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Research article

Embodied Energy and CO_2 Analyses of Mud-brick and Cement-block Houses

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Abstract: In building projects, the extraction of vast quantities of materials is too common. The extraction of materials and the erection of buildings consume embodied energy and emit carbon dioxide (CO_2) that impact negatively on the environment. Therefore it is necessary to consider embodied energy and CO_2 amongst other factors in selecting building materials for use in building projects. In most developing countries, building environmental performance analysis has yet to gain interest from the construction community. However, with recent increase in sustainability awareness, both developed and developing nations have engaged in efforts to tackle this challenge. Embodied energy and CO_2 are among the leading parameters in assessing environmental building performance. In Cameroon, studies about the assessment of embodied energy and CO_2 of building projects are scarce. Hence, professionals find it difficult to make alternative choices for building materials to use in their different building projects. This study uses a detailed process analysis approach supported by two popular housing types in Cameroon (mud-brick and cement-block houses) to assess the embodied energy and CO_2 impacts from building materials. The emerging Building Information Modelling (BIM) tool was used to validate the computational results of the process analysis method. The findings revealed the embodied energy and CO_2 for the mud-brick houses are 137934.91 MJ (2007.8 MJ/m^2) and 15665.56 Kg CO_2 (228.03 Kg CO_2/m^2); the cement-block houses are 292326.81 MJ (3065.51 MJ/m^2) and 37829.19 Kg CO_2 (396.7 Kg CO_2/m^2) respectively. Thus, the cement-block house expends at least 1.5 times more embodied energy and emits at least 1.7 times more embodied CO_2 than mud-brick house. Although these findings cannot be generalized, they nonetheless indicate the importance of considering embodied energy and CO_2 in making alternative choices for use in different building projects.

Keywords: BIM; Cameroon; embodied energy; embodied CO_2; Mud-brick house

1. Background

In 2009, buildings accounted for 32% of total global final energy IEA [1]. The building sector emits 8.1 Gt of CO_2 per year [2]. Also, the built environment consumes more natural resources than necessary and, therefore, generates a large amount of waste [3]. The high energy consumption, high CO_2 emissions, and wasteful resources all have huge negative impacts on the environment. Although the greatest share of emissions has so far been from developed countries, the greatest burden of the impacts is on developing countries. Thus, there is an urgent need for concerted efforts from both the developed and developing countries to minimise or eliminate activities that contribute to climate change. The increasing concern from developing countries has steadily been reflected in their participation in some high profile international conferences such as Conference of the Parties (COP) 15-Copenhagen, COP17-Durban, and lastly, COP 18-Doha in 2009, 2011 and 2012 respectively.

The afore-mentioned statistics confirm that the built environment is a major sector to consider in designing strategies for combating the impacts of climate. Some examples of strategies include the improvement of construction and energy efficiency processes/techniques/technologies, adoption of passive design, use of renewable energy and the appropriate selection of building materials. This study will focus on building materials used for housing construction because the share of materials often used in construction is huge and most other factors depend on them. Also, building materials constitute a significant share of house construction cost. Adedeji [4] noted that about 60% of the total house construction cost goes towards the purchase of construction materials. Embodied energy and CO_2 are currently two main parameters commonly used in assessing the importance of building materials [5]. The European Union (EU) Construction Products Directive has recommended embodied energy as a key factor in the selection of building materials or construction products [6]. Although CO_2 is the least potent of all the Kyoto greenhouse gases, it is by far the most plentiful and largest contributing compound in the greenhouse effect [7]. Because of the emerging nature of embodied energy and CO_2, this paper will investigate their shares in the two most common houses in Cameroon. Findings of this paper are important to Cameroon given that housing in that country has recently become too expensive for local residents, especially in urban areas where the cost of imported building materials is reported to be too exorbitant and less environmentally friendly than the locally available building materials [8]. Cerutti *et al.* (2010) argued in [9] that most of Cameroon’s market for domestic timber, for example, has been on the rise. Thus it is imperative to use parameters (e.g., embodied energy and CO_2) to guide the selection of environmentally benign materials from a list of options for alternative uses in buildings. Based on the review of the literature, there is a lack of quantitative studies in Cameroon regarding embodied energy and CO_2 of buildings (see section 2.2). To facilitate understanding, the assessment of embodied energy and CO_2 will be examined in the ensuing section.

2. Setting the scene: definition and assessment of embodied energy and CO_2[1]

2.1. Rationale and significance of embodied energy and CO_2 assessment in buildings

Embodied energy describes the amount of energy consumed in all processes associated with the production of a building, from mining and processing of natural resources/materials to manufacturing, transport and then the delivery of the product [10]. For many years, embodied energy content of a building was assumed to be small compared to operational energy. Consequently, most energy-related research efforts have been directed toward reducing operational energy largely by improving energy efficiency of the building envelope. Operational energy of buildings is the energy required to condition (heat, cool, ventilate, and light) the interior spaces and to power equipment and other services. Milne and Reardon [10] observed that according to research by the Australian-based CSIRO (Commonwealth Scientific & Industrial Organisation), an average household contains about 1000 GJ of energy embodied in the materials used in the construction of the house, and this is equivalent to 15 years of normal operational energy. Weight and Rawlinson[11] reported that the construction materials sector alone accounts for 5–6% of total UK emissions, with 70% of emissions being associated with the manufacturing and 15% being associated with the transportation of the materials.

In addition to embodied energy, the production of building materials (e.g., extraction, transportation and manufacturing processes) releases CO_2 mainly due to the use of fuel or electricity. This is often called embodied CO_2. Thormark [12] reported that embodied energy in traditional buildings can be reduced by approximately 10–15% through proper selection of building materials with low environmental impacts. González and Navarro [13] estimated that the selection of building materials with low impacts can reduce CO_2 emissions by up to 30%. Thus embodied energy and CO_2 are quite important in environmental building assessment. Before embarking on their assessment methodology, it is important to gain insights into the content of peer-reviewed literature about embodied energy and CO_2 in Africa in general and Cameroon in particular.

2.2. Embodied energy and CO_2—a literature review

To gain insights into how similar studies on embodied energy and CO_2 might have been conducted in the African continent and Cameroon in particular, a literature review was conducted. A systematic search of key peer-reviewed papers from renowned databases including ScienceDirect (http://www.sciencedirect.com/), EI Compendex (http://www.ei.org/) and EBSCO (http://www.ebsco.com/index.asp) about embodied energy and CO_2 analysis was conducted. Key phrases such as "embodied energy and buildings in Africa/or Cameroon", "embodied CO_2 and buildings in Africa/or Cameroon", "carbon footprint and buildings in Africa/or Cameroon" were used. These searches yielded few results with little relevance. The first overarching outcome was the general agreement among peer-reviewed literature about the importance of embodied energy and CO_2 in assessment of building impacts on the environment [14,15]. The second outcome was that despite acknowledgement of the need to consider embodied energy and CO_2 in building impact

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[1] Embodied carbon is often confused with embodied CO_2. In this study, we strictly stick to embodied CO_2, and embodied carbon can be computed from embodied CO_2 using molar mass relationships of the constituent elements.

analysis, very few quantitative studies have been conducted in this respect. Hugo *et al.* [16] computed embodied energy and CO_2 of construction materials of three South African Bus Rapid Transit stations. Irurah and Holm [17] demonstrated discrepancy and conflicts of data of basic embodied energy intensities of building construction materials between building systems and building types. What emerges from these findings is that studies on building embodied energy and CO_2 assessment with regards to Africa in general and Cameroon in particular are scarce. This outcome underpins the motivation for this study. The assessment methodologies based on life cycle analysis of embodied energy and CO_2 are examined in the ensuing section.

2.3. Assessment methodology

The dissipation of embodied energy, and the emission of CO_2 are directly associated with each phase of a building's life cycle and vary by building types [18]. Although there is a lack of consensus as to the different types of phases in a building life cycle, generally, the product phase (raw materials supply, transport and manufacturing), construction phase (transport and construction-installation on-site processes), use phase (maintenance, repair and replacement, refurbishment, operational energy use: heating, cooling, ventilation, hot water and lighting and operational water use) and end-of-life phase (deconstruction, transport, recycling/re-use and disposal) [19] are quite common and encompass most other life cycle classifications. The increased awareness of the importance of environmental protection, and the possible impacts associated with construction processes, have increased interest in the development of methods to better understand and address these impacts. The most widely used technique is the life cycle assessment (LCA) which considers the building's life cycle [19]. LCA is the most comprehensive tool in the assessment of inventories and environmental impacts and has been adopted for use in many types of products and processes by reputable institutions such as the International Standard Organisation (i.e., ISO 14040 environmental management standards), US Environmental Protection Agency, the European Union (i.e. European Standard) and the UK(i.e., British Standard).

In this study the assessment methodology adopted follows the European Standard which has been adopted as part of the British Standard for evaluating environmental impacts of building projects [20]. The standard provides the calculation method, based on the LCA to assess and evaluate the environmental performance and thus provides design options and specifications for new and existing buildings. The main guidelines of the standard stipulated in European and British standards are: the description of object of the assessment, the system boundary that applies at the building level, the procedure to be used for inventory analysis and the requirements for the data necessary for the calculation. The applications of these guidelines and their rationale will be examined in the ensuing sections.

2.4. The description of the object of the assessment and system boundary

The object refers to what is being developed or is in the process of being developed and the process of development and/or its existence after development has impacts on the environment. In this study two residential buildings are the objects of assessments. The two buildings represent typical houses common in Cameroon. One is predominantly made up of what is generally referred to as imported materials, i.e., cement-block house; the other is constructed predominantly out of local building materials, i.e. mud-brick house.

According to ISO 14040, the system boundary is a set of criteria specifying which unit processes are part of a product system. It also describes the limits of what is included or not included in the assessment of the whole life cycle for a new building or any remaining cycle stages for the existing building. Figure 1 is used to clarify the boundaries considered in this study.

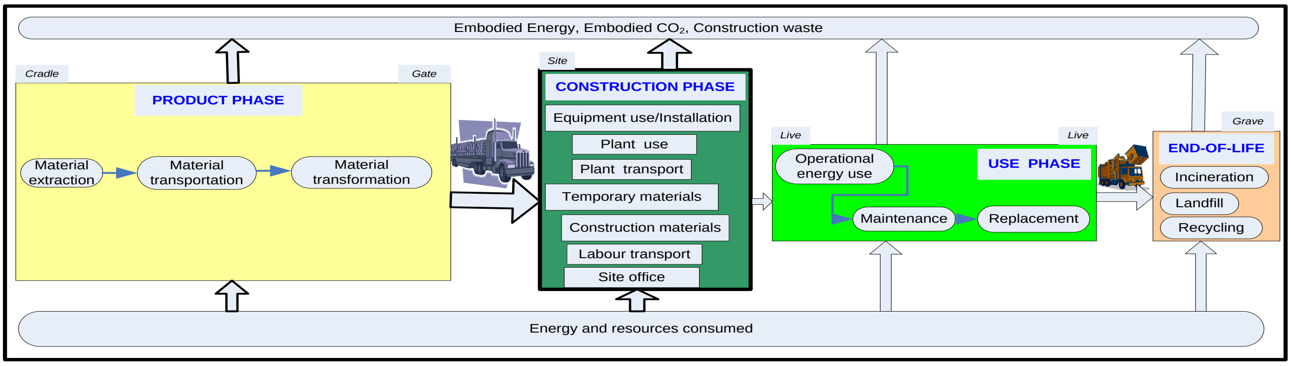

Figure 1. Life cycle phases of a typical house building project

The first boundary to be defined is around the product phase. Based on Figure 1, this boundary includes the extraction of material from its original sources and the transportation to the production unit where manufacturing into different products is undertaken. The manufactured components are then transported to the construction site where the construction phase begins. Thus, the physical boundary considered is from cradle to gate. This choice has a major advantage in that it provides the possibility to use directly the inventory of carbon and energy for construction materials developed by Bath University in the UK [5]. With respect to the boundary on processes or activities, the material extraction, material transportation, material transformation and transportation of components from gate to construction site have been considered.

The second boundary is about the construction phase. In practice, two major categories of activities that have impacts on the environment occur. The first category consists of activities that are aimed at erecting the building. In this study, four main activities make up this category. These are the site installation, the transportation of plants/equipment, plant/equipment use, and the use of temporary materials. The second category consists of induced activities that occur during the erection of the building. This includes onsite construction waste and the transportation of waste from packaging. In this study, only the first category will be considered. In particular, based on the limited information about site installation, only embodied energy and CO_2 of building materials used in erecting the houses will be considered while the transportation of plants/equipment is out of scope.

The use phase of a building consists of the operational energy use, the maintenance of degraded or defective parts, and the replacement of the defected or degraded parts. The impacts from building use are determined from appliances' characteristics in the building and thus, constitute operation energy or operation CO_2. The impacts from the maintenance activities are determined in the same way as in the construction phase. This includes the site installation, the transportation of plants/equipment, plant/equipment use, operation of site office and the use of temporary materials and transportation of waste. If the maintenance work entails repairs or replacement of materials originally installed, then the frequency of repairs will be required. However, because of limited data and information about the replacement of building components in Cameroon, only onsite construction phase will be considered.

Any building has a life cycle that begins with extraction of building materials and ends with demolition of the building when it becomes obsolete. When a building becomes obsolete, it is demolished or deconstructed and the materials are re-cycled for use, dumped in a landfill, taken to the incinerator, or a combination of the three. Similar to the construction phase, the impacts from the demolition phase can be determined. However, data and information about building demolition waste in Cameroon is not available; hence, it will not be considered in this study. After the establishment of the physical and process boundaries, the assessment methods considered in this study will be examined in the ensuing section.

2.5. The methods of assessment

In this section, the different embodied energy and embodied CO_2 assessment methods are examined. The aim is to establish which method(s) to use. In the literature, three methods of assessment are quite common: the input-output analysis, the process analysis, and the hybrid analysis.

Input-output LCA is a top-down method for analyzing the environmental interventions of a product using a combination of national sector-by-sector economic interdependent data which quantifies the dependencies between sectors, with sector level environmental effects and resource use data [21,22]. Using matrix operations, a change in economic demand from a sector can be quantified in environmental effects or resource use. For example, the purchase of a construction crane would directly impacts steel, aluminium, and plastic. Other examples are the indirect impacts from the production of steel as well as the entire supply chain of the plant through the economy.

In process LCA, known environmental inputs and outputs are systematically modelled through the utilisation of a process flow diagram. The process LCA is often called a bottom-up approach. This is because the subjects of analysis in process LCA are individual processing units and the flow rate and composition of streams entering and exiting such units. For example, a steel mill requires iron ore, coal and electricity and this will often be considered in process CA. However, indirect supplies such as office equipment, food, and vehicles are generally excluded to keep the analysis simple and manageable.

The above two life cycle methods of assessment have advantages and disadvantages which have been extensively discussed in [22,23,24,25]. In order to justify the choice of the methods used in this study, a summary of the advantages and disadvantages of the preferred choice is examined. Input-output analysis suffers from lack of representativeness being used due to over-aggregation of data. Also, national sector-by-sector economic interdependent data or sectoral matrix is often too old and out of date in developed countries and worse in developing countries. Process-based LCA allows for a detailed analysis of a specific process at a point in time and space. Nonetheless, it is often criticized for its subjectivity in the definition of the processes that should be considered and the data sources to be used. Also, process LCA can be complex if the building has so many different types of building materials. Furthermore, the emerging BIM can be used to model a building that can systematically simplify the complexity of building materials and hence facilitating the task of embodied energy and CO_2 assessment. In this study, BIM was employed to simplify and validate results obtained from manual implementation of the process-based method.

2.6. Data collection methods

Both the British Standard and PAS-2050 recommend that the data sources and key assumptions are to be explicitly stated in order to facilitate the verification of the environmental emissions quantified at the end of the assessment. To measure embodied energy and CO_2, building processes need to be identified first. Then, the activities involved and materials used in the processes are determined. Advanced drafting and modelling software applicable to the design of buildings, e.g., Revit, allow users to generate building quantities automatically from the 3D models. The generated quantities represented by the physical dimensions need to be converted to masses using relevant densities and then multiplied by suitable CO_2 emission factors from embodied energy and CO_2 inventories. While embodied energy and CO_2 inventories for developing countries are lacking, they are quite common in the developed countries and often used in environmental impact assessment studies. These inventories developed in developed countries are now also being used in developing countries [16] partly because most construction materials are imported from developed countries.

2.7. Inventory sources

The computation of environmental emissions depends largely on the accuracy, relevance and completeness of inventory data. However, in most cases, complete data is often impossible to obtain and the computation of emissions is often found on the “best evidence” as a compromise. As individual data inventories do not contain all the emission factors for the estimation of embodied CO_2 for all building processes, a combination of various inventories are often used to carry out the estimation. The common embodied energy and CO_2 emission inventories used include:

- The Bath Inventory of Carbon and Energy (ICE) which contains emission factors for construction materials. This is the most popular and most widely used emission factors dataset developed by the Sustainable Energy Research Team at the University of Bath [5]. The current version ICE V2.0 was developed in 2011;
- Eco-inventory database developed by the Swiss Centre for Life Cycle Inventories;
- Bilan Carbon 6 developed by the French Environment and Energy Management Agency;
- Emission factors for road vehicles by UK Department of Transport [26];
- Emission factors for off-road equipment by DEFRA [27];
- Intergovernmental Panel on Climate Change (IPCC) Emission Factor Database (EFDB): This is a web-based tool developed by IPCC that contains greenhouse emission factors for use by the community.

On investigating the different impact factors’ inventories afore-mentioned, the Bath ICE is more specific to buildings than all the others. Furthermore, it is widely used in Europe and is already being used in developing countries [16]. Consequently, Bath ICE will be used in this study. To maintain the applied objectivity of this study, the embodied energy and CO_2 results obtained from using the Bath ICE should be used in a comparative sense. To facilitate understanding of computation variables, mathematical models relating the different impact factors to the building material quantities will be examined in section 2.8.

2.8. Mathematical models underpinning the process analysis approach

The main reason for using emission or impact factors is to facilitate computation of emissions. By using emission factors, tedious tasks that would have involved chemical equations are avoided. This is because emission factors are expressed as quantity of embodied energy or CO_2 per functional unit. For example, according to Bath ICE, the emission factor of virgin aluminium is 11.46 $KgCO_2/Kg$. The functional unit is the "Kg" in the denominator as it denotes quantity of virgin aluminium in 1 Kg. Therefore, to compute the emission from a given quantity of virgin aluminium, a simple multiplication of the total quantity and the emission factor is conducted. If there are several construction materials considered, then the products of the emission from different materials are added. This is modelled mathematically as in equations (1) and (2).

$$EE_k = \sum_{k=1}^{n} (1+\xi_k)\cdot Q_k \cdot I_k \quad (1)$$

$$EC_k = \sum_{k=1}^{n} (1+\xi_k)\cdot Q_k \cdot I_k \quad (2)$$

Where:

- EE_k and EC_k are embodied energy and embodied CO_2 of material type k with units MJ and $KgCO_2$ respectively;
- ξ_k is the waste factor (dimensionless) of material type k;
- Q_k is the total functional quantity of material;
- I_k is the embodied energy factor or embodied CO_2 factor with units MJ/functional unit and $KgCO_2$/functional unit of material respectively.

Because of lack of information about waste data in Cameroon, the waste factor was considered to be zero.

2.9. Calculations and the use of tools

There are available calculation tools in the market for the computation of emissions. For example, the Greenhouse Gas Protocol Initiative toolset based on Excel Spread sheet can be used to calculate various greenhouse gases of different products. There are also emerging BIM authoring tools that can be used to automate the computational process of embodied energy and CO_2. Some of these tools (e.g., Revit, Bentley Systems, Tekla) have been reviewed in [28], hence their work will not be duplicated here. Given that some of these tools are not affordable, especially from developing countries perspectives, a manual computation process was adopted (see section 3.2) and then Revit, a BIM tool, was used to validate the manual computational results.

2.10. Data Aggregation

Aggregation is a straight forward task. First, the emissions from a category are added independently. In other words, emissions from all the different construction materials, equipment/plants, and personnel transport types used are independently computed. Then, the emissions from the three different categories are summed up to obtain a total. Sections 2.1–2.10 have all been about embodied energy and CO_2 assessment. These steps will now be implemented in assessing embodied energy and CO_2 of the two case studies considered.

3. Assessments of embodied energy and CO_2: case studies' applications

3.1. Description of case studies

Due to the complexity and variety of housing types in the construction sector, the Ministry of Housing and Urban Development (MINHUD) of Cameroon has categorised houses according to sizes and content. MINHUD categorises domestic dwellings according to the following minimum requirements: 1) Gross Floor Area (GFA) usually denoted (T1: GFA $\geq 20m^2$, T2: GFA $\geq 32m^2$, T3: GFA $\geq 62\ m^2$, T4: GFA $\geq 89\ m^2$, T5: GFA $\geq 106\ m^2$, T6: GFA $\geq 130\ m^2$). 2) All the dwellings except T1 must contain a kitchen, corridors, lounge and dining room. 3) T1 and T2 should contain 1 bedroom each while T3, T4, T5, and T6 should contain 2, 3, 4 and 5 bedrooms respectively. 4) T1, T2, and T3 should contain 1 toilet each, T4 and T5 should contain 2 toilets while T6 should contain 3 toilets. For purposes of this study T3 and T4 are employed as case studies for mud-brick and cement-block houses respectively. The choice is based on their popularity of use in Cameroon. The 2D drawings of T3 and T4 are presented in Figures 2 and 3.

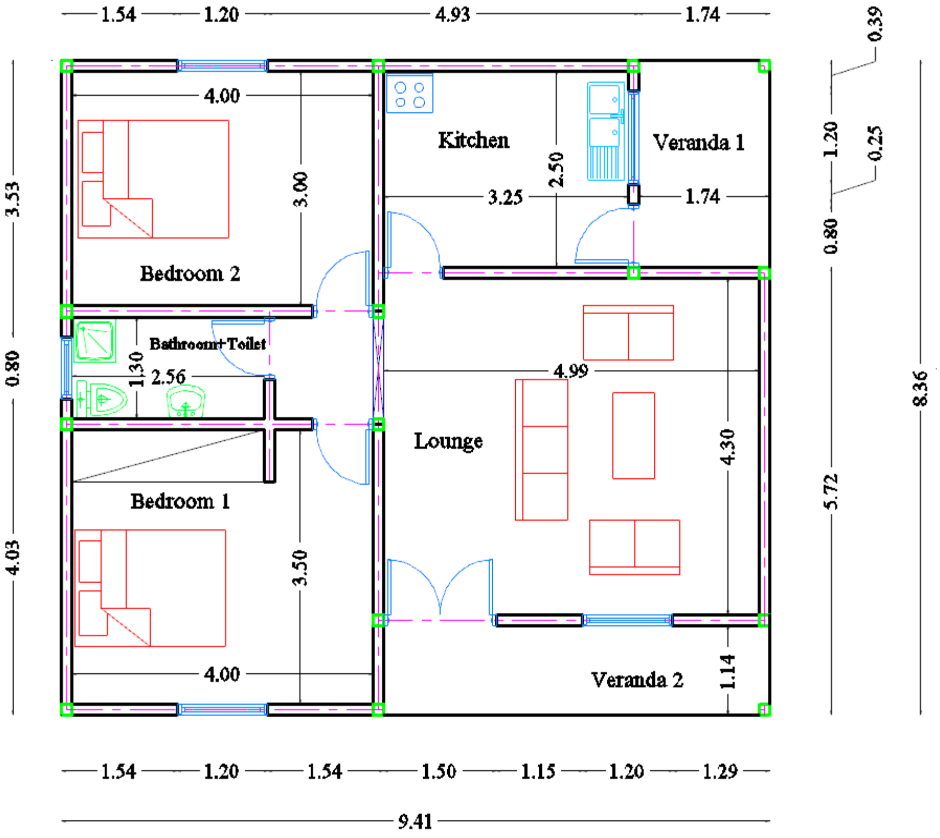

Figure 2. T3 mud-brick house

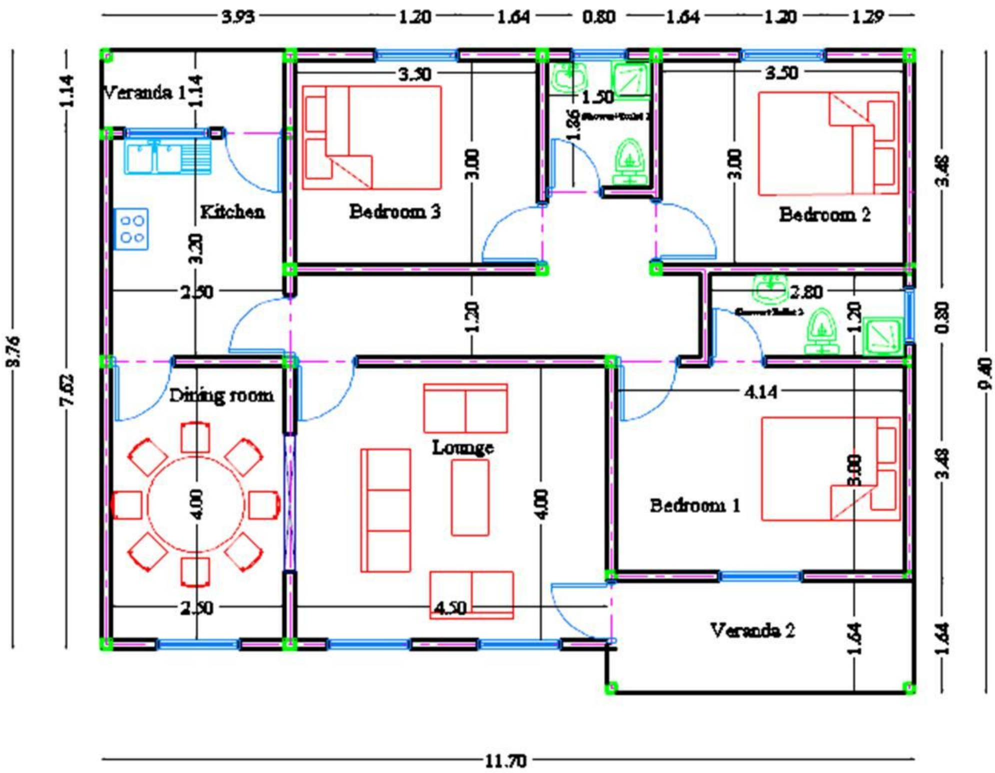

Figure 3. T4 cement-block house

3.2. Sample computation of a component

In this section, only the foundation components of the buildings have been chosen to illustrate the computation process of embodied energy and CO_2. The foundations of both T3 and T4 are geometrically the same in form except differences in dimensions. Consequently, for illustrative purposes detailed steps in computation of embodied energy and CO_2 performed on T3 will be presented. The results for the computation of the complete houses will be presented in summarized tabular forms.

The emission intensities used in the computation of the emissions consider the product phase excluding the manufacturing of components in the fabrication shop. Although construction waste has recently been noted to be significant in Cameroon [29,30], no studies have actually determined the share or fraction of construction waste in relation to the various construction materials used. Consequently, in this study the value for the construction waste factor is assumed to be zero. The quantity of the various parts of the foundation were measured and multiplied by the density of the respective materials to deduce their weight for use in the calculation of emissions.

3.2.1. Specimen calculation of foundation

According to the architect's specifications, the foundations have been used in bearing the concrete slab floor. The foundation dimensions are shown in Figure 4. The different foundation material components are:

- Lean concrete: Its role is to provide the uniform surface to the foundation concrete and to prevent the direct contact of foundation concrete from the soil. Its thickness is 5 cm. It is mixed at 150 Kg/m3;
- Concrete for ground beam, column footings: This is mixed at 350 Kg/m3;
- Ground floor slab: This is concrete with a cement finish. The concrete is mixed at 300 Kg/m3;
- Foundation wall: This wall is made up of cement blocks of dimension 20 × 20 × 40 cm completely filled with concrete;
- Damp proof course of thickness 0.05 cm;
- Substrate of gravel;
- Sand.

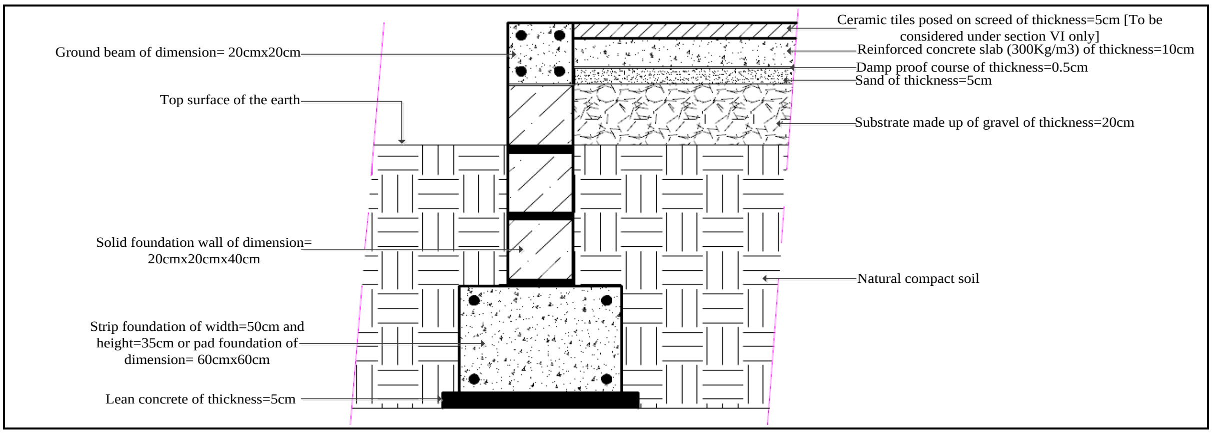

Figure 4. Cross-section of foundation

3.2.2. Calculation of the mass of the different materials in the foundation

In general, the mass, Q, of any substance is related to the Volume V through the formula: $Q = \rho V$, where ρ is the material density; Volume (V) = Length × Width × Thickness.

3.2.2.1. Lean concrete

Volume of lean concrete: $V_l = 3\ \text{m}^3$. Therefore, the total mass of lean concrete (Q_l) is given by: $Q_l = (22\ \text{kN/m}^3) \times 3\ \text{m}^3$; $Q_l = 6600$ Kg.

The total embodied energy is defined by $EE_{tp} = Q_{tp} \times I_{p(ee)}$, where $I_{p(ee)}$ is the embodied energy factor for concrete. In Bath ICE, the embodied energy and CO_2 intensities of concrete dosed at 150 Kg/m^3 have not been provided. However; values for concrete dosed at 120 Kg/m^3 and 200 Kg/m^3 have been provided. From Bath ICE the embodied energy intensities for concrete dosed at 120 Kg/m^3 and at 200 Kg/m^3 are 0.49 MJ and 0.67 MJ; while embodied CO_2 intensities are 0.06 KgCO_2 and 0.091 KgCO_2 respectively. While using the lower or upper values would be an underestimation or overestimation, an average of both values is most probable, especially as these intensities are increasing functions.

Based on this assumption, the computed embodied energy and CO_2 intensities for lean concrete dosed at 150 Kg/m^3 are:
0.58 MJ { = (0.58 + 0.67)/2} and 0.0755 $KgCO_2$ { = (0.06 + 0.091)/2}.
EE_l = 6600 Kg × (0.58 MJ/Kg); EE_l = 3828 MJ.
Total embodied CO_2:
$EC_l = Q_l \times I_{l(CO2)}$, where $I_{l(CO2)}$ is the embodied CO_2 factor for concrete.
EC_l = 6600 Kg × (0.0755 $KgCO_2$/Kg).
EC_l = 498.3 $KgCO_2$.

3.2.2.2. *Damp proof course*

The plastic used for damp proof is the general type and has thickness 5×10^{-4} m. The floor covered by the plastic is slightly higher than the gross floor internal. The value is $100m^2$. Therefore the volume is $100\ m^2 \times 5 \times 10^{-4}\ m = 0.05\ m^3$. The density of general plastic is 960 Kg/m^3.
Therefore mass $Q_{dp} = 0.05\ m^3 \times 960\ Kg/m^3 = 48$ Kg.
From the Bath ICE, the embodied energy and CO_2 intensities for general plastic are 80.5 MJ/Kg and 2.73 $KgCO_2$/Kg respectively. Therefore the embodied energy and CO_2 are:
EE_{dp} = 48 Kg × 80.5 MJ/Kg = 3864 MJ.
EC_{dp} = 48 Kg × 2.73 $KgCO_2$/Kg = 131.04 $KgCO_{2.}$

3.2.2.3. *Solid foundation wall*

The solid foundation wall is made up of cement-blocks of dimensions 20cm × 20cm × 40cm. It is arrayed in two columns along the perimeter of T3 floor plan as indicated in Figure 2. The total volume is 11.65 m^3. From the Bath ICE, its density, embodied energy and CO_2 are 1900 Kg/m^3, 1.33 MJ/Kg and 0.208$KgCO_2$/Kg respectively. Therefore the embodied energy and CO_2 emissions are:
$EE_{sw} = 11.65\ m^3 \times 1900\ Kg/m^3 \times 1.33$ MJ/Kg = 29439.6 MJ.
$EC_{sw} = 11.65\ m^3 \times 1900\ Kg/m^3 \times 0.208\ KgCO_2/Kg = 4604.1\ KgCO_2$.

3.2.2.4. *Mortar for foundation wall joints*

The volume of the mortar for the foundation wall is estimated at 1.93 m^3. Based on the Bath ICE, the density, embodied energy and CO_2 intensities are 1650 Kg/m^3, 1.11 MJ/Kg and 0.171 $KgCO_2$/Kg. Therefore the embodied energy and CO_2 emissions are:
$EE_{mf} = 1.93\ m^3 \times 1650\ Kg/m^3 \times 1.11$ MJ/Kg = 3535 MJ.
$EC_{mf} = 1.93\ m^3 \times 1650\ Kg/m^3 \times 0.171KgCO_2/Kg = 544.55\ KgCO_2$.

3.2.2.5. *Concrete for ground beam, column footings*

The total mass of concrete (Q_g) is given by:
$Q_g = (24\ kN/m^3) \times 4\ m^3$
$Q_g = 9600$ Kg
Based on this assumption the computed embodied energy and CO_2 intensities for concrete dosed at 350 Kg/m^3 are 1.025 MJ { = (0.91 + 1.14)/2} and 0.1505 $KgCO_2$ { = (0.06 + 0.091)/2}

EE_g = 9600 Kg × (1.025 MJ/Kg).
EE_g = 9840 MJ.
Total embodied CO_2 ECg = Qg × $Ig_{(CO2)}$, where $Ig_{(CO2)}$ is the embodied CO_2 factor for concrete;
ECg = 9600 Kg × 0.1505 $KgCO_2$/Kg.
ECg = 1445 $KgCO_2$.

3.2.2.6. Timber for formwork

The volume of the timber for the foundation wall formwork is estimated at 0.7 m^3. Based on the Bath ICE, the density, embodied energy and CO_2 intensities are 90 Kg/m^3, 10 MJ/Kg and 0.71 $KgCO_2$/Kg. Therefore, the embodied energy and CO_2 emissions are:
EE_{mf} = 0.7 m^3 × 90 Kg/m^3 × 10 MJ/Kg = 630 MJ
EC_{mf} = 0.7 m^3 × 90 Kg/m^3 × 0.71 $KgCO_2$/Kg = 45 $KgCO_2$

3.2.2.7. Ground floor slab

The total mass of concrete (Q_s) is given by:Q_s = (24 kN/m^3) ×8.69 m^3; Q_s = 20860 Kg.

Based on the Bath ICE embodied energy and CO_2 intensities for concrete dosed at 300 Kg/m^3 that were available and directly used, the values are 0.91 MJ and 0.131 $KgCO_2$ respectively.
EE_s= 20860 Kg × 0.91 MJ/Kg.
EE_s = 18979 MJ.
Total embodied CO_2 ECs = Qs × $Is_{(CO2)}$, where $Is_{(CO2)}$ is the embodied CO_2 factor for concrete;
EC_s = 20860 Kg × 0.131 Kg CO_2/Kg.
EC_s = 2733 $KgCO_2$.

3.2.2.8. Substrate of gravel

The substrate used is made up of crushed rocks of average thickness 2cm. The volume of substrate is estimated at 0.17 m^3. Based on the Bath ICE, the density, embodied energy and CO_2 intensities are 2240 Kg/m^3, 0.083 MJ/Kg and 0.0048 $KgCO_2$/Kg. Therefore, the embodied energy and CO_2 emissions are:
EE_{sg} = 0.17 m^3 × 2240 Kg/m^3 × 0.083 MJ/Kg = 32 MJ
EC_{sg} = 0.17 m^3 × 2240 Kg/m^3 × 0.0048 $KgCO_2$/Kg = 1.83 $KgCO_2$

3.2.2.9. Sand

The volume of sand is estimated at 0.04 m^3. Based on the Bath ICE, the density, embodied energy and CO_2 intensities are 0.2240 Kg/m^3, 0.081 MJ/Kg and 0.0048 $KgCO_2$/Kg. Therefore, the embodied energy and CO_2 emissions are: EE_{sa} = 0.04 m^3 × 2240 Kg/m^3 × 0.081 MJ/Kg = 7.30 MJ; EC_{sa} = 0.04 m^3 × 2240 Kg/m^3 × 0.0048 $KgCO_2$/Kg = 0.43 $KgCO_2$.

Thus, the total embodied energy and CO_2 values for the foundation are 70154.9 MJ and 10003.25 $KgCO_2$ respectively. Similarly, the embodied energy and CO_2 for the other components are computed and the summation takes to obtain the embodied energy and CO_2 for the whole T3 house as 137934.91 MJ and 15665.56 $KgCO_2$ respectively. Similarly, the embodied energy and CO_2 for the whole T4 house are 292326.81 MJ and 37829 .19 $KgCO_2$ respectively.

4. Validation of results using a BIM software

Based on the computation of embodied energy and CO_2 of the foundation the challenges encountered in doing the same for the whole building cannot be underestimated. This is a key weakness of manual computation, where mundane computational tasks are repeated for each identified building material. Furthermore, the manual process is very susceptible to errors and the chances of identifying the errors are slim. As discussed earlier in section 2.5, emerging BIM can be used to enhance the accuracy of process-based methods in the computation of embodied energy and CO_2. BIM also serves as an alternative to validate the computational results manually obtained. Based on literature review (e.g. [28]), there are many BIM software that have emerged and are currently being applied to model buildings. Revit is quite popular in the BIM software market. A major advantage of Revit is that its building models can readily be converted into interoperable or communicable formats that can be processed by other software [31]. A comma-separated value (CSV) is a common, relatively simple file format that is easily supported by Revit and Microsoft Excel. Data stored in CSV format can be read by Excel. Outputting or representing building model information in CSV can be read by Revit or MS Excel. The computational power of MS Excel lends it a great choice in modelling equations 1 and 2 which subsequently are used in computing embodied energy and CO_2. Also, MS Excel can easily be used to present computational results according to standard formats such as New Rules of Measurements in the UK and the Cahier des Prescriptions Techniques in France. These are rules of construction quantity measurements and output presentation. The latter was adopted for this study as it is more commonly used in Francophone countries including Cameroon. Based on the 2D drawings and Architects specification T3 and T4 were modelled in Revit. The 3D equivalents are presented in Figures 5 and 6.

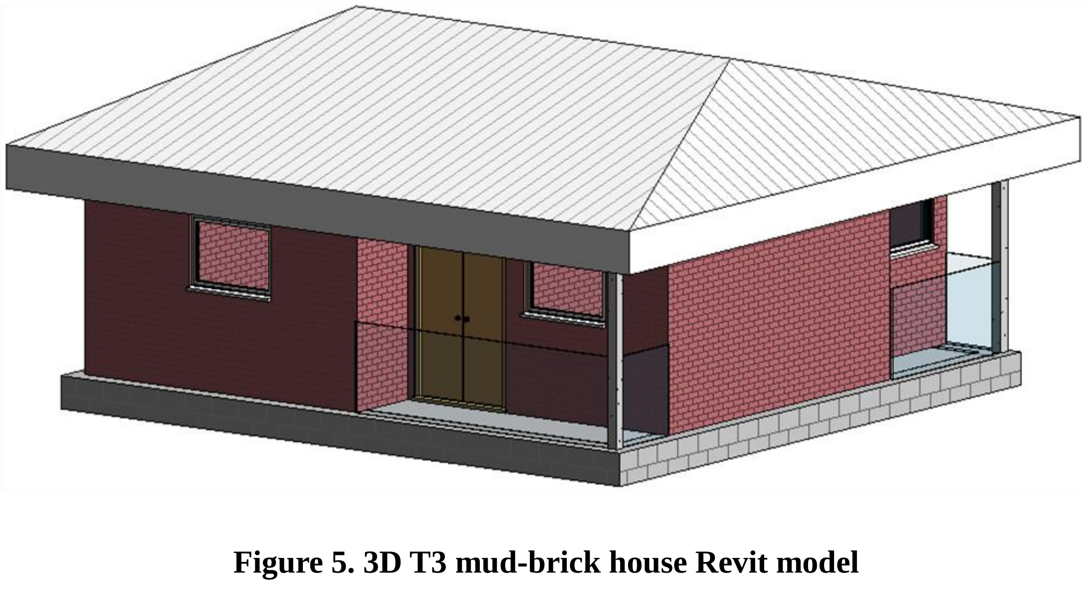

Figure 5. 3D T3 mud-brick house Revit model

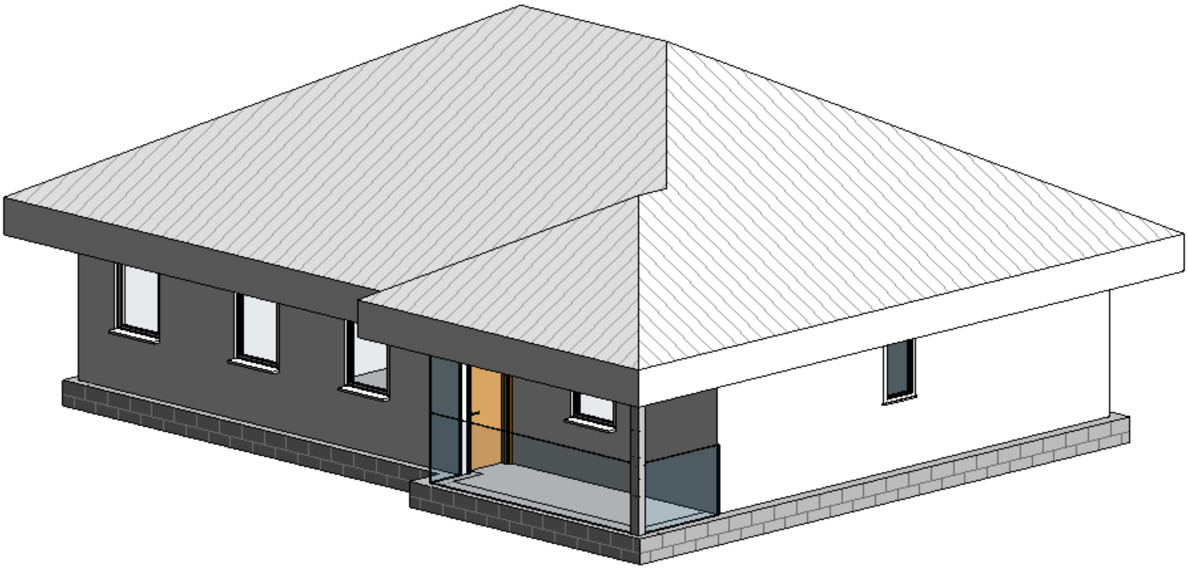

Figure 6. 3D T4 cement-block house Revit model

Schedules and quantities are then generated from these models using the "Modify Schedules/Quantities" function under the "View" tab in Revit 2014. The output is converted to CSV format using the "Export" function in Revit 2014. The CSV format is stored in any preferred location on the computer and read with MS Excel. Equations 1 and 2 are modelled in Excel and computations are easily conducted in this environment. The initial results obtained differ slightly from those obtained through manual computations in section 3.2.2. The manual process is rechecked to identify and correct errors. Also, the BIM model is rechecked to identify missing components. These activities were conducted several times until common results were obtained. The results are presented in Tables 1 and 2.

Table 1. Embodied energy and CO_2 assessment of T3 mud-brick house.

N °	**DESCRIPTION**	**Volume (m^3)**	**Density (Kg/m^3)**	**Qty (Kg)**	**Embodied Energy (EE) Intensity (MJ/Kg)**	**Embodied Carbon (EC) Intensity $KgCO_2/Kg$**	**EE Emissions (MJ)**	**EC Emissions ($KgCO_2$)**
O	**SITE INSTALLATION**	No data						
		Sub-total						
I	**FOUNDATION**							
1.1	Lean concrete mix at 150 Kg/m^3 of thickness = 5 cm	3.000	2200	6600	0.58	0.0755	3828	498.3
1.2	Damp proof course/membrane of thickness=0.05 cm(plastic-general)	0.050	960	48	80.5000	2.7300	3864	131.04
1.3	Solid foundation wall of dimension 20 cm × 20 cm × 40 cm	11.650	1900	22135	1.3300	0.2080	29439.55	4604.08
1.4	Mortar for wall joints	1.930	1650	3184.5	1.1100	0.1710	3534.795	544.5495
1.5	Concrete mix at 350 Kg/m^3 for footing, ground beam, substructure column	4.000	2400	9600	1.0250	0.1505	9840	1444.8
1.6	Timber for formwork (hardwood unspecified)	0.700	90	63	10.0000	0.7100	630	44.73
1.7	Concrete slab mix at 300 Kg/m^3 of thickness = 10 cm	8.690	2400	20856	0.91	0.131	18978.96	2732.136
1.8	Substrate made of gravel and crushed rocks of thickness = 20 cm	0.170	2240	380.8	0.0830	0.0048	31.6064	1.82784
1.9	Sand of thickness 5 cm	0.040	2240	89.6	0.0810	0.0048	7.2576	0.43008
		Sub-total					***70,154.17***	***10,001.89***
II	**ELEVATIONS**							
2.1	Brick walls (mud)	29.400	1730	50862	0.0000	0.0000	0	0
2.2	Mortar for wall joints	5.250	1650	8662.5	1.1100	0.1710	9615.375	1481.2875
2.3	Concrete mix at 350 Kg/m^3 for super-structural beams and columns	3.000	2400	7200	1.0250	0.1505	7380	1083.6
2.4	Timber for formwork (hardwood unspecified)	1.400	90	126	10.0000	0.7100	1260	89.46
		Sub-total					***18,255.38***	***2,654.35***
III	**CARPENTRY AND ROOFWORK**							
3.1	Timber joist of dimension 3 cm ×	0.850	90	76.5	10.4000	0.8900	795.6	68.085

	15 cm (sawn hard wood)							
3.2	Roof battens of dimension 8 cm × 8 cm (sawn hardwood)	0.250	90	22.5	10.4000	0.8900	234	20.025
3.3	Aluminium roof covering	0.060	2700	162.00	155.0000	8.2400	25110	1334.88
3.4	Ceiling plywood	0.320	540	172.8	15.0000	1.0700	2592	184.896
3.5	Aluminium ridge board	0.002	2700	5.4	155.0000	8.2400	837	44.496
3.6	Wooden fascia (sawn hardwood)	0.030	700	21	10.4	0.89	218.4	18.69
3.7	Aluminium on fascia	0.006	2700	16.2	155.0000	8.2400	2511	133.488
		Sub-total					***32,298.00***	***1,804.56***
IV	**ELECTRICITY**	No data						
		Sub-total						
V	**PLUMBING**	No data						
		Sub-total						
VI	**TILES AND PAINTINGS**							
6.1	Bathroom wall ceramic tiles of dimension 30 cm × 30 cm	0.040	2000	80	10.0000	0.66	800	52.8
6.2	Bathroom tiles 15 cm × 15 cm	0.008	1700	13.6	29.0000	1.5100	394.4	20.536
6.3	Mortar for posing of tiles	0.009	1900	17.1	1.3300	0.2080	22.743	3.5568
		Sub-total					***1,217.14***	***76.89***
VII	**WOOD AND STEEL WORKS**							
7.1	Wooden door panel of thickness 4 cm including frames	0.220	700	154	10.4	0.89	1601.6	137.06
7.2	Aluminium locks			3	155.0000	8.2400	465	24.72
7.3	Timber window including frames	0.200	700	140	10.4	0.89	1456	124.6
7.4	Glass louvers	0.090	25	2.25	15.0000	0.86	33.75	1.935
7.5	Aluminium glass louvers' holders			4	155.0000	8.24	620	32.96
7.6	Steel window protectors	0.075	7850	588.75	20.1	1.37	11833.875	806.5875
		Sub-total					***16,010.23***	***1,127.86***
	Grand-total						**137,934.91**	**15,665.56**

Table 2. Embodied energy and CO_2 assessment of T4 cement-block house.

N °	DESCRIPTION	Volume (m^3)	Density (Kg/m^3)	Qty (Kg)	Embodied Energy (EE) Intensity (MJ/Kg)	Embodied Carbon(EC) Intensity $KgCO_2/Kg$	EE Emissions (MJ)	EC Emissions ($KgCO_2$)
O	**SITE INSTALLATION**	No data						
		Sub-total						
I	**FOUNDATION**							
1.1	Lean concrete mix at 150 Kg/m^3 of thickness = 5 cm	3.850	2200	8470	0.58	0.0755	4912.60	639.49
1.2	Damp proof course/membrane of thickness = 0.05 cm (plastic-general)	0.070	960	67.20	80.5000	2.7300	5409.60	183.46
1.3	Solid foundation wall of dimension 20 cm × 20 cm × 40 cm	16.640	1900	31616	1.3300	0.2080	42049.28	6576.13
1.4	Mortar for wall joints	2.400	1650	3960	1.1100	0.1710	4395.60	677.16
1.5	Concrete mix at 350 Kg/m^3 for footing, ground beam, substructure column	5.840	2400	14016	1.0250	0.1505	14366.40	2109.41
1.6	Timber for formwork (hardwood unspecified)	0.900	90	81.00	10.0000	0.7100	810.00	57.51
1.7	Concrete slab mix at 300 Kg/m^3 of thickness = 10 cm	11.500	2400	27600	0.91	0.1310	25116.00	3615.60
1.8	Substrate made of gravel and crushed rocks of thickness = 20 cm	0.240	2240	537.60	0.0830	0.0048	44.62	2.58
1.9	Sand of thickness 5 cm	0.060	2240	134.40	0.0810	0.0048	10.89	0.65
		Sub-total					***97,114.99***	***13,861.97***
II	**ELEVATIONS**							
2.1	Cement blocks for walls (Cement-sand mix ratio 1:3)	38.000	1900	72200	1.3300	0.2080	96026.00	15017.60
2.2	Wall joint mortar (Cement-sand ration 1:4)	6.100	1650	10065	1.1100	0.1710	11172.15	1721.12
2.3	Concrete mix at 350 Kg/m^3 for super-structural beams and columns	4.000	2400	9600	1.0250	0.1505	9840.00	1444.80
2.4	Timber for formwork (hardwood unspecified)	1.700	90	153	10.0000	0.7100	1530.00	108.63
2.5	Mortar for wall plastering	4.300	1900	8170	1.3300	0.2080	10866.10	1699.36
		Sub-total					***129,434.25***	***19,991.51***

III	**CARPENTRY AND ROOFWORK**							
3.1	Timber joist of dimension 3 cm × 15 cm (sawn hardwood)	1.050	90	94.50	10.4000	0.8900	982.80	84.11
3.2	Roof battens of dimension 8 cm × 8 cm (sawn hardwood)	0.350	90	31.50	10.4000	0.8900	327.60	28.04
3.3	Aluminium roof covering	0.080	2700	216	155.0000	8.2400	33480.00	1779.84
3.4	Ceiling plywood	0.480	540	259.20	15.0000	1.0700	3888.00	277.34
3.5	Aluminium ridge board	0.003	2700	8.10	155.0000	8.2400	1255.50	66.74
3.6	Wooden fascia (sawn hardwood)	0.026	700	18.20	10.4	0.89	189.28	16.20
3.7	Aluminium on fascia	0.007	2700	18.90	155.0000	8.2400	2929.50	155.74
		Sub-total					***43,052.68***	***2,408.00***
IV	**ELECTRICITY**	No data						
		Sub-total						
V	**PLUMBING**	No data						
		Sub-total						
VI	**TILES AND PAINTINGS**							
6.1	Bathroom wall ceramic tiles of dimension 30 cm × 30 cm	0.075	2000	150.00	10.0000	0.66	1500.00	99.00
6.2	Bathroom tiles 15 cm × 15 cm	0.015	1700	25.50	29.0000	1.5100	739.50	38.51
6.3	Mortar for posing of tiles	0.020	1900	38.00	1.3300	0.2080	50.54	7.90
		Sub-total					***2,290.04***	***145.41***
VII	**WOOD AND STEEL WORKS**							
7.1	Wooden door panels of thickness 4cm including frames	0.220	700	154.00	10.4	0.89	1601.60	137.06
7.2	Aluminium locks			4.00	155.0000	8.2400	620.00	32.96
7.3	Timber window including frames	0.200	700	140	10.4	0.89	1456.00	124.60
7.4	Glass louvers	0.130	25	3.25	15.0000	0.8600	48.75	2.80
7.5	Aluminium glass louvers' holders			6.00	155.0000	8.24	930.00	49.44
7.6	Steel window protectors	0.100	7850	785	20.1	1.37	15778.50	1075.45
		Sub-total					***20,434.85***	***1,422.31***
	Grand-total						**292,326.81**	**37,829.19**

5. Discussion and analysis

From the Spreadsheet, the total embodied energy and total embodied CO_2 for the construction materials of a cement-block house used in the sub-structure, superstructure, floor and wall finishes are 292326.81 MJ and 37829.19 $KgCO_2$ respectively. When converted to energy and carbon footprint (using Gross Internal Area (GIA) = 95.36 m^2), the values are 3065.51 MJ/m^2 and 396.7 $KgCO_2/m^2$ respectively. Other elements such as ceiling finishes, fittings and building services are not included in the result due to the lack of design specification data. Also, the embodied energy and CO_2 for the mud-brick house are 137934.91 MJ and 15665.56 $KgCO_2$ respectively. By dividing by the GFA (68.7 m^2), the following values are obtained: 2007.8 MJ/m^2 and 228.03 $KgCO_2/m^2$ respectively.

Current available data or computation results about embodied energy and CO_2 for houses are scarce, and when they exist, they are very diverse and lack consistency. Hence, it is often too difficult to compare results from different research and draw generalizations. These disparities in results are often caused by differences in computational methods and boundary systems and differences in construction materials, technologies and techniques used and discrepancies in the various database inventories used. However, to appreciate the findings of this study, results from other studies will be discussed. Pullen [32] has reported an embodied energy value of 3.6 GJ/m^2 for a residential building. Hammond and Jones [5] reported a mean of 5.3 GJ/m^2 and 403 $KgCO_2/m^2$ embodied energy and CO_2 respectively for 14 residential case studies. Twelve of the 14 case studies are in the UK while the other two are in the US. Dixit *et al.* [25] also reported a mean of 5.506 GJ/m^2 of embodied energy for residential buildings. In India, Reddy and Jagadish [33] reported embodied energy values of 4.21 GJ/m^2, 2.92 GJ/m^2 and 1.61 GJ/m^2 for a clay brick masonry walls building with reinforced concrete structure, load bearing brickwork and a soil-cement block house respectively. Also, another study in India revealed the embodied energy for reinforced cement concrete and mud houses are 3702.3 MJ/m^2 and 2298.8 MJ/m^2respectively [34].

What emerges from these studies is the fact that the values obtained for embodied energy and CO_2 for two typical houses in Cameroon are in the same range to those from other countries, especially India. The results reveal that a cement block house (T4) expends at least 1.5 times more embodied energy than earth or mud brick houses (T3). Furthermore, a cement block house emits at least 1.7 times more embodied CO_2 than a mud brick house.

While embodied energy and CO_2 are important factors, it is also important to consider the effects of material choice on the energy requirements for cooling and heating over the life time of the building [35,36]. Some studies have revealed embodied energy to be equivalent to a few years of operating energy [37], although cases in which embodied energy can be much higher have also been reported [10,38]. In particular, in most developing countries, embodied energy of most traditional buildings can be largely compared to operating energy [37]. What these discrepancies suggest is that a holistic approach should be undertaken where embodied energy and operational energy should be considered in assessing the energy use and environmental impacts of a building.

6. Conclusions

In this study, the process-based approach supported by some mathematical models was used to compute embodied energy and CO_2 for two typical houses in Cameroon. The process-based approach was manual and because of susceptibility of such an approach to errors, BIM software was used to validate the computational results. Because of lack of data, embodied energy and CO_2 for site installation, electricity and plumbing were not computed. Also because of data scarcity, emissions from transport of construction materials and personnel and onsite equipment such as concrete mixer and vibrator were not assessed. It is important to note that this is an emerging field and knowledge in this field is gradually being explored. Hence, only emissions from construction materials were assessed. The results obtained were converted to per unit m^2 to facilitate comparison. Furthermore, when compared to other studies, the computational results were in the same range, although significantly lower than values obtained in the developed countries (e.g. UK). The comparison revealed cement-block houses consumed more embodied energy and CO_2 than mud-brick houses.

Conflict of interest

The authors declare that there are no conflicts of interest related to this study.

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