Embodied Energy Assessment of Building Structural Systems Using Building Information Modeling

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Abstract

Buildings contribute to socio-economic development of the human societies, but they are also among the main consumers of energy and contributors to the greenhouse gas emissions during their lifecycles. The construction phase of building projects is typically recognized for substantial use of natural resources and energy consumption. Steel, reinforced concrete, and engineered wood are the most common structural materials used in the Canadian construction industry. The environmental impact of the structural material is typically overlooked mainly because the industry lacks a documented assessment framework. There were some research efforts that studied energy consumption of the construction phase of building projects, but they mostly used a large number of complex calculations to estimate the consumed energy and emission. This paper introduces an innovative framework for the environmental assessment of the construction of building structural systems. This method uses a building information modelling platform to automate data extraction and then links them to certain databases to calculate embodied energy and emissions. This framework considers production, transportation, wastage, and installation/construction processes to calculate the impacts. An experimental study was carried out on two residential buildings, with a similar layout but different structural systems, to evaluate the practical use of this framework. It demonstrated a straightforward method to estimate embodied energy and emission of the structural system using the BIM model of the design. Similar to other studies, the manufacturing phase has the greatest impact on the embodied energy and emission of a building structure.

Keywords –

Embodied energy; Embodied carbon; Building information modelling; Structural system

1 Introduction

Buildings use energy either directly in the construction, operation, maintenance, renovation, and final demolition, or indirectly in the initial production of the construction materials, consumables, and other embodied energies [1]. Operational energy (OE) and embodied energy (EE) are the two types of energy consumption in buildings, where the embodied energy includes the energy used in extraction, manufacturing, transportation, and construction of building elements, and the operational energy covers with range of energy types used for operation of a building (e.g. lighting, and heating and cooling). It is estimated that the direct energy used in buildings is about 30%-40% of all primary energy, which results in 40%-50% of total GHG emissions [2].

Although operational energy constitutes 80%-90% of the total energy consumption of a building in its lifecycle [3], the embodied energy of the construction phase still can have a considerable environmental impact. Structural system is estimated to have the largest portion (more than 50%) of the total embodied impact of a building [4-5]. Several selection criteria, such as cost, speed of construction, mechanical performance, and availability of the material are usually considered to choose a certain structural system; however, the environmental impact is usually ignored [6].

A number of studies investigated the embodied energy and embodied carbon while using different structural materials and systems. The scopes and viewpoints of these studies, however, were different. A research stream assessed the impact of different structural materials and systems through the entire lifecycle of buildings using lifecycle assessment (LCA) framework. They commonly reported that the energy use in the operation phase has the greatest portion [7-8]. Another group of research efforts focused on the embodied impacts of different structural systems in the construction stage. The embodied carbon (EC) of the structure can vary by up to 18% in different subclasses of steel- and concrete-framed structures with different number of floors [6]. The finding of case studies in Italy

[9] and Iran [10] revealed that the embodied energy of the steel-framed buildings is usually greater than the reinforced-framed structures. Application of high-strength concrete instead of regular concrete could also reduce energy consumption and CO_2 emission in the construction phase [11]. There was, however, a research study that showed similar embodied carbon levels in three steel and concrete-framed buildings (about 200kg CO_2/m²), and it was argued that the embodied carbon of the medium rise buildings with regular geometry and no basement is around this value. There are, however, opportunities to reduce the embodied impact through careful modifications [4]. Moreover, embodied energy of particular structural elements such as slabs [12] and beams [13] were investigated.

Although most of these studies reported a lower total embodied energy for concrete-framed buildings compared to the steel structures, on-site construction of cast-in-place concrete requires greater on-site equipment and labor efforts, which in turn results in larger amount of on-site energy consumption and emission [14-15].

Cost, speed of construction, stakeholder requirement, and availability of the material and skilled labor are typically considered during the selection process of a structural system for a building project. Embodied energy and carbon of the alternatives, however, is not usually ignored. Lack of an easy-to-use and documented assessment framework is a reason for this, because the research efforts on this subject used a large number of manual calculations for different processes to obtain the results. Building information model (BIM) of a project contains variety of information for different building components, which can be used to develop an automated embodied energy assessment system for different structural systems. Certain attributes of structural elements, such as material type, and geometrical and spatial data, could be extracted and used to estimate the embodied energy of the building components. There are a number of BIM-based systems for lifecycle assessment and modelling of the operational energy usage of buildings [16-17]; but only a few research efforts exclusively employed BIM for embodied energy estimation of the construction phase. For example, automated quantity take-offs (QTO) from a BIM model were mapped to embodied energy [18-19] and CO_2 databases [18] to estimate the embodied energy and carbon of building projects. The scopes of these methods, however, are limited to the manufacturing processes and they do not estimate the impact of transportation and on-site construction processes.

This paper presents an innovative BIM-based framework to estimate the embodied energy and carbon of the construction stage of different structural systems. The scope of this framework covers the construction phase, which includes the manufacturing of the structural material, transportation, and onsite installation/construction. This system extracts structural elements and their properties from a BIM model, and then estimates manufacturing, transportation, and onsite construction energies using a created model, defined databases, and user inputs.

2 Methodology

The architecture of the proposed system is presented in Figure 1. The first module of the system extracts the required data from a BIM model. Then the calculation model sorts elements' attributes and maps them to the corresponding energy and CO_2 inventories to estimate the impacts of production/manufacturing, transportation, and construction phases of the potential structural systems.

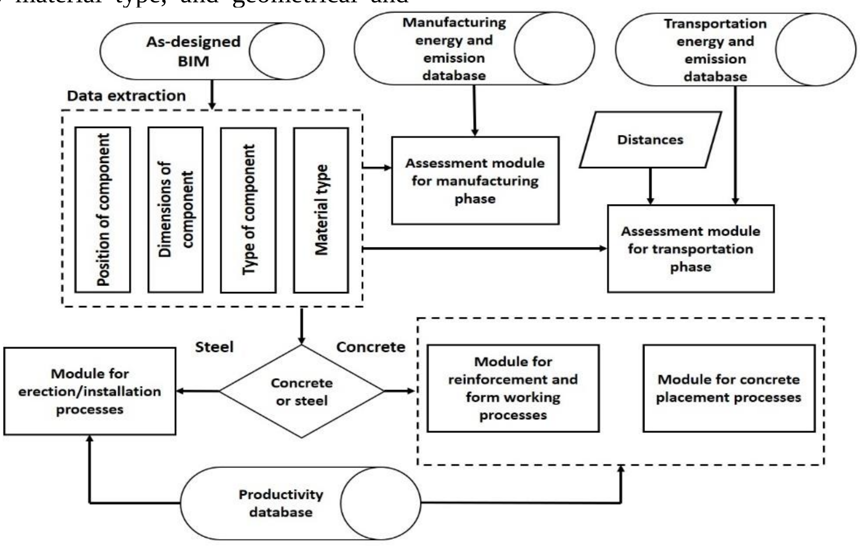

Figure 1. Architecture of the proposed framework

2.1 Data Extraction from BIM

Accurate quantity estimation from the design is essential in the construction industry [20], and this data are also necessary for environmental impact assessment. Completeness and accuracy are the most important factors in QTO and getting reliable estimates requires detailed model of a building project. Most BIM platforms have an automated QTO tool which calculates work quantities by extracting properties of building elements, such as material type, size, volume, space area, location, and weight, from the BIM model and reports them to the user-defined tables [21]. It is also possible to extract attributes of the elements' directly from an Industry Foundation Classes (IFC) file [21]. This module uses a script to extract all the main structural elements (i.e. columns, beams, bracing, floor slabs, and shear walls) and some of their main properties, including material type, and geometrical and spatial data.

2.2 Assessment Model for the Manufacturing Phase

Calculation of energy consumption during the manufacturing phase is mainly based on the embodied energy of the structural materials. The database of Inventory of Carbon and Energy (ICE) was used for the manufacturing embodied energy and carbon [22]. Table 1 shows the embodied energy and carbon coefficients of the main structural material.

Table 1. Embodied energy and carbon coefficients [22]

Materials	Embodied Energy(EE) (MJ/kg)	Embodied Carbon(EC) (kg CO_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

The overall manufacturing embodied energy and embodied carbon of the structural system are calculated using Equations 1 and 2, respectively.

$$EE_m = \sum m_i EE_i \tag{1}$$

$$EC_m = \sum m_i EC_i \tag{2}$$

where EE_m = overall energy used in material manufacturing process; m_i = mass of elements i needed in the building; EE_i = embodied energy coefficient of material i; EC_m = overall embodied carbon during manufacturing phase; and EC_i = embodied carbon coefficient of material i.

It is common to have some level of material waste in the building construction process for various reasons, including the need to extract uniquely shaped building elements from standard-sized manufactured items, defects in products, poor handling, and damage to material during delivery. The wastage should be considered in the estimation of embodied energy and is commonly calculated as a percentage of the required amount of material. The waste factor depends on the type of building materials and the waste factors for the main material were considered as: 0.05 for steel and 0.025 for concrete and timber [23].

2.3 Assessment for the Transportation Stage

The differences in the embodied energy of material transportation are attributed to size, type, distance, and the quantity being transported [11]. The type of vehicles can also affect energy consumption in the transportation stage, which can complicate the estimation process. Some of the previous LCA studies ignored transportation or simplified the problem by assuming direct travel from the manufacturing plant to the jobsite. However, it is common for the manufactured structural materials, such as steel and timber elements, to go through several distribution centers before arriving at the construction site. Loading and unloading processes in each distribution center consume energy, which are considered in this study.

Energy consumption and CO_2 emission factors reported by Hong et al. [24] were used for the material transportation vehicles. To simplify the estimation process, GHG emission factors were converted to carbon dioxide equivalent (CO_2e), based on the global warming potential (GWP) of each form of greenhouse gas, where the GWP for carbon dioxide is 1, for Methane is 25, and for Nitrous oxide is 298 [25].

Both haul and return trips between the manufacturing plant/distribution center and construction site were considered by this system. It was estimated that the energy consumption and emissions in empty return trips is about 66% of the value of full-load trips [26]. Moreover, the energy consumed for loading/unloading in distribution centers were considered in transportation of steel, rebar, and forms, which were calculated similar to the lifting process of the erection stage (described in the next section). Energy usage and GHG emissions of transportation stage were calculated using equations 3 to 6.

For concrete:

$$E_t = 1.66 \sum m_i EE_i^t . D_i \tag{3}$$

$$GHG_t = 1.66 \sum m_i EC_i^t . D_i \quad (4)$$

For steel and Plywood (forms) products:

$$E_t = 1.66 \sum m_i EE_i^t . D_i + n. E_{LP} \quad (5)$$

$$GHG_t = 1.66 \sum m_i EC_i^t . D_i + n. EC_{LP} \quad (6)$$

where E_t = energy consumption during transportation; GHG_t = CO_2 equivalent emissions during transportation; m_i = weight of material i (including waste); EE_i^t = Energy consumption per kilometer per ton of material i; EC_i^t = CO_2 equivalent emissions per kilometer per ton of material i; D_i = Distance traveled between the origin and destination of material i; n = number of distribution centers; E_{LP} = Energy consumed for material handling process in a distribution center; EC_{LP} = Emission of material handling process in a distribution center.

2.4 Assessment Model for the Onsite Construction Stage

There are specific construction equipment and methods for onsite construction of different structural systems. Energy consumption during onsite construction, e.g. erection and installation, is represented by the energy used by various pieces of construction equipment. Mobile cranes are commonly used for material delivery in steel- and wood-framed buildings, and a concrete pump or a crane is employed for concrete pouring in low- to mid-rise concrete buildings. Mobile cranes are also used for delivering rebars and forms to the installation location in the concrete-framed structures.

Equipment working hours were the basis to estimate energy consumption and emission of the onsite construction operations. The energy consumption of the equipment is calculated using equation 7.

$$E_{equipment} = \sum E_i = \sum T_i \times ECF_i \quad (7)$$

where E_i = Energy usage of equipment i; T_i = Working hours of equipment i; ECF_i = Energy consumption factor of the equipment i (MJ/h).

The first step is to calculate the energy consumption factor of the envisioned equipment. A calculation model (see Equation 8) was adopted from Food and Agriculture Organization [27] to estimate the rate of fuel consumption per machine-hour for each equipment type.

$$LMPH = \frac{K \times GHP \times LF}{KPL} \quad (8)$$

Where LMPH presents liters used per machine hour; K is the rate of fuel consumed per hp/hour in kg; GHP is the gross engine horsepower; LF is the load factor in percent; KPL is the fuel density in kg/liter.

Given gross engine horsepower (GHP) of the selected equipment and the related values in Table 2 [27], fuel consumption of the machines (LMPH) were estimated. Then, the energy and emission conversion factors of diesel and gasoline [25] were used to estimate energy consumption and emissions (see Equations 9 and 10).

Table 2. 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

$$ECF = LMPH \times Energy\ coversion\ factor \quad (9)$$

$$EF = LMPH \times Emission\ conversion\ factor \quad (10)$$

Where ECF is the energy consumption factor and EF is the emission factor.

2.4.1 Equipment Working Time

Mobile crane operations include two processes: (1) Lifting process; (2) Installation process.

There are five motion types in a lifting process: hoist down for the element, hoist up with the load, slew with the load, hoist down the load, and slew without load. One piece of structural element is carried in each cycle. The lifting time (T_{LP}) is the total duration of the five operations. Duration of each motion was calculated based on the slewing and hoisting speeds of the selected mobile crane, the lifting height, and the angle between the component loading area and the installation position (please see [28] for details). The spatial data of each structural element were used to obtain the last two pieces of information, which were extracted from the BIM model (See Figure 2).

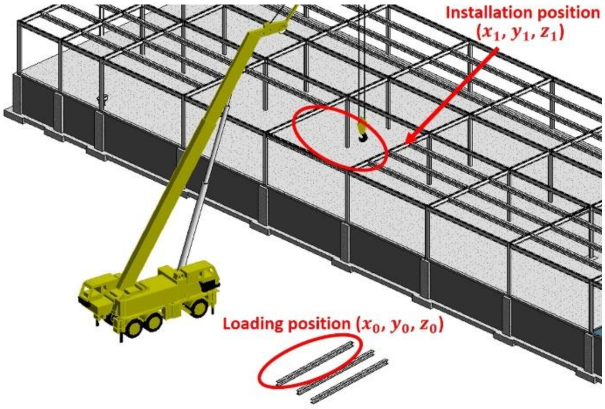

Figure 2. Sample 3D view of the spatial data for lifting of each element

Given the lifting process duration, the energy consumed in the lifting process (E_{LP}) was estimated as: $E_{LP} = T_{LP} \times ECF_{Crane}$.

In addition to the lifting time, the crane has to keep the component in its installation position until the crew initially fix it. The system calculates the installation time (T_{IP}) based on the productivity of the crew, which were obtained from RSMeans construction cost data. Given the installation process time, the energy consumed in the process (E_{IP}) was estimated as: $E_{IP} = T_{IP} \times ECF_{Crane}$.

Additional processes are required in the construction of concrete-framed structures (e.g. form working and rebars). If the reinforcement details exist in the BIM model, the system is able to extract them. Availability of such data, however, depends on the required level of details (LoD) and some BIM models might not include them. This system calculates formwork materials using the geometrical data of the structural component extracted from the BIM model. A mobile crane is considered for delivery of formworks and rebars, which has two types of processes: lifting and installation operations. The lifting efforts were estimated similar to the lifting of steel elements and the installation times were calculated using RSMeans.

A mobile concrete pump was selected for concrete placement in this model. The working time of the concrete pump (T_P) for each component was estimated by dividing the concrete volume of the element by the crew productivity (using RSMeans database). Given the concrete placement time, the energy consumed in this process (E_P) was estimated as: $E_P = T_P \times ECF_{Pump}$.

3 Case Study

A reinforced concrete and a steel-framed residential building with rather similar layouts were used to assess the developed system. Both of the buildings include three stories and ground level, where the total gross floor area of the concrete- and steel-framed buildings were 5,490.7 m^2 and 4,934.6 m^2, respectively. Concrete building had a one-way slab flooring system and the steel-framed structure had composite steel decks.

3.1 Quantity Take-off

Both designs were modelled in the Revit environment. The required element attributes, including length, width, volume, location, reinforcement volume, and customized shared parameters, namely formwork area, were extracted from the models.

3.1.1 Implementation of the Manufacturing Phase Model

Embodied energy and emission values for the manufacturing phase are calculated by multiplying the quantities of materials, including wastage, and corresponding embodied energy and carbon coefficients (see Equation (1) and Equation (2)). Figure 3 illustrates the embodied energy and emission values of the different materials used in the two studied structures. It is evident that the manufacturing embodied energy of the steel structure is larger than the concrete structure. The embodied carbon of the concrete structure, however, was larger than the steel-framed one. This is mainly due to the much greater ratio of the embodied carbon to embodied energy of concrete compared to steel (See Table 1). Because, large amounts of CO_2 are released during production of cement due to high temperature of clinker production as well as the CO_2 release in chemical reactions.

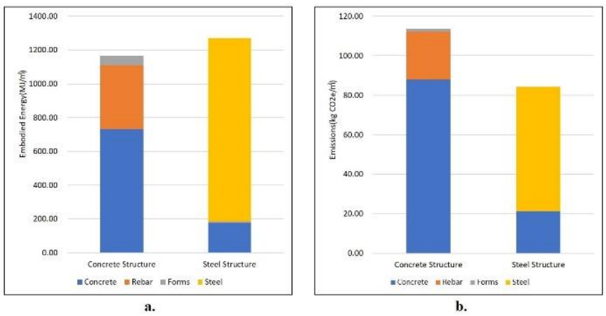

Figure 3. Results of the assessment of manufacturing phase of the studied buildings for: a) embodied energy; b) embodied carbon

3.1.2 Implementation of the Transportation Phase Model

This case study assumed 1000 km, 2000 km, and 3000 km distances for transportation of steel and rebar products, with the number of distribution centers varying from zero to three. For the concrete components, 25km transportation distance was assumed, because fresh concrete is a locally-sourced material. These numbers can be altered by the user.

Energy consumption and GHG emissions in the transportation stage were calculated by applying energy consumption and GHG emission factors of the selected vehicles and the quantity of materials in equations (3), (4), (5), and (6). Figure 4 shows the variation of the embodied energy and emissions values in the transportation stage with changes in transportation distance and the number of distribution centers. These figures show 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 for rebars and formworks on the concrete structure is greater than it is on the steel structure.

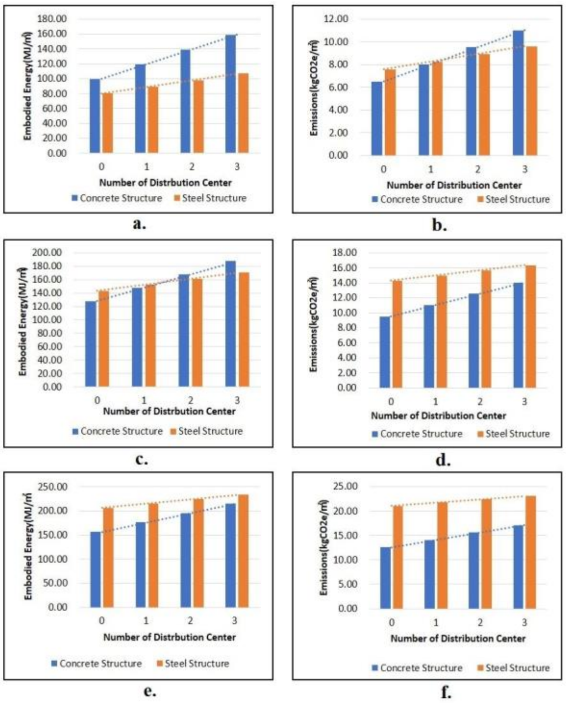

Figure 4. Embodied energy and carbon in the building structures during transportation stage: a) EE in 1000 km; b) EC in 1000 km; c) EE in 2000 km; d) EC in 2000 km; e) EE in 3000 km; f) EC in 3000 km

3.1.3 Implementation of the Onsite Construction Model

This module of the system estimates the onsite energy consumption by multiplying equipment working hours and energy consumption factor. A 30 t mobile crane with engine power of 164hp, maximum hoist speed of 136 m/min, and maximum slewing speed of 2 RPM was considered for lifting processes in this case study. A truck-mounted boom pump with a 395hp engine was selected for concrete pouring operations. The hoisting and slewing speeds were assumed between 40% and 60% of the maximum speeds. The swing angles (between loading area and installation position) of 90° to 105° were assumed for component delivery. Figure 5 shows the results of this phase, in which the concrete structure sample resulted in greater energy consumption and emissions than the steel-framed building (See Figure 5).

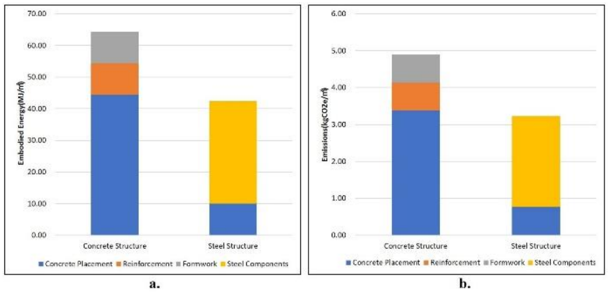

Figure 5. Results of the assessment of erection/construction phase of the studied buildings for: a) EE; b) EC

4 Discussion

The findings of this the study showed that application of different structural systems in a building project could result in different embodied energy and emissions. The manufacturing phase has the highest portion of the total embodied energy in both structural types (81%-91%). The results of this research were close to the ranges that were reported by other studies [6 and 29], but there are some differences (see Table 3). For example, the embodied energies differ from the results reported in [10]. One main reason was the difference between the energy inventories, in which their database included larger values for material and transportation. This is an important consideration, because production technologies and methods vary in different countries and should be adjusted in assessments.

Table 3. The estimated EE and EC of the concrete and steel structures studied previously

Research	Embodied energy and embodied carbon during construction			
	Embodied Energy (MJ/ m^2)		Embodied Carbon (kg CO_2-e/ m^2)	
	Concrete Structure	Steel Structure	Concrete Structure	Steel Structure
[29]	328-678	1419-2976	-	-
[6]	-	-	153-168	153-163
[10]	1720-3580	2540-4180	-	-
This study	1400-1520	1463-1624	163-175	125-142

In addition, the results were compared against the results of manual assessment by two groups of senior Civil Engineering students. The results for the manufacturing and transportation phases had the lowest difference, which were 3.8% and 4.5% for steel and concrete structures, respectively. But the estimation of the embodied energy for the erection/installation phase had larger differences, which were 7.2% and 10.7% for steel and concrete structures, respectively. These larger differences were due to large number of parameters and assumptions needed for the erection/installation process, whereas the values in manufacturing and transportation phases mainly depend on QTO and delivery distances that have less uncertainties.

This system, however, has some limitations. First, the LoD of model (e.g. reinforcement details) could have a significant impact on the accuracy of the results. Second, data inventories for material production and transportation are different in different locations, because employed technologies and methods vary in locations and they should be modified accordingly. Third, transportation data, such as the distances and the number of distribution centers might not be easily obtained in some practical cases.

5 Conclusion

A BIM-based framework was developed to estimate the embodied energy and carbon dioxide equivalent emissions of building structural systems. Different energy and emission calculation models were developed and data inventories were used for different construction phases of structural systems. This system automatically extracts required data from a BIM model and links the calculation model to the databases. A case study on a concrete and a steel-framed building showed that the type of structural system could result in a significant difference in the embodied energy and the emission of a building. It was also found that the energy consumption of the manufacturing phase has the greatest impact on the overall embodied energy of a structural system. In the transportation stage, the energy consumption is affected by the material transportation distance and the number of distribution centers. Finally, concrete-framed building consumed more energy than the steel structure in the onsite construction phase.

The future research will investigate the impacts on other building components, such as architectural, mechanical, and electrical elements.

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