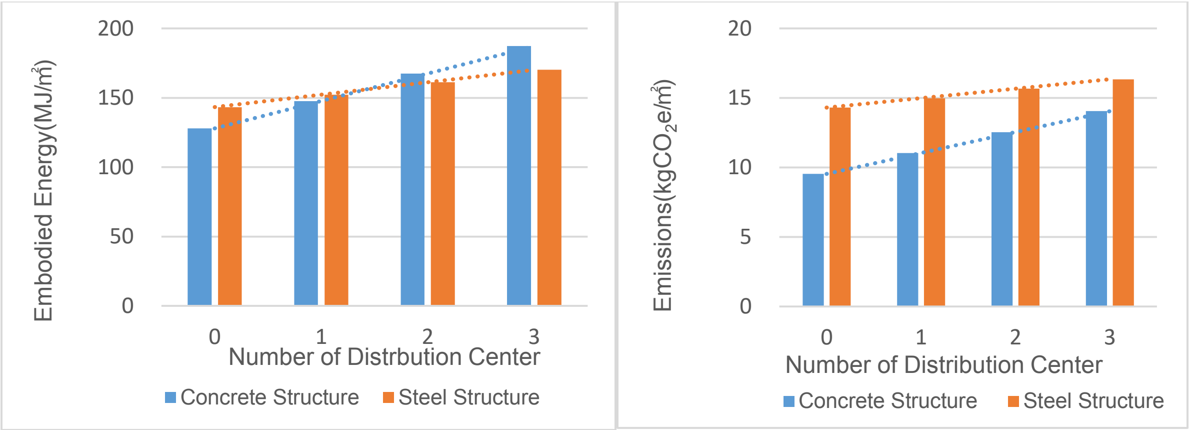


Figure 26: Embodied energy and emissions in the building structures during transportation stage (2000km)

In Figure 26, when the transportation distance rises to 2000 km, the embodied energy in the transportation stage of the steel structure shows a significant increase, nearly double than that in Figure 25. However, the increased embodied energy of the concrete structure is not that obvious because the transportation distance of the main material (concrete) is constant at 25 km. The increased embodied energy is caused by the forms and rebar which are small quantities compared to concrete. The same trend exists for the steel frame during the transportation stage when the distance increases to 3000 km. To summarize, when the transportation distance rises from 1000 km to 3000 km, more noticeable growth in energy and emissions is found in steel structure. However, the impact of the number of distribution centers on the embodied energy and emissions is greater in the concrete structure.

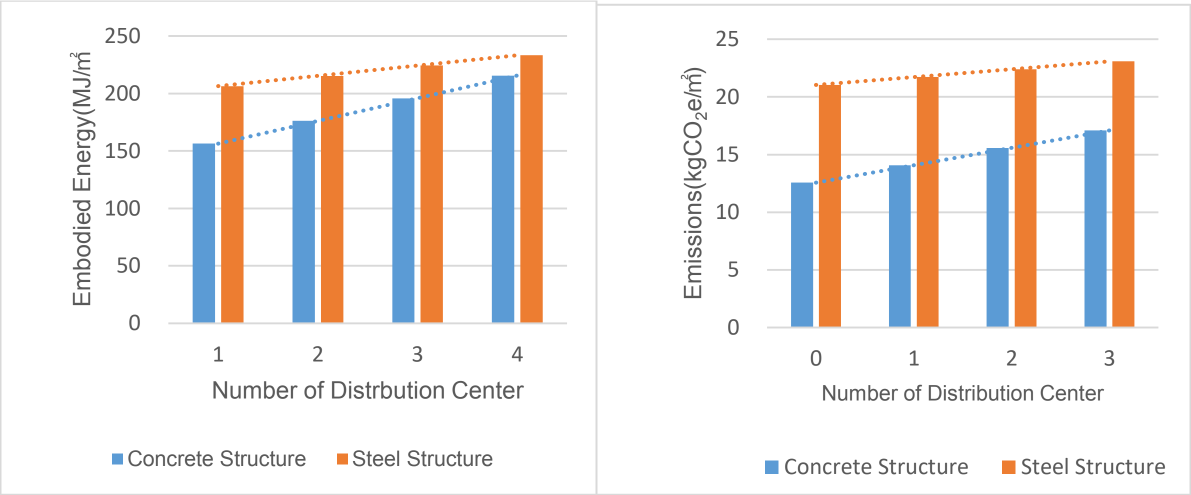


Figure 27: Embodied energy and emissions in the building structures during transportation stage (3000km)

5.2.2 Erection stage

Figure 28 and Figure 29 illustrate the embodied energy and emissions values for the studied structural systems during the erection stage.

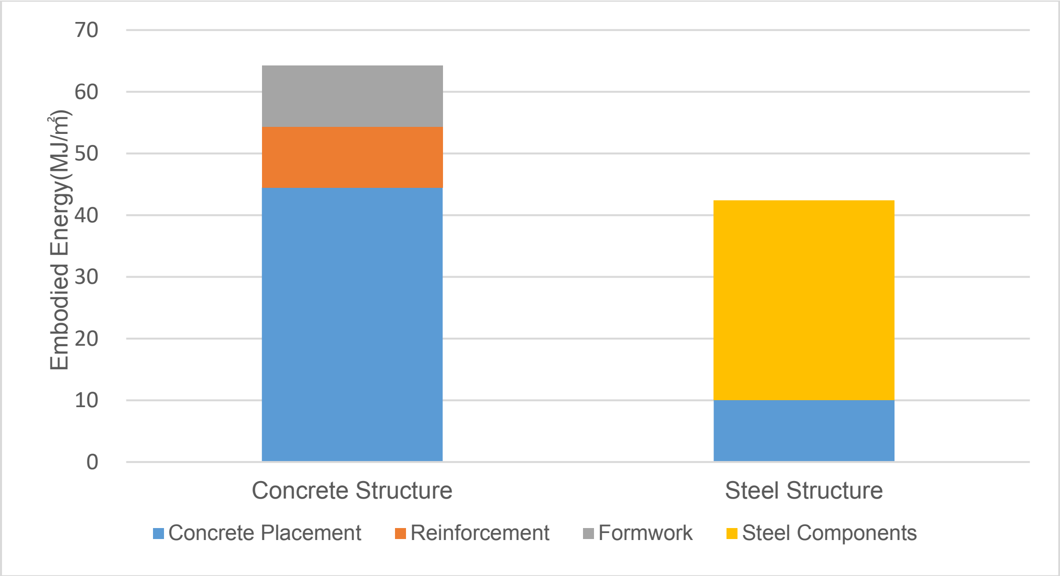


Figure 28: Embodied energy in the building structures during the erection stage

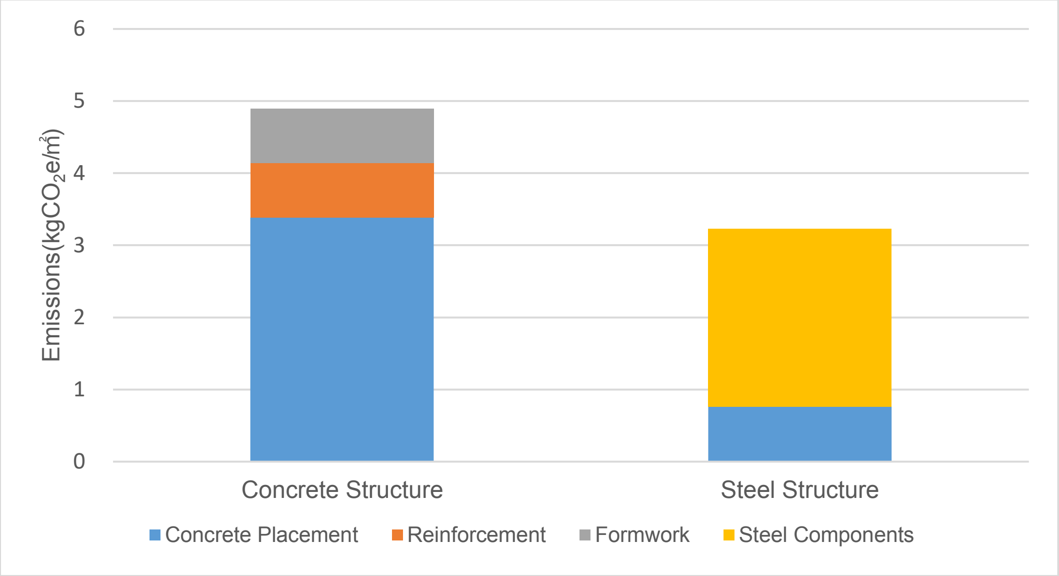


Figure 29: Emissions in the building structures during the erection stage

The energy consumption and emission of the concrete structure occur due to the lifting of the forms and rebars, and concrete placement tasks. More than half of the energy consumption and emissions is caused by concrete placement (44.46 MJ/m^2 and 3.38 kgCO$_2$e/m^2) in the concrete-framed construction processes. The forms and rebar lifting processes share quite similar proportions, because these two processes are performed by the same mobile crane and the working time of both depend on the pieces of assemblies (columns and beams). The main portion of the energy consumption and emissions of steel structure in the erection stage are due the installation of steel elements (e.g. beam and columns), which account for 32.37 MJ/m^2 energy consumption and 2.46 kgCO$_2$e/m^2 emission. In total, concrete structure consumes more energy and produces more emissions in the erection stage than steel structures, which indicates consistent results with previous findings (Guggemos and Horvath, 2005; Cole, 1998).

5.2.3 Transportation and Erection

Figure 30, Figure 31, and Figure 32 present the contribution of transportation and erection stage to the embodied energy and GHG emissions in the concrete structure during construction phase. Figure 33, Figure 34, and Figure 35 display the contribution of transportation and erection stage to the embodied energy and GHG emissions in the steel structure during the construction phase.

For the concrete structure, with the increase of transportation distance and number of distribution centers, the embodied energy rises from 163.81 MJ/m^2 to 279.92 MJ/m^2. With the same transportation distance, when the number of distribution center increases from 0 to 3, the variation of embodied energy is 59.33 MJ/m^2. The maximum variance ratio is 36.22% with a distance of 1000 km; the minimum variance ratio is 26.89% with a distance of 3000 km. The impact of the number of distribution centers on embodied energy during construction phase of the concrete structure becomes smaller with longer transportation distances.

Similarly, keeping the number of distribution centers constant, when the transportation distance increases from 1000 km to 3000 km, the variation is 56.79 MJ/m^2. The maximum variance ratio is 34.67% occurring under the condition of no distribution center and the minimum variance ratio is 25.45% occurring under the condition of three distribution centers. The impact of transportation distance on embodied energy during construction phase of concrete structure also becomes smaller with more distribution center. However, it is possible that more significant effects on concrete structure during the construction phase were caused by transportation distance rather than number of distribution centers.

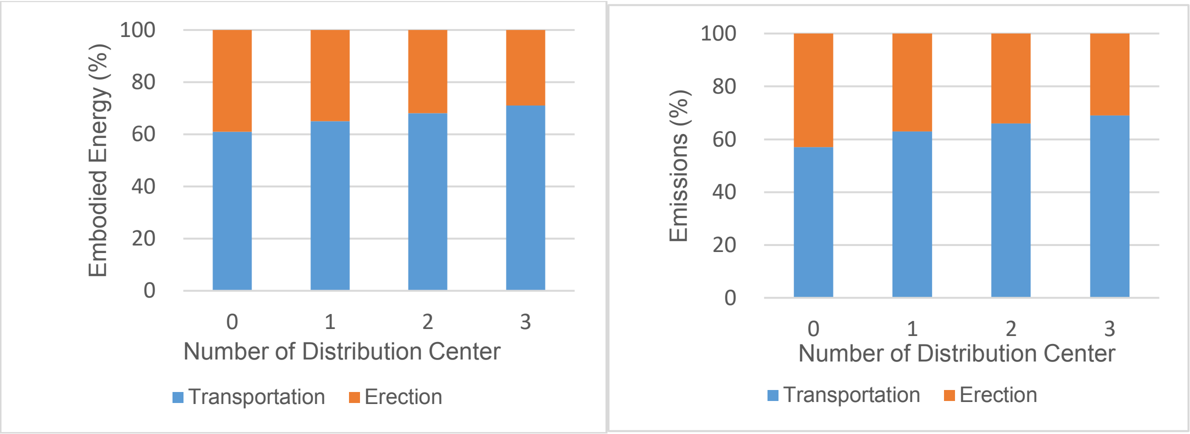


Figure 30: Embodied energy and emissions in concrete structure during construction phase (1000km)

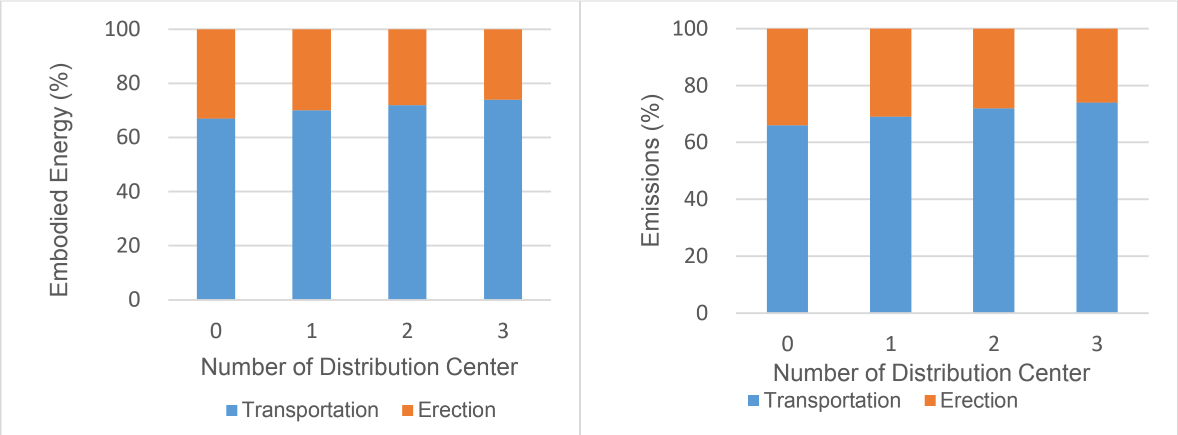


Figure 31: Embodied energy and emissions in concrete structure during construction phase (2000km)

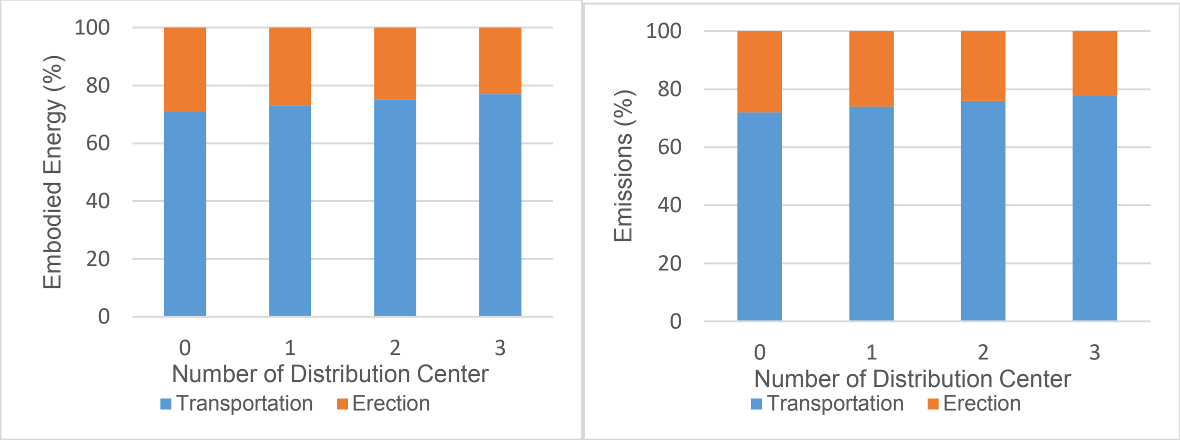


Figure 32: Embodied energy and emissions in concrete structure during construction phase (3000km)

For the steel structure, the embodied energy during the construction phase grows from 122.62 MJ/m^2 to 275.72 MJ/m^2 with the increase of transportation distance and distribution centers. Keeping the transportation distance constant, when the number of distribution centers increases from 0 to 3, the variation of embodied energy is 26.82 MJ/m^2. The maximum variance ratio is 21.88% with a distance of 1000 km. The minimum variance ratio is 10.78% with a distance of 3000km. Keeping the number of distribution centers constant, when the transportation distance increases from 1000km to 3000km, the variation is 126.26 MJ/m^2. The maximum variance ratio reached 102.97%, occurring under the condition of no distribution centers. The minimum variance ratio is 84.48%, which occurred under the condition of three distribution centers. Comparing the influence of transportation distance and distribution center on concrete and steel structures, the impact of transportation distance during the construction phase is higher for the steel structure. However, the effect of number of distribution centers is higher for the concrete structure.

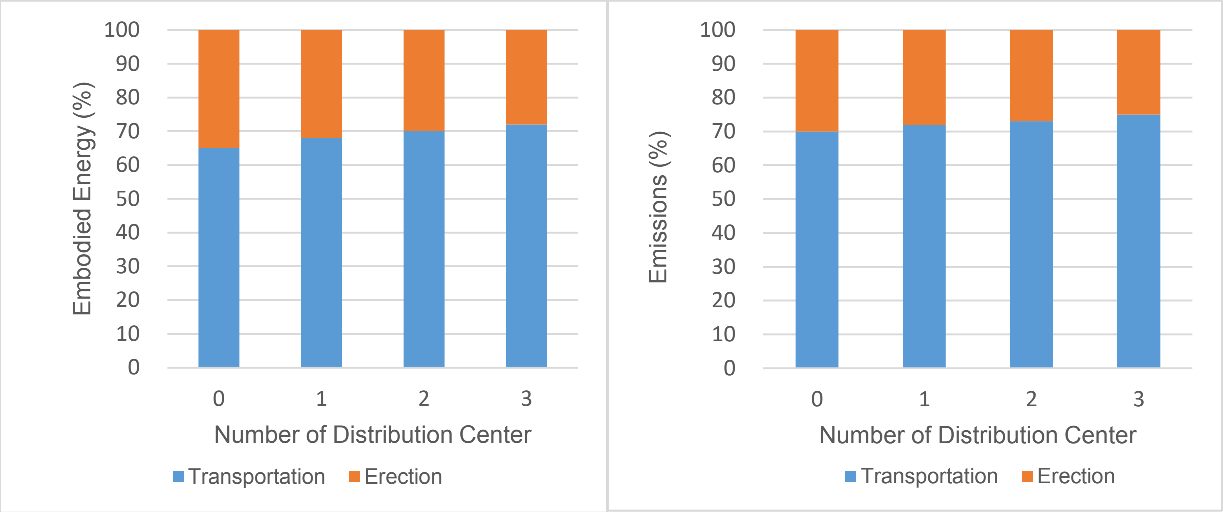


Figure 33: Embodied energy and emissions in steel structure during construction phase (1000km)

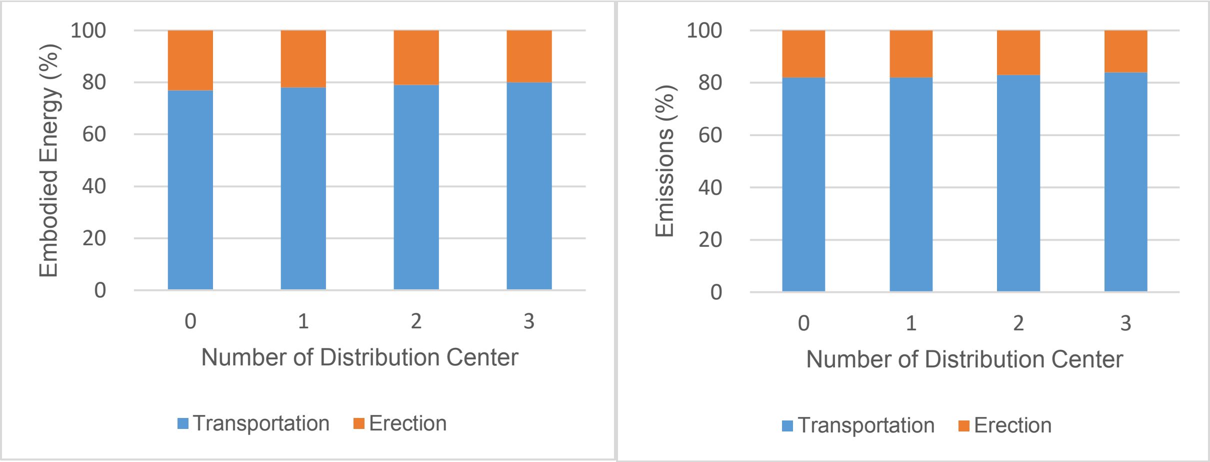


Figure 34: Embodied energy and emissions in steel structure during construction phase (2000km)

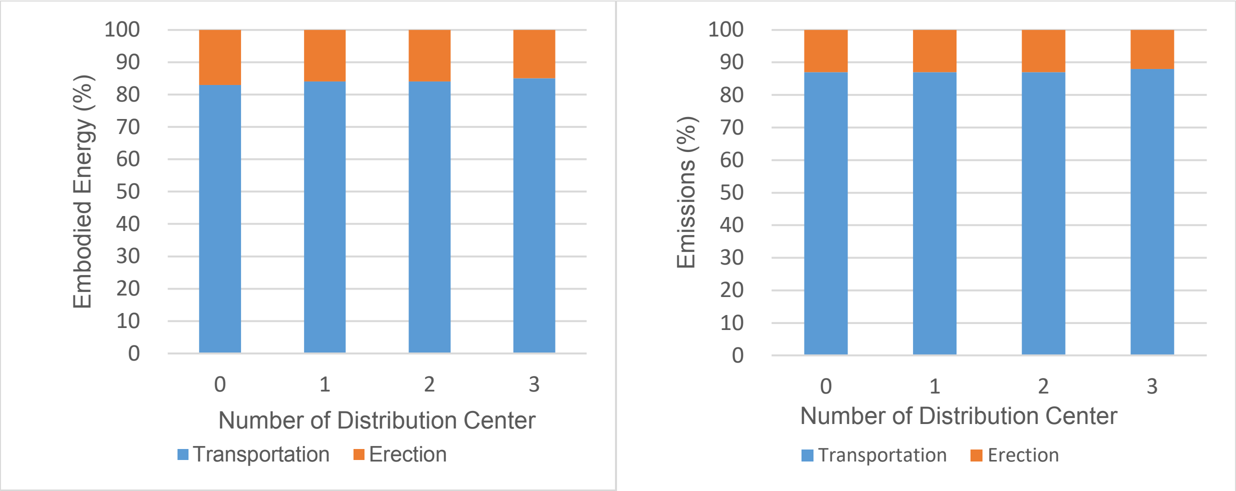


Figure 35: Embodied energy and emissions in steel structure during construction phase (3000km)

5.3. Discussion of Total Embodied Energy and Emission

This section compares the total embodied energy and emissions values of the concrete and steel structures.

Concrete structure

Figure 36, Figure 37, and Figure 38 present the total embodied energy and emission per square meter of the concrete structure with different transportation distances and number of distribution centers. The total embodied energy were 1331.53 to 1447.64 MJ/m^2 and emissions were 153.39 – 163.98 kgCO$_2$e/m^2 for the concrete structure. It is clear that the manufacturing phase is the element with the most energy consumption and emissions in the concrete structure. The manufacturing phase accounts for 80.66% to 87.70% of total embodied energy, and 86.60% to 92.57% of the total emissions in the concrete structure in different transportation scenarios. Next, the transportation represents 7.48% to 14.90% of total embodied energy and 4.24% to 10.42% of total emissions. Lastly, the erection stage consumed the least portion of energy and carbon emissions, which accounted for 4.44% to 4.82% of total embodied energy and 2.98% to 3.19% of total emissions, respectively. Therefore, the energy consumption and emissions of the construction phase represent 12.30% to 19.34% of the total embodied energy and 7.43% to

13.40% in of the GHG emissions.

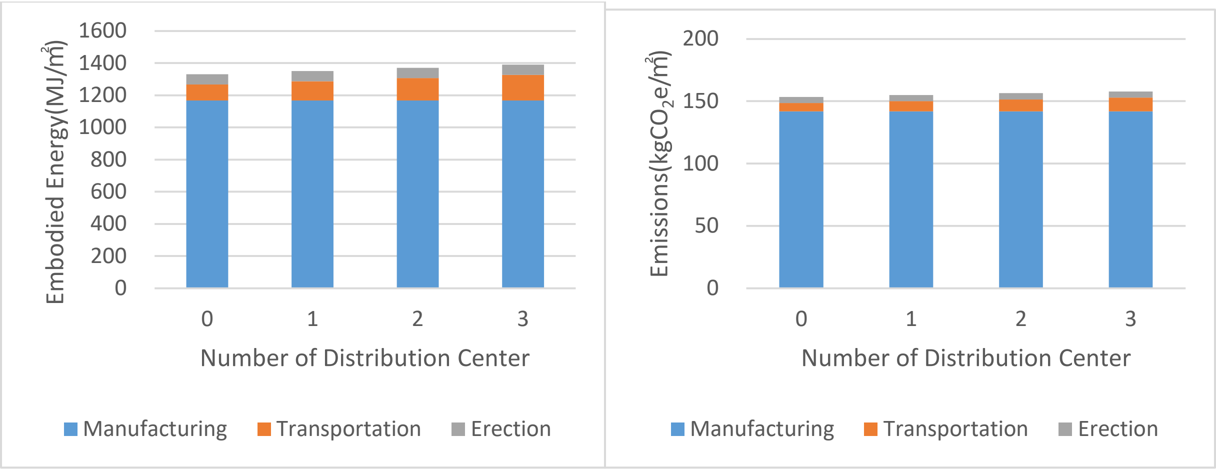


Figure 36: Total embodied energy and emissions in concrete structure (1000km)

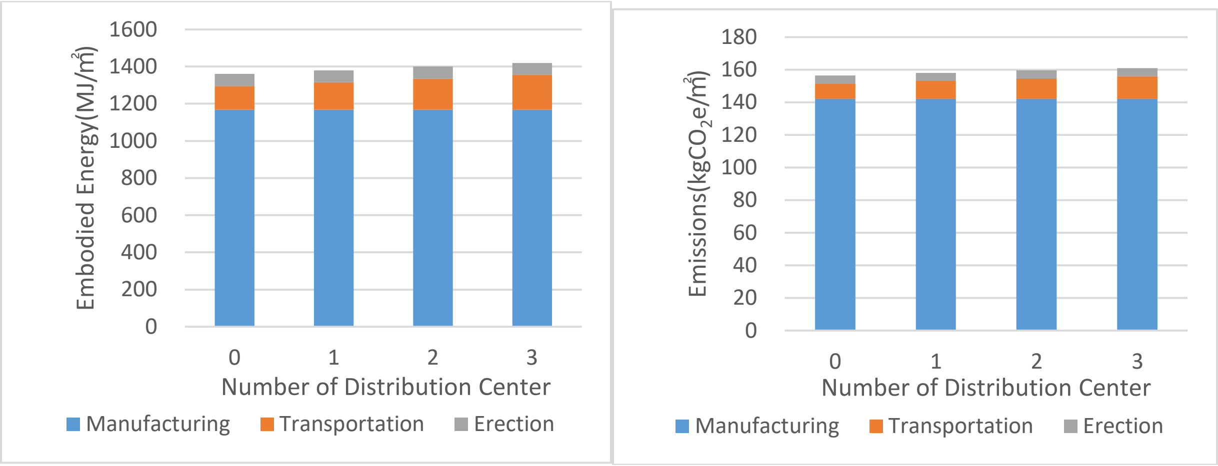


Figure 37: Total embodied energy and emissions in concrete structure (2000km)

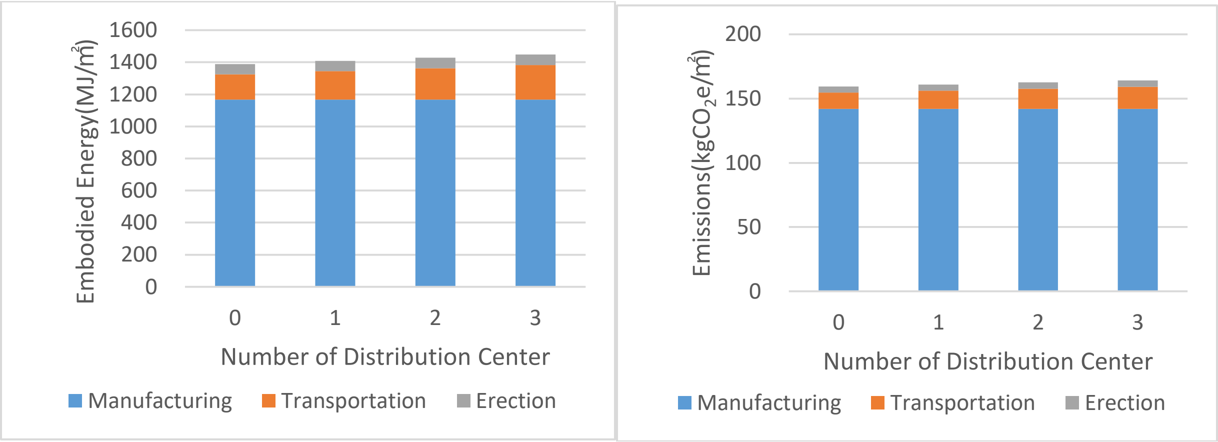


Figure 38: Total embodied energy and emissions in concrete structure (3000km)

Steel Structure

Figure 39, Figure 40, and Figure 41 present the total embodied energy and emission per square meter results of the steel structure associated with different transportation distances and number of distribution centers. The total embodied energy levels were between 1393.56 and 1546.66 MJ/m^2 and GHG emissions were 116.27 to 131.79 kgCO$_2$e/m^2 in the steel-framed building. The manufacturing phase in the steel structure represented 82.17% to 91.20% of the total embodied energy and 80.03% to 90.71% of the total GHG emissions. Consequently, the proportions of the construction phase in total embodied energy and emissions in the steel structural system were 8.80% to 17.83%, and 9.29% to 19.97%, respectively. To be specific, the transportation activities constitutes 5.76% to 15.08% of the total embodied energy and 6.51% to 17.52% in total emissions, whereas the erection stage only makes up 2.74% to 3.04% in total embodied energy and 2.45% to 2.77% in total emissions.

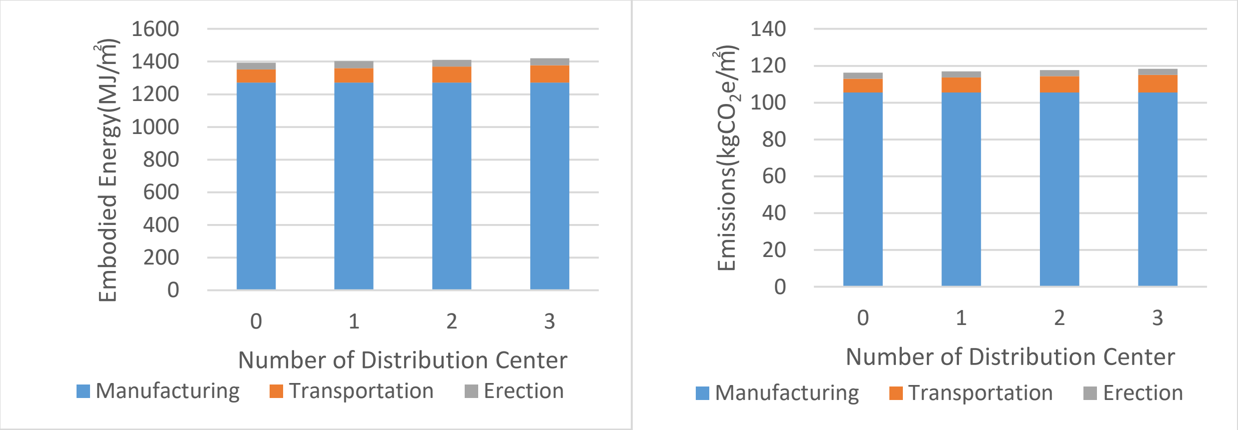


Figure 39: Total embodied energy and emissions in steel structure (1000km)

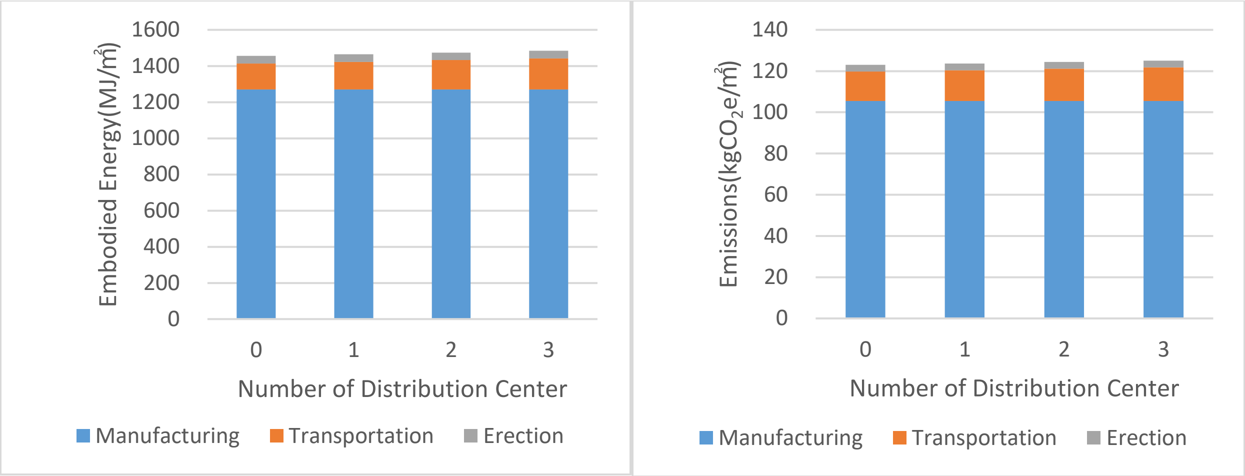


Figure 40: Total embodied energy and emissions in steel structure (2000km)

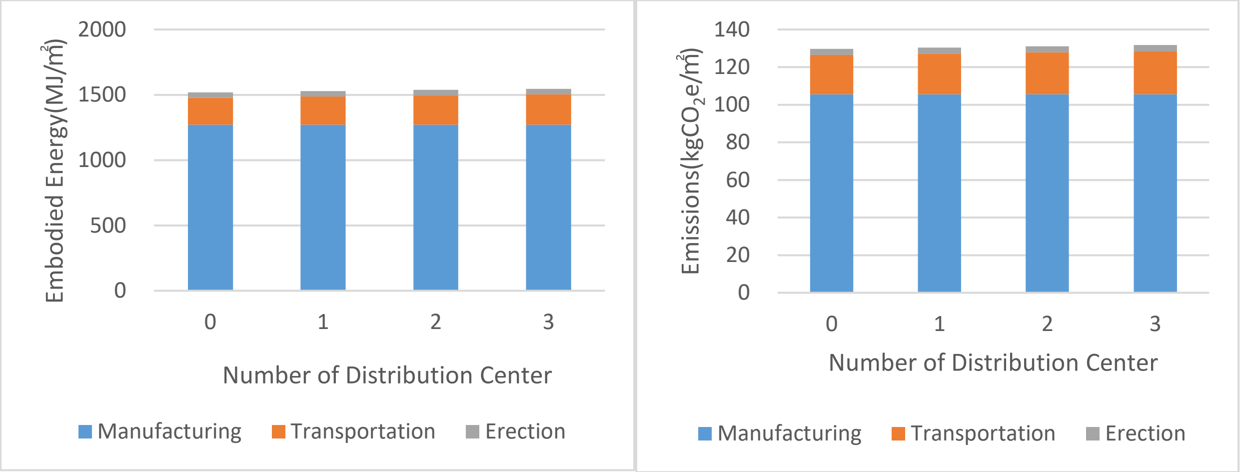


Figure 41: Total embodied energy and emissions in steel structure (3000km)

Based on the change of the ratios in total embodied energy and GHG emissions, it can be concluded that the impact of transportation distance and the number of distribution centers is considerable, namely for the steel-framed structural system. The variation rate of the total embodied energy is 8.72% for the concrete structure and 10.99% for the studied steel structure. The variation rate of the GHG emissions is 6.90% for the concrete structure and 13.35% for the steel structure. It is found that the sample concrete structure consumed slightly less energy per square meter, but produced more emissions per square meter than the steel structure.

Figure 42 and Figure 43 present the contribution of columns, beams, and slabs to the embodied energy and emissions. The results indicate that in the concrete structure, the contribution of the slabs in the total embodied energy was 53%, and 34% was attributed to the beams and 13% belonged to the columns. In total, 880.66 tons of carbon dioxide equivalent were emitted for the concrete structure, in which 62% was due to the slabs, 28% was for beams, and 10% was attributed to the columns (Figure 42). On the contrary, beams and joists resulted the biggest portion of total embodied energy in the steel structure, which was 72%. The ratio for the slabs and columns were 15% and 13%, respectively. For the GHG emissions, a total of 612.04 tons of carbon dioxide equivalent were emitted for the steel structure. The beams & joists are the main factor, accounted for 65% of the total emissions; the slabs resulted in 23%, and the least emissions, 12%, produced by the columns (Figure 43).

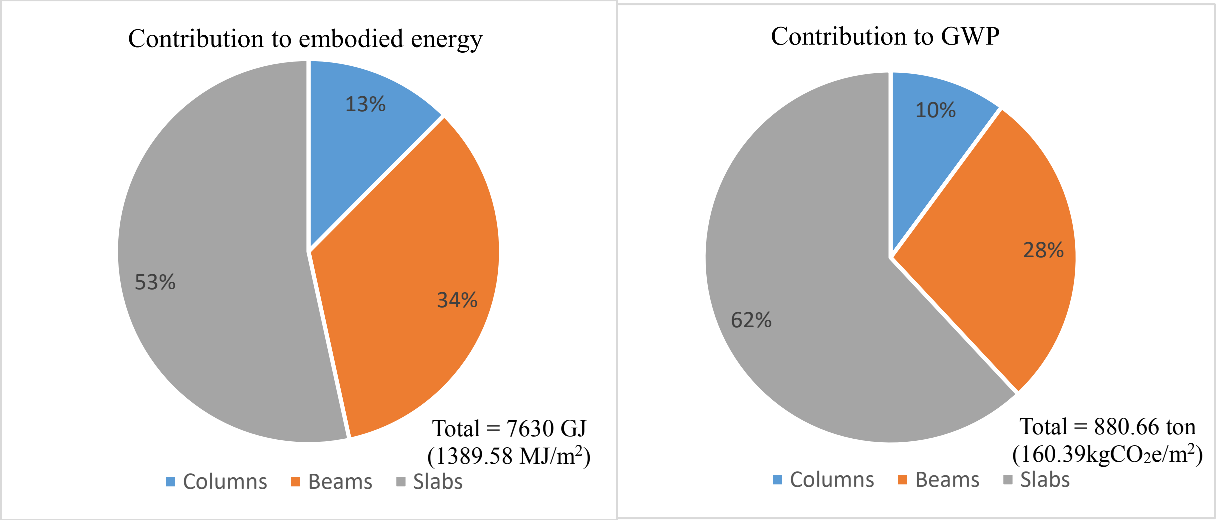


Figure 42: Contribution of columns, beams, and slabs to the embodied energy and GHG emissions in the concrete structure

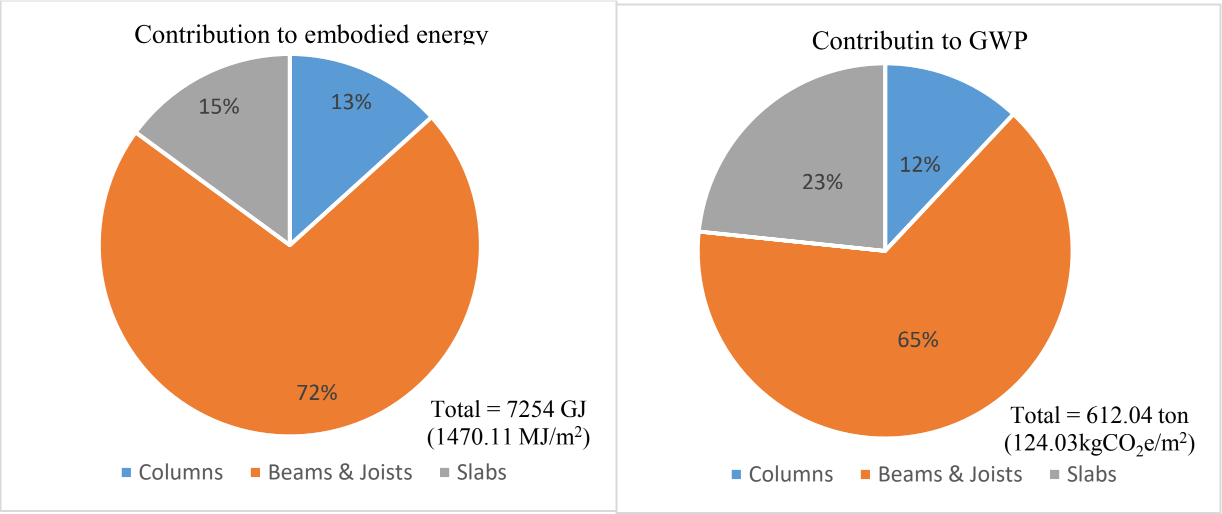


Figure 43: Contribution of columns, beam, and slabs to the embodied energy and GHG emissions in the steel structure

Table 31 and Table 32 summarize embodied energy and carbon footprint of a number of reinforced concrete and steel-framed structures studied in previous research projects. The findings of this research are quite similar to most of them, namely to the most recent studies (Heravi et al., 2016; Nadoushani & Akbrnezhad, 2015). Differences, however, exist in the results. Those studies considered the foundation in calculations as well, which was not the focus of this study as the size of the foundation was quite similar in both designs. Nonetheless, the effect of the foundation was considered in both models and was added to Table 31 and Table 32. Second, different databases and different construction equipment and methods were considered in these studies. Despite these factors, the ranges for the carbon emissions in the majority of the studies, including this project are rather similar.

Results of one study, however, was considerably lower than the others. The reason is that the case study of Monteiro (2015) was based on a simple one-story building structure (assembled with simple columns and beams), which was not an actual building with multiple floors, and the results were lower than the others which used real building models. The results from one of the research projects (Heravi et al., 2016) were greater than others, because the majority of the studied structures had more than eight floors. The finding on this study and another research work (Nadoushani & Akbrnezhad, 2015) supports a theory that the embodied energy (per unit of area) and GHG emissions (per unit of area) increases with the increase of the building floors. In other words, embodied energy and carbon rates are greater for high-rise structures compared to the low-rise buildings (Nadoushani & Akbrnezhad, 2015; Treloar et al, 2001). High-rise buildings require higher energy intensive structural components to resist lateral and vertical loads (Treloar et al, 2001) and in addition, the elements of a high-rise building require more erection energy due to more crane and hoist operation times.

Table 31: The estimated embodied energy of concrete and steel structures in similar studies

Description	Embodied Energy (MJ/m^2)				Location
	Concrete Structure		Steel Structure		
	Manufacturing Phase	Construction Phase	Manufacturing Phase	Construction Phase	
Cole (1998)	-	20-120	-	3-7	Canada
Monteiro (2015)	300-620	28-58	1400-2920	19-56	Denmark
Heravi et al. (2016)	1600-2579	140-220	2100-3780	260-370	Iran
This study	1167.72	163.81-279.92	1270.94	122.62-275.72	Canada
This study (incl. foundation)	1224.81	171.82-293.61	1334.46	128.75-289.50	Canada

Table 32: The estimated carbon footprint of concrete and steel structures in similar studies

Description	Embodied Carbon (kg/m^2)				Location
	Concrete Structure		Steel Structure		
	Manufacturing Phase	Construction Phase	Manufacturing Phase	Construction Phase	
Cole (1998)	-	0.4-1.0	-	5-20	Canada
Jonsson et al. (1998)	128	-	87	-	Sweden
Nadoushani & Akbrnezhad (2015)	132-204	21-30	132-190	14-18	Australia
This study	142	11.39-21.99	105.48	10.8-26.32	Canada
This study (incl. foundation)	151.18	12.13-23.41	113.77	11.65-28.39	Canada

CHAPTER 6 – Conclusion and Future Directions

This chapter summarizes the main findings and highlights limitations of this research. It also provides some directions for the future research.

6.1. Summary

The building construction sector is an energy-intensive industry; thus, it is important to reduce the energy consumption of buildings. Most of the recent studies focused on the operation phase of buildings' lifecycle, because it consumes the majority of energy during buildings life cycle (up to 90%) (Ramesh et al., 2010). The energy consumption in the construction phase, however, is still considerable (Winther and Hestnes, 1999; Thormark, 2002) and could have substantial environmental impacts. Some research efforts examined energy consumption and carbon footprint of various structural systems, but they used a number of databases and complex calculations, which do not offer an easy-to-use framework for decision-makers. This research introduced a BIM-based assessment framework to estimate the embodied energy and carbon dioxide equivalent emissions of different building structures, and a case study was presented to assess this framework in estimating the embodied energy and emissions of different structural systems.

First, according to the building construction life cycle, the embodied energy of the building is divided in to two phases: the production phase and construction phase. Different energy and emission calculation models and data inventories were created in spreadsheets for different phases and different structural systems. With the help of a BIM platform, the quantity take-offs can be automatically extracted from the design model and be linked with the encoded calculation model and databases in the spreadsheet. The BIM-based quantities list not only the structural elements and their volumes/masses, but it also contains valuable information needed for further processes, such as item location and material type.

6.2. Conclusion

By performing the methodology on similar concrete- and steel-framed structures, it was confirmed that the type of structural system has a significant impact on the embodied energy and emission of a building. It was found that the energy consumption of the manufacturing phase in the steel structure is more than that of the concrete structure. In the transportation stage, the energy consumption is affected by the material transportation distance and the number of distribution center, but it still can be found that the concrete structure consumes more energy than steel structure when the distance is no longer than 1000 km. When the distance is longer than 3000 km, the steel structure consumes more energy. For the distance between 1000 km to 3000 km, energy consumption depends on the number of distribution center. Finally, in the erection stage, concrete-framed building consumed more energy than the steel structure. Considering both transportation and erection stages as a construction phase, more energy is consumed by the concrete structure except when the transportation distance is longer than 3000 km.

The main contribution of this research is to provide a convenient framework to assess the embodied energy and emissions of a building structure to facilitate decision making process in the structural design stage. It can provide embodied energy and emission per square meter of concrete and steel-framed structures, which could be used to compare alternative structural systems. In addition, it considers the reality that energy is consumed in each distribution center during transportation stage and analyzes its impact on the overall embodied energy. Moreover, this framework uses BIM platform to perform materials quantity take off, which makes the process more accurate and easy-to-use.

6.3. Limitations

First, the quantity takeoff cannot be performed when the structure design is created by a conventional computer-aided design platform, such as Autodesk CAD, because the elements are simply modeled by point, lines, and planes, and do not include objects' attributes. In addition, the accuracy of the system depends on the level of details (LoD) of the modeled structure, for example reinforcement details may not exist in every BIM model.

Second, this framework is designed for assessing low-rise residential buildings. The equipment selected for the erection stage is based on the low-rise building construction. Assessment of the other types of buildings requires changing the equipment and corresponding data in the spreadsheet model. For example, tower cranes are the main choice to deliver material and building elements to the installation location, which have specific production and energy consumption (mainly electricity) rates.

Third, the database used for production phase and construction phase are from different sources. Although they are reliable, it is still possible to generate errors in the final report. As mentioned in the discussion section, data inventories for material production and transportation can differ in countries based on the employed technologies and methods. In addition, the embodied energy and carbon data from ICE used for the production phase might be less than the actual value. For example, some steel components cannot be directly used to build a structure, and they should be fabricated to columns or beams. Therefore, the estimated final results of the embodied energy and emissions could be less than the actual value. Finally, wooden structures were not covered in the case study due to lack of the equivalent timber structure design.

6.4. Future Directions

This study presented a promising step to automate assessment of embodied energy and emission of building structures using BIM platform. Future research is required to overcome the limitations of current framework in this study. First, the system could be expanded to include all the other building components, such architectural elements, in the estimation. Second, this system could be integrated with the BIM based platforms that model the operational energy of the building structures, which helps better understanding of energy consumption in a whole life cycle of a building structure. The system could be also expanded to estimate the embodied energy and carbon emission of the construction of more complex infrastructures, such as different bridge systems and industrial structures.

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