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SIMULATING TOTAL EMBODIED ENERGY OF BUILDING PRODUCTS THROUGH BIM

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ABSTRACT

The total energy involved in building construction and operation can be divided in two parts, Operational Energy and Embodied energy. Many researches have focused on simulating operation energy but the embodied energy is not much discussed for simulation or alternative selection purposes. There are a lot of complex variables that need to be quantified and analyzed before any meaningful optimization of embodied energy can be achieved. Building Information Model (BIM) is used as a platform to hold the data as a context aware, intelligent and interactive database This paper discusses the means for realizing the embodied energy data in the BIM model through linking the model with external database thus laying a foundation for the data exchange and retention needed to perform the simulations in the next phase of research. Plug-ins are developed to calculate the embodied energy for different scenarios. Finally, a case study is conducted of a simplified manufacture plant to implement the proposed methodology.

1 INTRODUCTION

Aiming for most sustainably constructed building by using limited additional resources has become a prime goal for most construction projects. Energy being an important part of the sustainability drive, usually takes a lead role in determining the achievement of the sustainability goal. The energy required in obtaining the materials from their rawest form, transportation of the material to the site and finally its assembly in the form of a structure is referred to as Embodied Energy (EE). To quantify this energy is almost a challenge in itself, but a bigger challenge is to generate realistic alternatives based on EE and simulate these alternatives to find the alternative with optimum EE. To collect the data pertaining to embodied energy of the case project, a questionnaire was developed which consists of mainly four parts: (i) Material, Machinery and Personnel Transportation (ii) Construction Equipment Utilization (iii) Auxiliary Works and (iv) Temporary Works. All these parts probed the energy consumption during the respective activity. Energy embodied in transportation for materials and crew was calculated based on number of shipment, round trip distance and fuel consumption of the specific vehicle. Construction equipment utilization was limited by equipment type, use stage, total working hours and fuel consumption.

2 LITERATURE REVIEW

2.1 Building Sustainability

Policies, laws and regulations around the world are pushing the construction sector to adopt sustainable innovation in terms of products and processes (Hellstrom 2007; Steurer 2011). Building sustainability refers to a building structure and the processes for its use that are environmentally responsible and resource-efficient throughout the building's life-cycle: from siting to design, construction, operation, maintenance, renovation and demolition (UEPA 2011). This encompasses efficient utilization of resources (energy, water etc.), reduction in environmental degradation due to pollution & waste and regeneration of resources through onsite mechanisms & treatment plants. Sustainability assessment can be defined as the process of identifying, predicting and evaluating the potential impacts of initiatives and alternatives (Devuyst 2000). Achieving sustainable buildings is possible through a broad range of products and services like heat pumps, solar collectors, insulation systems, shading devices, phase-change materials heating and cooling equipment, photovoltaics, sensor systems for intelligent energy management and energy control and monitoring systems (Kolokotsa 2011). Therefore, to make a particular building sustainable stakeholders need to do market search and comparison of various solutions based on sustainability criteria, such as return-on-investment, CO2 emissions, the potential for reducing energy consumption etc.

2.2 Building Energy

Forecasts of the EIA (2010) show that energy consumption in buildings is increasing at a rate comparable to those of the industrial and transportation sectors. Interestingly, the building sector has the highest energy saving and pollution reduction potential, given the flexibility of its demands (Ipcc 2007). As far as building energy is concerned, Embodied energy (EE) and Operational energy (OE) together constitutes a building's life cycle energy (LCE). EE involves the initial energy of the construction (material and burden associated with material consumption in buildings) and OE reveals the energy utilized in operating phase (Praseeda et al. 2016). There are two more types associated with building energy namely demolition and disposal energy but these are rarely addressed as they together form less than 1% of life cycle energy (Sartori and Hestenes 2007; Ramesh et al. 2010).

2.2.1 Embodied Energy

To obtain the embodied energy for the material a methodology known as Life Cycle Analysis or LCA is adopted. There are three approaches used in life cycle analysis: process analysis, input–output (I–O) analysis and hybrid analysis. Due to the complexity of the upstream requirements for goods and services, the process analysis which is used widely has some disadvantages. The second method, I–O analysis, uses national average data for each sector of the economy and is considered by many researchers to be more comprehensive than process analysis. On the other hand, I–O analysis is usually used as a "black box", with little understanding of the values being assumed for each process (Crawford 2008). These models also have different assumptions regarding the system boundaries such as cradle to gate etc. (Chang et al. 2016). The hybrid approach is a mixed approach of the previous two approaches which incorporates convenient aspects of the previous approaches. Such an approach was adopted by Atmaca (2016) for the calculation of embodied energy by using Inventory of Carbon and Energy (ICE) Version 2.0 database (Hammond and Jones 2011). The ICE includes the embodied energy coefficients for a large number of materials. However, this information is usually based on some assumptions and a certain locality. Furthermore, this information is usually limited to extraction or production of the material, transportation and construction aspects are missing (Capper et al. 2012). For a project specific evaluation, transportation impacts can be calculated by incorporating hauling distances, vehicle efficiencies and heating value of fuel. As far as construction energy is concerned, it can be calculated by evaluating the method of construction specified in the standards such as R.S.Means (Means 2010) and field data.

2.3 Building Information Modelling

Building Information Modeling (BIM) is one of the most promising developments in the Architecture, Engineering and Construction (AEC) industries. According to National BIM standards, 'BIM is a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National BIM Standards (NBIMS 2010).

2.3.1 BIM and Building Energy

A study conducted by Ajayi et. al. (2015) evaluated the extent to which building material specification affects life cycle environmental performance, using a building information modelling (BIM)-enhanced LCA methodology. This study employed Revit, Green Building Studio (GBS) and ATHENA Impact Estimator as LCA tool but the methodology involved manual export and import within various tools, final evaluation of alternatives and comparisons were also manually performed. In another effort to perform LCA within BIM environment, Shrivastava and Chini (2012) realized the embodied energy values in the BIM model, but the values were manually added and there was no link between the BIM model and embodied energy value source/database. Anton and Diaz (2014) studied the integration of Life Cycle Assessment in the BIM environment and highlighted a missing link between the Environmental Information (such as Embodied energy and Carbon) with the BIM objects as shown in the Figure 1 below.

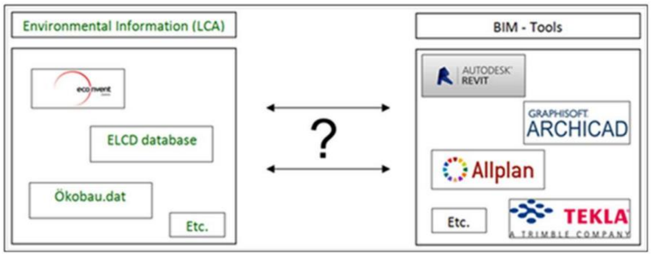


Figure 1: Seeking an automatic and efficient link between BIM models and environmental information (Anton and Diaz 2014).

Nevertheless, BIM authoring tools are flexible enough to hold additional information and perform calculations on the combination of additional and built-in information (Alwan et al. 2014). Additionally, an external database is required to hold the large amount of data may be needed for a specific material or construction process (Jrade et al. 2013). Since to embed this additional information manually to a BIM model would be a cumbersome task, plugins are used to automate these tasks. A number of frameworks have adopted API's to efficiently run their operations consisting of multiple software applications (Oti et al. 2016). A similar framework and tool has been proposed by shadram et. al. (2016), which utilizes Extract Transform Load (ETL) technology to ensure BIM-LCA interoperability. It is based on different databases containing predefined component recipes and environment product declaration of various materials. It utilizes Revit and Power Pivot to perform the integration of these databases. Although the approach promotes automation, the databases lacks standardization and authenticity.

3 METHODOLOGY

Based on the above discussion, this paper proposes a novel approach of linking the BIM model with the ICE database and realizing the embodied energy values directly in the BIM environment without any manual inputs or imports. The framework shown in Figure 2 illustrates the proposed approach in detail. A set of external databases are populated with the embodied energy coefficients (obtained from ICE database), distances between material supplier and construction site (obtained from the construction manager), material transportation vehicle information (obtained from Chinese construction standards), Equipment and manpower efficiency (obtained from past experience). The data mentioned above along with the material quantities extracted from the BIM model are used to determine the embodied energy by using equations such as eq.1.

$$\mathrm{EE_M} = \sum_{i=1}^{\infty} \mathrm{EE_{M_i}} = \sum_{i=1}^{\infty} \mathrm{V} \times \omega \times \rho \times \varepsilon \tag{1}$$

Where, V is Volume extracted from BIM, ω is the waste factor, ρ is the density of the material, ε is the embodied energy coefficient from ICE. The proposed methodology is implemented on a simplified manufactory plant, the following section details implementation process.

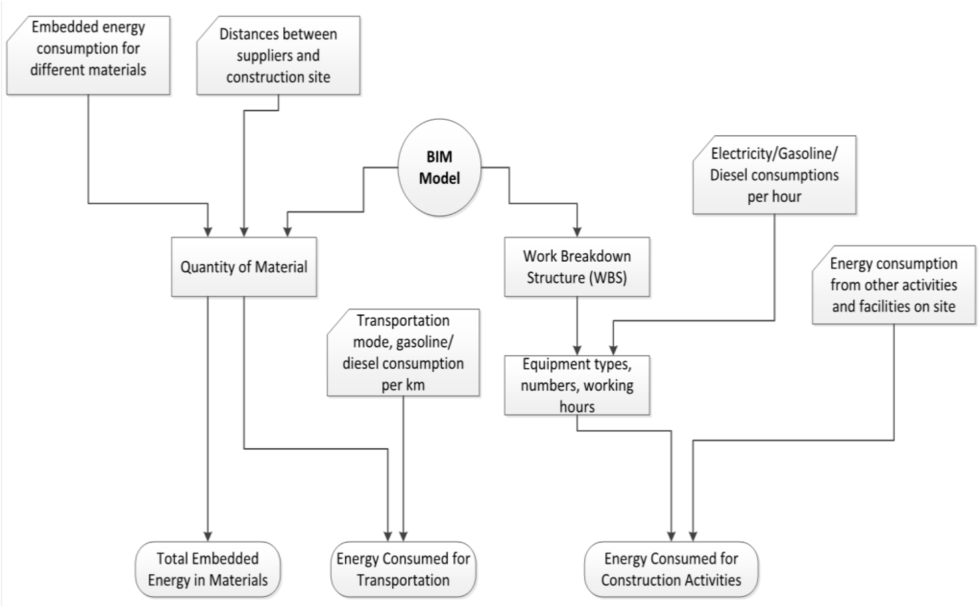


Figure 2: Framework for quantifying and realizing Embodied Energy data in BIM.

4 IMPLEMENTATION

The implementation of the above methodology requires four steps (i) BIM model development (ii) External database management, (iii) Plug-in development and (iv) Linking the model with database environment. First a BIM model of the manufactory was built using Revit 2016 as shown in Figure 3 below.

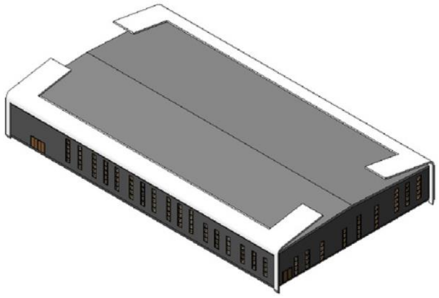
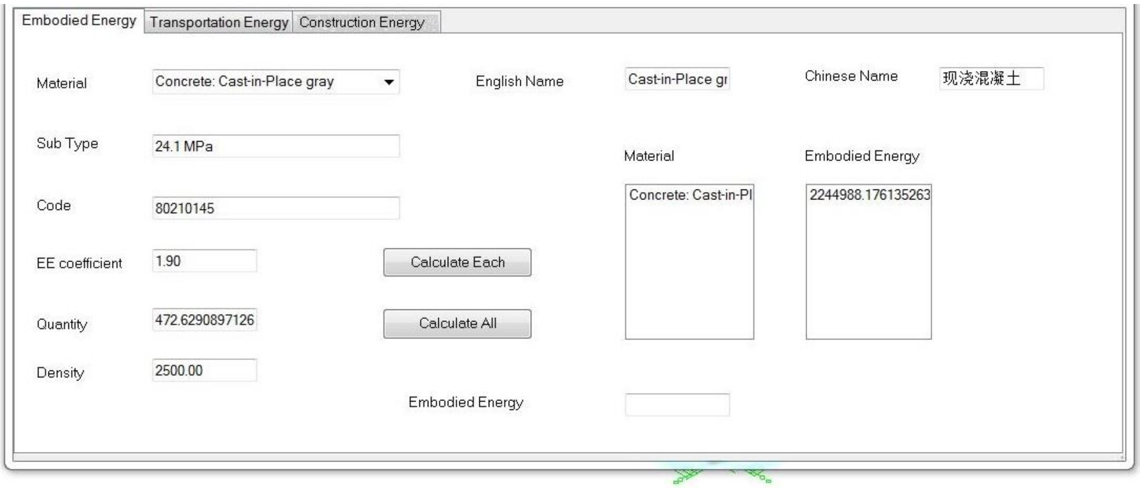


Figure 3: BIM model of the manufactory.

This BIM model was then exported to a database environment of Microsoft Access by using Revit DB Link- a built in tool for Revit. Additional data needed for calculation of embodied energy such as embodied energy coefficients, distances between material supplier and construction site, material transportation vehicle information and Equipment and manpower efficiency were added as separate tables to this database. By using C-sharp, a plug-in was developed for the Revit to calculate the embodied energy as shown in Figure 4 below.

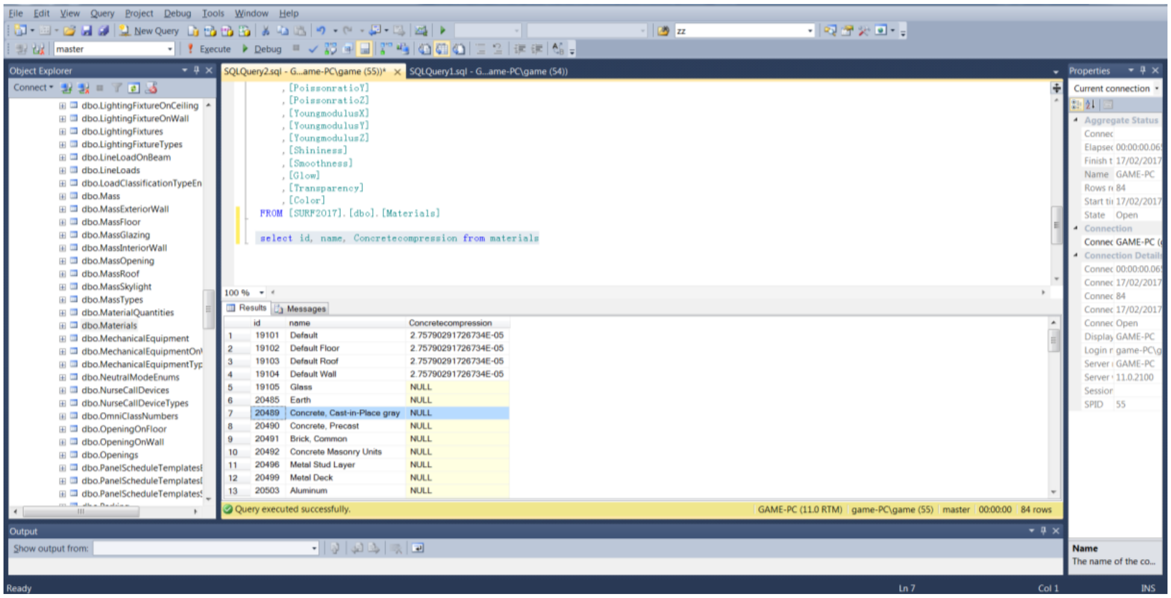


Material: Concrete: Cast-in-Place gray
English Name: Cast-in-Place gr
Chinese Name: 现浇混凝土
Sub Type: 24.1 MPa
Code: 80210145
EE coefficient: 1.90
Quantity: 472.6290897126
Density: 2500.00
Embodied Energy:

Material	Embodied Energy
Concrete: Cast-in-Pl	2244988.176135263

Figure 4: Screen Shot of Plug in for calculation of Embodied Energy.

SQL was used to query the data from the database, once the model was updated and exported again through DB-Link a glitch seem to distort the working of the plug in. Upon investigation it was found that the exporter was performing two unexpected operations, for one, it was repeating the entries for the elements that were modified after the last export, in other words changes were not properly handled when the updated model was exported again. Secondly, some property information was missing in material quantity table which was needed to determine the nature of particular material (in our case concrete strength). This can be seen in the Figure 5 below.



```
      , [PoissonratioY]
      , [PoissonratioZ]
      , [YoungmodulusX]
      , [YoungmodulusY]
      , [YoungmodulusZ]
      , [Shininess]
      , [Smoothness]
      , [Glow]
      , [Transparency]
      , [Color]
  FROM [SURF2017].[dbo].[Materials]

  select id, name, Concretecompression from materials
```

	id	name	Concretecompression
1	19101	Default	2.75790291726734E-05
2	19102	Default Floor	2.75790291726734E-05
3	19103	Default Roof	2.75790291726734E-05
4	19104	Default Wall	2.75790291726734E-05
5	19105	Glass	NULL
6	20485	Earth	NULL
7	20489	Concrete, Cast-in-Place gray	NULL
8	20490	Concrete, Precast	NULL
9	20491	Brick, Common	NULL
10	20492	Concrete Masonry Units	NULL
11	20496	Metal Stud Layer	NULL
12	20499	Metal Deck	NULL
13	20503	Aluminum	NULL

Query executed successfully.

Figure 5: DB Link Export glitches.

So, another approach was applied to get access to these values, instead of exporting the model in MS access, only the additional data was stored in Access and the plug-in was used to extract the values from the Revit environment in real time.

4.1 Case Study

A manufacture plant was selected as the case study. The quantities extracted as volumes from the Revit model were combined with their densities and embodied energy coefficients (already present in the external databases) to determine the Material Embodied energy. The total energy embodied in materials was found to be 7856 GJ. Table 1 illustrates the material embodied energy for different materials, and Figure 6 shows proportion of energy embedded in various materials. More than half of the total energy embedded in materials is consumed by cast concrete (53.78%). Polystyrene and aluminum accounts for 14.04% and 10.67% of total energy embedded in materials respectively, which are the second and third largest proportion holders. The rest of the materials contribute to around one fifth of the total energy consumed by materials. The smallest contributor to energy embedded in materials in this case study is softwood.

Since mass is usually associated with the proportion of embodied energy, Figure 7 combines mass proportion and relative embodied energy. It is noteworthy to mention, that although concrete accounts for 89.4% of material mass but the embodied energy contribution is just above 53%. In contrast, polystyrene, aluminum and steel have less contribution in mass but relatively greater contribution in the total material embodied energy.

Table 1: Quantities of materials and embodied energy.

Materials	Mass (kg)	Mass Percentage	EE (MJ)
Aluminium	5336.714957	0.16%	838397.9197
AAC (Autoclaved aerated concrete)	188376.1022	5.80%	678153.9679
ALC (Autoclaved light weighted concrete)	110730.4767	3.41%	398629.7162
Concrete, cast	2905975.538	89.40%	4224828.234
Glass	3117.687756	0.10%	57677.22348
Polystyrene	11023.23935	0.34%	1103316.026
Softwood	494.1926148	0.02%	2742.769012
Steel	25548.32959	0.79%	551843.9192
Total	**3250602.281**	**100%**	**7855589.776**

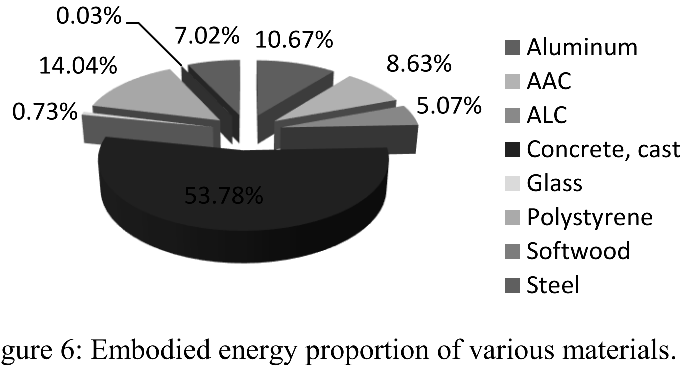


Figure 6: Embodied energy proportion of various materials.

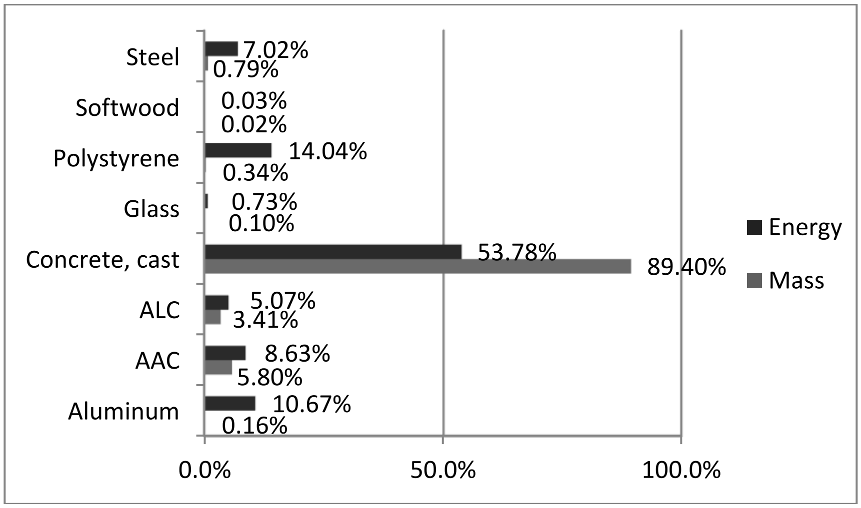


Figure 7: Mass and energy consumption of materials.

Energy embodied in transportation includes worker transportation and material transportation. The material transportation can be incorporated in to energy intensity of materials by extending the system boundary from cradle-gate to cradle-site. On the other hand, energy embodied in worker transportation is assessed based on unit area of the manufacture plant. The transportation methods and vehicles differ, depending on the type of material. For example, concrete may be transported in a concrete mixing truck, while steel may be transported in flat deck truck. Therefore the external database holds; Vehicle capacity (ton/trip to trip/ton), Average haul distance for a round trip, Diesel consumption per km of the vehicle (Average load 50%) and heating value of diesel as shown in Table 2. Number of shipments are calculated by dividing the material quantity (obtained from the Revit) by the vehicle capacity. Round trip distance is obtained from the questionnaire, Fuel energy coefficient is obtained from the vehicle manufacturer database and heating value of fuel. However, missing information is assumed for some materials through expert judgement.

Table 2: Embodied Energy for Material Transportation.

Material	No. Shipments	Round Trip Distance (km)	Fuel energy coefficient (MJ/100km)	Embodied Energy (MJ)	Percentage
Ready mixed concrete	600	164.6	417.96	413777	51.34%
Steel	105	32.8	417.96	18659.5	2.32%
AAC&ALC	360	248.8	417.96	374358	46.45%
Windows, doors	15	3.2	417.96	200	0.02%
Total				**805995.5**	**100%**

Worker transportation is the energy used to transport the crew from and to the job site. Several assumptions have been made in combination with information collected from interviews including; all the workers are transported to and from construction site (round trip) individually in gasoline fueled vehicles and the distance of all workers to construction site is same. Also, workers work for 8 hours a day. So, the external database for transportation include; the project duration in person hours, total distance of one round trip, Gasoline consumed of the vehicle per km and heating value for gasoline. Number of round trips can be calculated by dividing project duration time with daily working hours. The worker transportation is considered in the case where staff lives outside of the job site. A different scenario may be envisioned considering energy consumption of on-site accommodation provided for the workers, which is not considered in this case study. Table 3 is compiled based on information collected from interviews. The energy embodied in worker transportation is calculated as 505 GJ.

Table 3: Energy Embodied in worker transportation.

Method	**No. Shipments**	**Round trip distance(km)**	**Fuel consumption**	**Fuel heating value**	**Total embodied energy (MJ)**
Passenger Car	2622	60	8.3 L/100km	38.7MJ/L	505327.6

The main data source for construction process was on-site interviews, while information in R.S. Means was incorporated as well. Embodied energy in construction mainly considers installation of building materials. In the construction phase of energy use life cycle, power tools and equipment use, on-site fabrication and transportation and other site works are concerned. Energy used for power tools and equipment is quantified by multiplying equipment use hours and energy use rate (litres of fuel consumed per hour, or electricity used). Advantage of using R.S. Means as data source is that it simplifies the calculation. In order to access more specific information, data from site interviews is incorporated. Based on site interview Table 4 was compiled. Total working hours were provided by the contractor directly. The conversion factor is 3.6 MJ/kW. In consistency with previous results, equipment use in concrete work accounts for the largest part of total embodied energy consumed on site. Excavator used in soil work (foundation work) also takes up a significant part in this case study. Equipment used to construct the case building consumes about 1340 GJ energy.

Table 4 On-site equipment use.

Equipment	**Working Hours**	**Power (kW)**	**Stage**	**EE (MJ)**	**Percentage**
Mortar Mixer	4200	1.1	Concrete Work	16632	1.24%
Pump	1600	110	Concrete Work	633600	47.27%
Welder	1600	25	Rebar work	144000	10.74%
Cutter	800	5.5	Rebar work	15840	1.18%
Straightener	960	15	Rebar work	51840	3.87%
Excavators	1200	110	Soil Work	475200	35.46%
Hauler	400	2.2	Soil Work	3168	0.24%
Total				**1340280**	**100%**

5 RESULTS AND DISCUSSION

In total, 10507.2 GJ of energy was embodied the case building. Figure 5 shows proportions of energy consumption in different stages of the case building project. Materials accounts for the dominant portion of total embodied energy (74.8%). Transportation and on-site construction consume roughly even energy, occupying 12.48% and 12.76% of the total embodied energy respectively.

The results indicate significance of materials in the energy cycle of building product. The mass of materials and material selection both affect energy consumption. The case study was conducted in process model, one of the three variants in LCA (process model, economic input-output model and hybrid model). This model is greatly information dependent and requires large amount of work in data acquiring and processing.

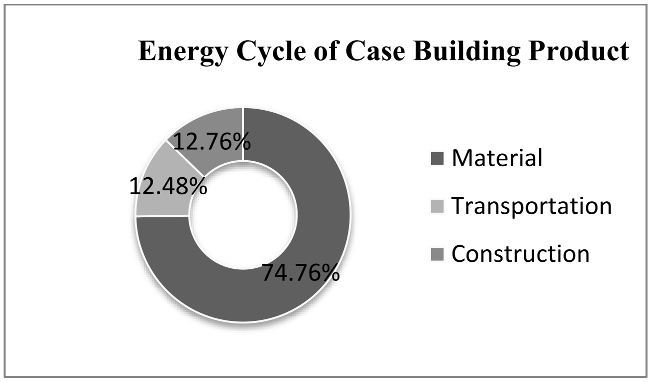


Figure 8: Energy cycle of case building product.

6 CONCLUSION AND FUTURE WORK

This paper is a part of a study on Life Cycle Evaluation of building sustainability, simulating embodied energy constitutes a major chunk of the study. Automated quantification of embodied energy is an important step before simulation could be performed for different scenarios. Therefore, this paper proposes a framework for quantifying and realizing the embodied energy data in the BIM environment and demonstrates the proposed methodology on a case project. The embodied energy was calculated separately for material, transportation and on-site assembly. The method combines a number of data sources and state of the art modelling techniques by using BIM and authentic data sources. After the automated quantification of embodied energy, the future work includes optimization of Embodied Energy through simulating different scenarios. Since, EE is constituted from material energy, transportation energy and construction energy, therefore, three different simulations need to be performed to optimize EE. Material energy can be optimized by selecting various alternatives to a specific material, transportation energy can be optimized by different route planning studies and finally, the construction energy can be optimized by using simulation tools such as symphony.

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