Embodied Energy Modeling of Modular Residential Projects Using BIM

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Abstract –
Energy-efficient buildings have gained an increasing attention in the construction industry due to their significant contribution to the world's energy consumption. Life Cycle Assessment (LCA) provides an opportunity to improve the energy performance of buildings through a holistic assessment of their life cycle. Previous studies have mainly applied Building Information Modeling (BIM) to export buildings' data into other LCA tools. This process is considerably time-consuming and error-prone, especially when matching and importing BIM data into the LCA software are conducted manually. This paper aims to develop a framework to quantify the embodied energy (EE) of modular buildings through BIM-LCA approach. Despite current practices, this model can contribute to facilitate changes during early design stages, delivering more energy-efficient buildings. To do so, the EE of modular residential building is estimated based on the boundaries defined by EN15978 Standard. An integration scheme of BIM and LCA is established in Autodesk Revit as a platform to evaluate the contribution of different building materials and stages in EE consumption. The proposed framework is validated and verified by conducting a real case study on an under construction modular project. This study can be used as a base platform to quantify EE and reduce the environmental impacts of the modular buildings by guiding architects and designers to come up with more sustainable building plans.

Keywords –
Life Cycle Assessment; Building Information Modeling; Energy Efficiency; Modular Construction; Embodied Energy

1 Introduction

Growing concerns about energy consumption and its environmental impacts around the world are pushing the construction industry to adopt sustainable approaches by introducing stricter policies and regulations [1, 2]. Building sustainability refers to all activities and processes throughout the building life cycle which have the least harmful environmental and social impacts [2]. Energy consumption during a building life cycle plays a critical role in the environmental and economic aspects of its sustainability as it utilizes a considerable amount of natural resources and investments [3]. Construction industry has become a significant contributor to the world's energy usage, and its environmental impact is still increasing [4]. It has been reported that this sector accounts for up to 40% of energy consumption globally [5], raising the need to apply innovative methods to reduce energy consumption in order to achieve sustainability standards. In addition to poor environmental performance for which the construction industry has been criticized, this sector is also far behind other industries in terms of productivity and employment of new technologies [6, 7]. Modular construction has been promoted as a promising way moving towards modernization and greener buildings [8]. Modular construction has been gaining an important status in recent years as it is predicted to be the future application for the construction field; therefore, assessing and improving its energy performance has become a critical issue [9].

Buildings consume energy throughout their life cycle from raw material extraction to final disposal of demolished wastes [10]. Life Cycle Assessment (LCA) method has been widely utilized as an appropriate approach to evaluate buildings' energy performance during their lifetime. Applying LCA in construction projects at the early design stage simplifies making possible changes associated with different stages of a construction project to improve its energy efficiency and sustainability [11, 12] . Until recently, the main attention had been placed on the operational energy (OE) as operation phase is the longest phase in a building life cycle. However, this focus has been shifted from OE to embodied energy (EE) since significant enhancement has been achieved in reducing OE in recent years [13]. Despite current comprehensive research in the field of buildings LCA modeling, there are still significant gaps and limitations in the quantification of EE specially in modular construction which needs further studies.

This paper aims to develop a conceptual framework for estimating the EE usage in modular residential buildings based on the system boundary introduced by EN 15978 Standard. This study integrates Building Information Modeling (BIM) with LCA to reduce the time and effort required to gather all data needed for the energy evaluation of different stages of a building during its lifetime. Furthermore, despite previous studies in which energy consumption in transportation, plant, and construction phases of the project were ignored in EE evaluation, this research contributes to quantification of these phases as well.

This paper will continue with a comprehensive literature review on the current LCA assessment methods of the residential projects. It then focuses on the development of an integrated framework to conceptualize and model the EE of modular residential projects based on EN 15978 phase boundaries. To verify the applicability of the framework and validate the developed model, a case study is conducted on a real under construction project, and EE used for this modular residential project is estimated.

2 Literature Review

Different types of classifications have been developed to refer to the energy consumption during the building life cycle, in which the EE and OE have been widely used in previous studies [14]. Demolition energy (DE) also has been introduced in a few studies which refers to the deconstruction of the building and the transportation of the waste material to the recycling plants or landfill centers. However, because DE includes a small portion of a building life cycle, it could be included in EE, rather than being separately classified [14]. Thus, in some studies, EE refers to all the energy utilized in material production, transportation, site activities, and final deconstruction phases. OE is the energy consumed while the building is in its operation phase including all activities which provide comfortable conditions for the occupants such as heating, cooling, lighting, and operating equipment [15].

2.1 BIM-LCA Integration

Due to the long duration, various resources, and risks and uncertainties, construction projects require more integrated energy evaluation approaches to be able to measure the consumed energies in different phases more accurately [14]. LCA has been established as a method to predict the buildings' impact on the environment throughout all stages of their life cycle [14, 16]. However, the complexity of LCA process makes it cumbersome and time-consuming for designers to employ it. BIM can reduce this complexity and can assist the design team in making LCA more practical and more user friendly [17]. BIM is a platform representing physical and functional characteristics of buildings which can be shared with different stakeholders [18].

Shadram and Mukkavarra [4] used a BIM-LCA approach based on a multi-objective optimization method to balance between EE and OE in a building during its design process by considering the impact of various types of materials and their quantities on different stages of a building lifetime. Najjar et al. [12] integrated BIM and LCA to evaluate the negative endpoint impacts of building material and their related energy consumption on the environment at the early design stage. Cavalliere et al. [17] developed several LCA databases for different stages of the design process and linked them to the BIM model according to the level of development. Their framework can facilitate LCA in the design stage and ensure that reliable data is used throughout the whole process of building design. In an effort for evaluating EE, Rock et al. [13] proposed a BIM-LCA model to visualize the impacts of various types of building elements including structural parts including walls and floors on the environment. The EE was calculated using the Ecoinvent database and processed in Autodesk Dynamo. However, only the effect of different building materials on the EE was considered, and the energies used in transportation, plant, and construction site were not measured.

2.2 Energy Modeling Approaches

Different approaches have been adopted for EE evaluation while conducting BIM-LCA integration. These energy modeling approaches have been classified into four main categories [2]. In the first energy modeling scheme, researchers have not developed a comprehensive framework to be applied to other projects. Instead, they have mainly focused on the project-based outcomes. In the second energy modeling group, BIM software is used as a platform to export material quantities to other LCA tools. In the third modeling plan, transportation, and construction phases in a building life cycle have been excluded from LCA system boundary. In the fourth energy modeling scheme, either not adequate details have been provided in the framework process due to simplification, or the proposed methodology is too complex and cumbersome, making it impractical to be adopted in further studies [2].

3 Methodology

The proposed methodology in this study is based on the integration between BIM and LCA and aims to formulize the EE consumption of modular residential buildings including material production energy, transportation energy, and off-site and on-site construction energy. In this study, LCA has been conducted according to ISO 14040 and ISO 14044 guidelines. The first step of conducting LCA based on these guidelines is that the main goal and intention of carrying out LCA should be clearly stated, and then the system boundary should be specified. At the next stage, which is considered as the most time-consuming stage, all the required data within the system boundary should be collected. Life Cycle Inventory (LCI) analysis mainly includes gathering all the building information defined in the system boundary and calculating the related inputs and outputs which have been set during defining the LCA scope and goal stage. The proposed methodology comprises several steps that have been depicted in Figure 1.

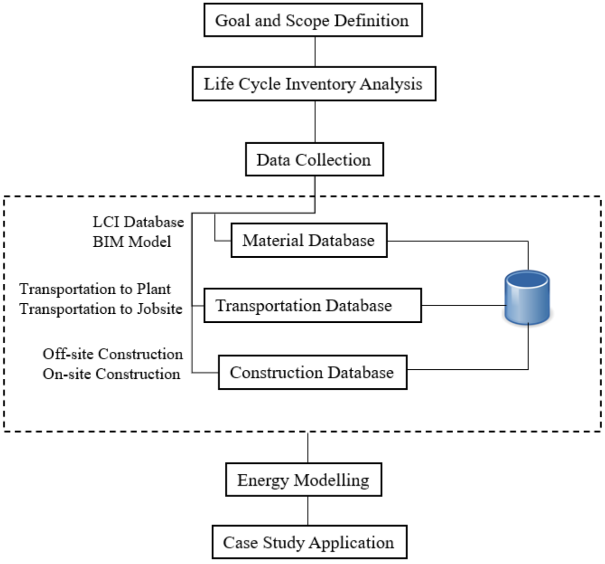


Figure 1. Proposed research framework on BIM-LCA integration.

3.1 Definition of Goal and Scope

The goal of performing LCA study in this paper is to formulize and quantify the EE consumption of modular buildings using BIM tools. This energy modeling will have different applications and can promote design decisions and schemes in order to reduce the EE consumption of a building. The system boundary selected in this study and different considered stages in a building lifetime are based on EN 15978 Standard. The system boundary defined in this standard consists of several stages, including product stage, construction stage, use stage, and end of life stage. The subcategories of each stage can be found in Figure 2. The system boundary in this study encompasses modules A1 to A5.

3.2 LCI Analysis

This step focuses on LCI analysis based on the boundaries defined in EN 15978 Standard. As this study intends to measure the EE of modular residential buildings, only product stage (A1 to A3) and construction stage (A4 and A5) will be investigated.

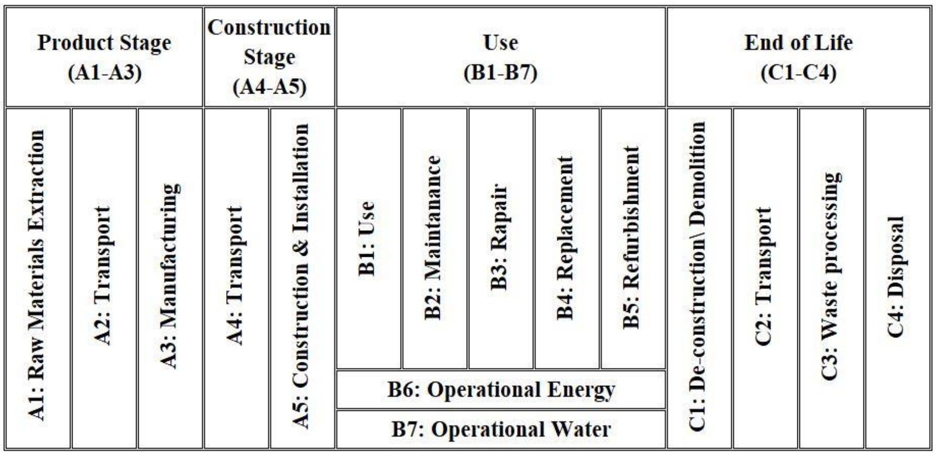
3.2.1 Data Collection

As one of the main steps of LCI analysis, different sources of data should be provided. In this paper, Bath Inventory of Carbon and Energy (ICE) was used to obtain the energy that is embodied in raw construction materials. This LCI database was selected because it solely focuses on the construction materials and does not include EE of other products in different industrial sectors. ICE is a cradle-to-gate database that includes all the energy usage during raw material extraction, transportation, and production stages of the construction materials. Further, Autodesk Revit software was used to access BIM models of modular buildings as it is a common tool for designing and visualizing both architectural and structural plans and also widely utilized as a technical communication platform amongst different phases throughout buildings life cycles. A custom script was developed in Autodesk Dynamo visual to create a database of material quantities and properties. Dynamo is an open-source visual programming plug-in for Autodesk Revit that consists of nodes to create algorithms in order to perform various tasks within Revit.

3.2.2 EE Formulization

The objective of this section is to quantify the EE of modular residential building and formulize the energies used in different phases of A1 to A5 defined in EN 15978 Standard. As per this guideline, EE is the total energy consumed during material production (E_M) (A1-A3), transportation energy (E_T) (A4), and processing (Ep) and construction energy (E_C) (A5). It should be noted that, unlike conventional buildings, EE of modular buildings in stage A5 has two stages of processing (off-site construction) and construction (installation and assembly). In modular approach, construction materials need be transported to another plant to be processed for modules and panels preparation which is known as off-site construction. The energy consumption of this processing stage on raw construction material is missing in LCI databases and should be separately calculated as an extra EE item in modular buildings. As previously discussed, ICE only covers EE in raw natural material extraction, transportation of these raw material to the factory, and production of construction materials. As per discussions above, the total EE consumption in modular buildings can be calculated based on Equation (1).

$$E_{Total} = E_M + E_T + E_P + E_C \qquad (1)$$



Product Stage (A1-A3)			Construction Stage (A4-A5)		Use (B1-B7)					End of Life (C1-C4)			
A1: Raw Materials Extraction	A2: Transport	A3: Manufacturing	A4: Transport	A5: Construction & Installation	B1: Use	B2: Maintanance	B3: Rapair	B4: Replacement	B5: Refurbishment	C1: De-construction\ Demolition	C2: Transport	C3: Waste processing	C4: Disposal
					B6: Operational Energy								
					B7: Operational Water								

Figure 2. Buildings' system boundary defined by EN 15978 Standard.

Material production stage is one of the main contributors to EE. It is noted that the functional unit defined in ICE is one kilogram of the material, thus the embodied energy of the materials is presented in (MJ/kg). To have the total weight of each specific construction material, its volume (V) needs to be extracted from Revit Autodesk software to be multiplied by its density (ρ). E_M can be quantified based on Equation (2) by simply multiplying all the materials' quantities to their related energy coefficients (C_e) derived from ICE database.

$$E_M = \sum_i^n E_{mi} = \sum_i^n V_i \, \rho_i \, C_{ei} \qquad (2)$$

E_T is all the energy used to transport the construction materials from the material production factory to the construction site. For modular buildings, transportation is typically conducted in two different steps of material transportation from construction material factory to processing plant for module production and then module transportation from plant to construction site. Energy consumption for transportation stage of a modular constructions can be calculated using Equation (3).

$$\begin{aligned} E_T = E_{TP} + E_{TS} &= \sum_i^n E_{TPi} + \sum_i^n E_{TSi} \\ &= \sum_i^n \frac{D_i ES_i EL_i \, F_i \, L_{hvi}}{V_i} \end{aligned} \qquad (3)$$

In which, E_{TP} refers to material transportation to the plant for modular fabrication and E_{TS} refers to modules' transportation from plant to the jobsite. D is distance of transportation, and ES, EL, F, and V are engine size, engine load, fuel consumption, and average speed of the equipment, respectively. L_{hv} is lower heating value of the fuel.

As discussed, the construction stage (A5) of modular projects is conducted in two steps of material processing (E_P) for modules production and on-site installation and assembly of modules (E_C). The construction energy can be quantified by summing of all the energy used by different equipment in both plant and jobsite to perform various tasks toward constructing and installing modules and panels. Knowing activities and their related equipment, the construction energy in both module production and module installation can be calculated by multiplying the amount of estimated time takes that the equipment performs the activity (h), its engine size, and its engine load. The Kilo-Watt hour (KW.h) unit should be converted to Mega-Joule (MJ), thus a factor of 3.6 would be used for this conversion. It is noteworthy that the embodied energy of modules' manufacturing is not a simple task to be quantified. This is due to the reason that the process of manufacturing modules does not necessarily belong to a single project, and a particular plant is producing the modules of several projects at the same time. In Equation (4), E_P and E_C refer to the energy consumption of equipment used for module preparation in the plant and modules installation in the jobsite, respectively.

$$E_C = E_P = \sum_i^n E_{Ci/Pi} = \sum_i^n 3.6 \, h_i \, ES_i EL_i \qquad (4)$$

4 Case Study

The proposed framework is implemented on a real case study to verify the applicability of the methodology to quantify the EE of a modular building. An under construction modular building in Sydney, NSW Australia, was selected for the case study. The total building area of this building is 493 m^2. Figure 3 shows a BIM model of the building as designed in Autodesk Revit.

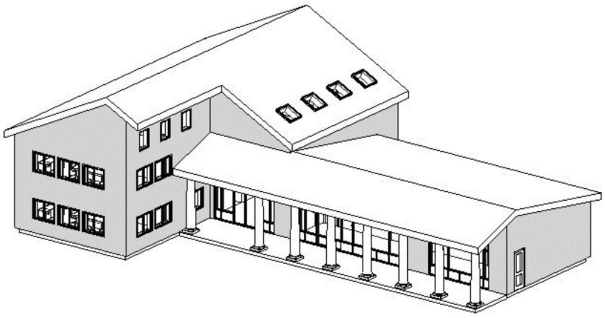


Figure 3. A BIM model of the case project.

Different sources of data have been used in this study. As the first step, all the geometrical data, the bill quantity of materials, and their relevant properties were obtained from the BIM model in Dynamo platform, and the material database was then created. Table 1 presents the materials inventory and their corresponding EE.

As previously explained, the EE data regarding material production in ICE database (stages A1 to A3) only incudes raw construction material production, and extra energy consumption for transportation and production of modular elements are not considered in the database. To acquire relevant information for transportation and construction phases, numerous interviews were conducted with the project management teams. Transportation has two stages of transporting materials from raw construction material production factory to the processing plant to make the modules and then transporting modules to the jobsite for installation. The relevant database was created by having the weight of raw materials and modules, and also the distance between factory, plant, and the jobsite. The transportation energy for this case project has been quantified in Table 2 and Table 3, respectively.

In modular construction approach, construction is conducted in two off-site and on-site phases. Off-site construction refers to the processing of material and producing the modules and panels. On the other hand, on-site construction is related to the installation of the modules in the jobsite. The quantification of off-site and on-site construction phases including the used equipment and machinery have been presented in Table 4 and Table 5, respectively.

Table 1. Material production energy

Element	Type of Material	Volume V (m^3)	Density ρ (kg/m^3)	Mass m (kg)	Energy Coefficient C (MJ/kg)	Material Energy E_M (MJ)
Foundation	Concrete	121.94	2360	287778.4	1.95	561167.88
	Steel	5.23	7850	41055.5	25.30	1038704.15
Floor	Concrete	156.87	2360	370213.2	1.95	721915.74
	Steel	6.53	7850	51260.5	25.30	1296890.65
Roof	Galvanised Steel	0.97	7800	7566.0	22.60	170991.60
	Laminated Veneer Lumber	5.20	1050	5460.0	9.50	51870.00
	Timber	17.10	950	16245.0	10.00	162450.00
	Fiberglass	26.00	40	1040.0	28.00	29120.00
Exterior Wall	Timber Panel	90.00	950	85500.0	10.00	855000.00
	Plaster Board	7.20	800	5760.0	1.80	10368.00
Interior Wall	Timber Panel	32.10	950	30495.0	10.00	304950.00
Columns	Steel	1.54	7850	12089.0	25.30	305851.70
Alfresco Columns	Marble Stone	7.60	2700	20520.0	2.00	41040.00
Total						5550319.72

Table 2. Transportation energy form factory to plant

Material	Mass m (t)	Distance D (km)	Engine Size ES (Kw)	Engine Load EL	Fuel Consumption F (L/kw.h)	Average Speed V (Km/h)	Lower Heating Value L_{hv} (MJ/L)	Transportation Energy E_T (MJ)
Concrete	657.99	25	260	0.7	0.207	50	42.7	67564.55
Steel Bar	92.32	300	250	0.7	0.207	70	42.7	106066.80
Steel Columns	12.09	300	250	0.7	0.207	70	42.7	13258.35
Galvanised Steel	7.57	300	200	0.7	0.207	70	42.7	10606.68
Laminated Veneer Lumber	5.46	200	200	0.7	0.207	60	42.7	8249.64
Timber	17.96	200	200	0.7	0.207	60	42.7	16499.28
Fiberglass	1.04	100	150	0.07	0.207	60	43.7	316.61
Timber Panel	116.00	200	250	0.7	0.207	60	42.7	103120.50
Plaster Board	6.84	200	220	0.7	0.207	60	42.7	9074.60
Total								334757.01

Table 3. Transportation energy from plant to jobsite

Product	Mass m (t)	Distance D (km)	Engine Size ES (Kw)	Engine Load EL	Fuel Consumption F (L/kw.h)	Average Speed V (Km/h)	Lower Heating Value L_{hv} (MJ/L)	Transportation Energy E_T (MJ)
Concrete Slabs	406.04	60	250	0.7	0.207	40	42.7	120650.99
Piles	316.94	60	250	0.7	0.207	40	42.7	97448.87
Steel Columns	12.09	60	250	0.7	0.207	40	42.7	4640.42
Wall Panels	1.04	50	250	0.7	0.207	40	42.7	15468.08
Roof Panels	24.80	50	200	0.7	0.207	40	42.7	12374.46
Marble Columns	20.52	200	250	0.7	0.207	60	42.7	20624.10
Total								271206.92

Table 4. Off-site construction energy

Product	Equipment	Working Hour h (hr)	Engine Size ES (KW)	Engine Load EL	Construction Energy E_p (MJ)
Concrete Slabs	Concrete Pump	16	97	1	5587.2
	Vibrator	16	3	1	172.8
	Bar Bender and Cutter	8	7	1	201.6
Piles	Concrete Pump	20	97	1	6984.0
	Vibrator	20	3	1	216.0
	Bar Bender and Cutter	15	7	1	378.0
Steel Columns	Steel Cutter	4	7	1	100.8
	Welder	24	30	1	2592.0
Roof Panels	Electric Saw	70	15	1	3780.0
	Nailing Machine	70	2	1	504.0
Wall Panels	CNC Machine	120	15	1	6480.0
	Production Lines	300	50	1	54000.0
	Forklift	153	116	0.75	47919.6
Total					128916.0

Table 5. On-site construction energy

Task	Equipment	Working Hour h (hr)	Engine Size ES (KW)	Engine Load EL	Construction Energy E_C (MJ)
Land Levelling	Loader	12	70	0.8	2419.2
	Truck	9	200	0.6	3888.0
Detailed Excavation	Excavator	20	60	0.7	3024.0
Unloading Products	Crane	25	150	0.5	6750.0
Pile Driving	Pile driver	80	208	0.5	29952.0
Slab Assembly	Crane	90	150	0.5	24300.0
Wall Installation	Crane	120	150	0.5	32400.0
Columns Installation	Crane	56	150	0.5	15120.0
Roof Assembly	Crane	70	150	0.5	18900.0
Electricity Supply	Generator	550	2	1	3960.0
Total					140713.2

As achieved results of this case project showed in Figure 4, 87.37% of total EE is associated with the construction material production showing the high contribution of this stage in energy usage. A significant 9.43% of the total EE energy for this case study has been used for transportation including the transportation between factory and plant (5.21%), and also between plant and jobsite (4.22%). Eventually, minor 2.01% and 2.19% of total EE content were consumed in off-site and on-site construction, respectively in this selected project. It should be noted that though the amount of energy in transportation and construction phases has significantly less contribution to the total EE in the building life cycle compared with material production stage, they should not be ignored in buildings energy evaluation as they are still huge energy consumers.

The main objective of conducting this case study is to demonstrate the applicability and practicality of the developed research framework in EE measurement. This case project is to be investigated further in the future studies to include all other elements of the building including the internal parts, fittings, and facades.

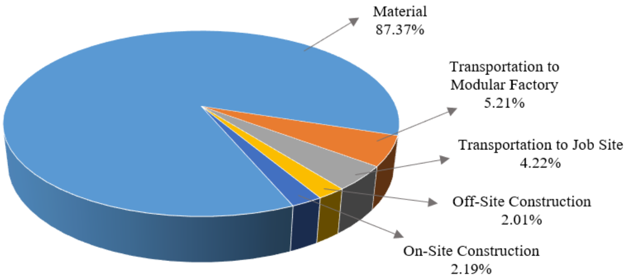


Figure 4. The proportion of energy used in different phases of the studied case project.

5 Conclusions

This paper proposed a framework to evaluate the EE for the life cycle of modular construction projects. The system boundary of the framework breaks down the EE in material production, transportation, and construction stage according to EN 15978 Standard. Further energy consumption regarding modular construction, namely transportation to processing plant and off-site construction, was also included in the EE quantification. LCI was conducted through BIM software for material take-off and numerous interviews were performed with project management teams for transportation and construction data collection. After formulization of the EE based on the selected system boundary, the methodology was implemented in a modular case project to test its applicability. As shown in the case study, the total amount of EE in a modular building's life cycle and the contribution of each construction stage can be quantified. As this framework can provide a detailed EE analysis, it can be practically used by architects to take into consideration the EE in their designs which results in a more sustainable construction.

This study can be further extended to include the EE of the other construction elements such as internal parts, decorations, facades, and fittings to yield a more accurate and more reliable EE consumption of construction projects. Further, a trade-off between EE and OE of the buildings can be conducted by the researchers in the early development phases to achieve more energy-efficient projects.

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