EMBODIED ENERGY ANALYSIS OF A PRECAST BUILDING SYSTEM

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DECLARATION

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Prof. (Mrs.) C. Jayasinghe Date:

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Prof. M.T.R. Jayasinghe Date:

ABSTRACT

Buildings are evolving throughout the history of mankind. When a new building system is introduced, the usual evaluation method is the monetary value. The adaptability to the climate conditions, structural capabilities and constructability are some other criteria for the evaluation. The building industry is consuming a vast amount of natural resources and also been responsible for a significant energy usage. With the recent developments in the environmental concerns all over the world, there is an increased the attention for the building sector. Due to the above reason new buildings have to be more environmental friendly than more conventional building systems.

A novel walling system has been considered in this study, which consist of lightweight foam concrete panels manufactured with recycled expanded polystyrene (EPS) up to 50% of the total volume. Even though those panels have lot of advantages over the conventional construction methods, they need to be compared with the other conventional methods for the environmental aspects. Embodied energy analysis is such an established method to quantitatively analyse the environmental impact caused by a product. Therefore, detailed study was carried out to determine the embodied energy of those foam concrete panels. A comparative study carried out using a typical single storey and for a two-storey house and different building materials.

Final results done for the case studies, indicated that houses constructed with cement sand blocks has the least amount of embodied energy and embodied carbon. However, houses constructed with EPS based lightweight foam concrete precast panels, can be a good competitor in terms of embodied energy and embodied carbon analysis, since it yields results much closer to the cement sand blocks. Reduced sand usage of EPS panelled walls is also an added advantage. Hence, it has the potential to be promoted as a mainstream walling material.

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Abbreviation	Description
EE	Embodied Energy
EPS	Expanded Polystyrene
LCEA	Life Cycle Energy Analysis

1. INTRODUCTION

1.1. Background

Buildings are being evolved through the centuries with the need of better shelters for human. This evolution is visible in both structural and architectural forms of buildings with the advent of modern construction technologies, usage of new machineries and introduction of new materials. This makes the building construction, a rich field for the researchers, around the world. Evaluation of these modern buildings for their benefits and limitations is a challenging task. So, the shear financial benefits, or the monetary value is no longer enough for a comparison. Along with the structural performance and thermal efficiency of the building, environmental benefits and impacts should also be evaluated.

With the growing populations, more and more buildings are built. With these buildings, many natural resources are over exploited, harming the sustainability in the global context. Recycling and reusing of materials, is a global trend followed by many developers, to improve the sustainability of their buildings. In many cases, it has double benefits of cost reduction and removal of harmful materials from the environment.

Expanded polystyrene (EPS), is such a material which is not bio-degradable. And it can take hundreds of years to naturally decay, because it does not absorb any water. However, due to its ultra-light weight, exceptional thermal performance and durability, most of the packaging materials and insulation products are made out of EPS. Since, almost all packaging material is disposed as waste, waste generated from EPS is problematic.

It has been found that EPS can be mixed with cement-sand mix, and produce a lightweight concrete mixture. (Fernando, 2016) A wall panel system has been introduced to Sri Lanka, which uses this mix while, 50% of recycled eps is being used. This has addressed two important questions- trapping waste eps which otherwise be problematic and producing a precast wall panel, which is lightweight and easy to handle. This particular wall panel is produced by sandwiching the eps based lightweight mix in between two cement fibre sheets. The panel is easily sizable even with an electrical hand saw. Labour requirement is also low with this panel.

Sri Lanka's residential buildings represent about one third of the construction sector, in terms of fixed capital formation. With growing needs and population, faster and more affordable methods of construction are required to cater the housing requirements in the country. Precast building systems come handy in this aspect. Due to the good quality control and fast erectable precast buildings can minimize the cost and time dramatic manner. There is a new precast beam, column, slab system developed with prestress technology, which has simple connection details. Along with precast lightweight wall panels, this system is said to be capable of constructing small buildings up to 3 floors height. Since, the wall panels do not require lot of finishing touches, this system is a faster way of construction. And it has the potential to be a mainstream walling material due to the aforementioned advantages. This system is considered in this study to do a detailed analysis on environmental performance.

Since early 1980's, the effect of climate change related to the energy consumption in the built and natural environment has been drawing significant attention worldwide. In the branch of environmental consideration, energy analysis and carbon footprint analysis have gained significant attention in evaluating buildings. Since, building industry is one of the biggest consumers of global energy, these analyses can be expected to yield better solutions for the construction industry. The lifecycle energy is a building, can be divided in to three main categories. Namely, Embodied energy, operational energy and energy at demolishing and disposing of the building. Out of these three, operational energy dominates in countries or regions with adverse weather conditions. However, in tropical climatic countries like Sri Lanka, embodied energy represents a significant portion of total energy.

1.2. Objectives

The main objectives of this research study are as follows;

1. Determination of embodied energy of wall panels with 50% of EPS in recycled form.
2. Comparative study of embodied energy of a single storey and a two-storey house constructed with above wall panels and conventional materials like burnt clay bricks and cement sand blocks.
3. Embodied carbon analysis for the same structures with those three types of building materials selected.

1.3. Methodology

The following methodology was adopted in order to achieve the above objectives;

1. A comprehensive literature review was carried out in order to identify the knowledge gap in relation to embodied energy analysis, embodied carbon analysis and life cycle analysis of buildings
2. The embodied energy of EPS based foam concrete panels with 50% EPS as recycled content has been assessed considering the production process.
3. The embodied energy of a single storey house and a two-storey house, constructed using foam concrete-based wall panels were assessed.
4. A comparative study was conducted with the same houses out of cement, sand blocks and moulded burnt clay bricks.
5. The suitability of introducing the foam based concrete panels as a mainstream building material has been assessed.

1.4. Arrangement of the Thesis

- Chapter 2 of the thesis presents the findings of the literature review.
- Chapter 3 provides the data collected from field surveys. Several work studies done at some manufacturing plants and processors in Sri Lanka and related to the building materials used, vehicle efficiencies and fuel consumption of some

of the vehicles used in construction related activities and details collected from questionnaire surveys are presented in this chapter.

- Chapter 4 and 5 presents two case studies done in the embodied energy of a single storey house, and the a two-storey house.
- Chapter 6 presents the conclusion.

2. LITERATURE REVIEW

2.1. General

Buildings located in tropical climatic countries can be run on free running or air conditioned. In countries with moderate climatic condition many houses are operated as a free running while low energy consuming means are used for thermal comfort, thus avoiding the need for air conditioning. When buildings are operated as free running, the operational energy becomes relatively lower and hence the contribution of embodied energy to the total energy consumed during the life span of the building becomes significant. Therefore, when new building systems are introduced, it is necessary to pay sufficient attention to the embodied energy as well.

This literature review can be broadly divided into two topics. One is the precast building system that has been considered in this study. The other one is the details pertaining to the embodied energy.

2.2. The Precast building system

Precast concrete or prefabricated concrete is a concept where major structural concrete components are standardized and produced in plants away from the construction site. (Brzev & Guevara-perez, 2002; Deb, 2012) Many countries use precast building systems, mainly to provide low-income housing for the urban communities. With the modern developments in environmental concerns, precast buildings offer attractive solutions for architects and engineers with construction speed, improved quality, cost efficiency and reduced weight in the structure. (Wijanto & Andriono, 2008) In precast buildings, material wastage is also less, compared to the in-situ cast concrete buildings. (Rushabh A. Shah &, 2013)

Mainly, four types of precast building systems are described in literature, depending on the load bearing structure. (Rushabh A. Shah &, 2013) They are,

- Large-panel systems
- Frame systems

- Slab-column systems with walls
- Mixed systems

Out of these four, large panel system is used in multi-storey buildings, which have large wall/floor concrete panels. (Deb, 2012) Frame systems consists of beam-column sub-assemblages. The connection details of these elements are very important. Slab-column system with shear walls, is a system where the shear walls sustain the lateral loads while the slab column structure mainly handling gravity loads. (Rushabh A. Shah &, 2013).

The precast building system considered in this study is a frame system, which to consist of precast column, beam and slabs. All these are prestressed and it creates more advantages over other systems.

2.2.1. Precast columns

The precast column used for the system consists of 150*150mm, 250*150mm or 350*350mm sections. 250mm*150mm section is used for the connection of beams. 350*350mm section is used at T junctions. The pre-stressing used will depend on the load and number of 5mm diameter, which can vary from 8-12. Figure 2-1 and Figure 2-2 shows several columns manufactured at the casting yard located at Ekala. (Fernando, 2016)

After casting, the columns are left for 1-3 days for curing, before the pre-stressing is released. Grade 40 concrete is used for pre-stressing while the strands are of 6mm in diameter. The structural capability of these columns has been assessed by Fernando, and has proven to be having sufficient strength characteristics up to 2 storied high buildings (Fernando, 2016)

Figure 2-1: 150×250mm column with the provision of two 40mm grout holes (left) and three 150×150mm columns with T25 anchor bar fixed (right)

Figure 2-2: 150×150mm columns- stacked at the yard with untrimmed prepressing strands

2.2.2. Precast beams

The precast beams will support the precast slab panels. The beams can have a depth of 250mm to 400mm depending on the span. The width is generally 150mm so that they can be easily placed on top of columns, to transfer the load. (Fernando, 2016) They are pre-stressed with 8 numbers of 5mm strands and grade of the concrete used is grade 40.

2.2.3. Precast slab panels

The precast panels can be cast with 65mm-85mm thickness. The number of 5mm pre-stressing strands vary from 11 to 20 depending on the span. Normally, for spans up to 4m, 65mm panels are used and for spans from 4m to 6m, 85mm panels are used, for residential buildings. However, panels can be cut at the construction site, to the required size using a hand grinder. The weight of a panel is about 620kg for 65mm panel and about 1200kg for 85mm panel. Therefore, lifting and handling of these panels require a crane or a boom truck. For the handling purposes, four steel hooks are provided on either side of each panel.

Figure 2-3: Pre-stressed strands of an 85mm thick slab panel (From casting yard at Ekala)

Figure 2-4: Concreting of slab panels with at the casting yard at Ekala (2015)

Figure 2-5: Lifting a panel using a crane at a construction site *(A photo from the construction of a new hospital building at Negambo Hospital-2015)*

Figure 2-6: The joint between two slab panels is interlocked with pieces of 10mm steel bars *(A photo from the construction of a new hospital building at Negambo Hospital-2015)*

After precast panels are laid, 50mm screed is provided on top of the panels. Normally the concrete grade is 40. The screed is reinforced with 6mm diameter mild steel at 200mm spacing or 6mm BRC net as shown in the Figure 2-7.

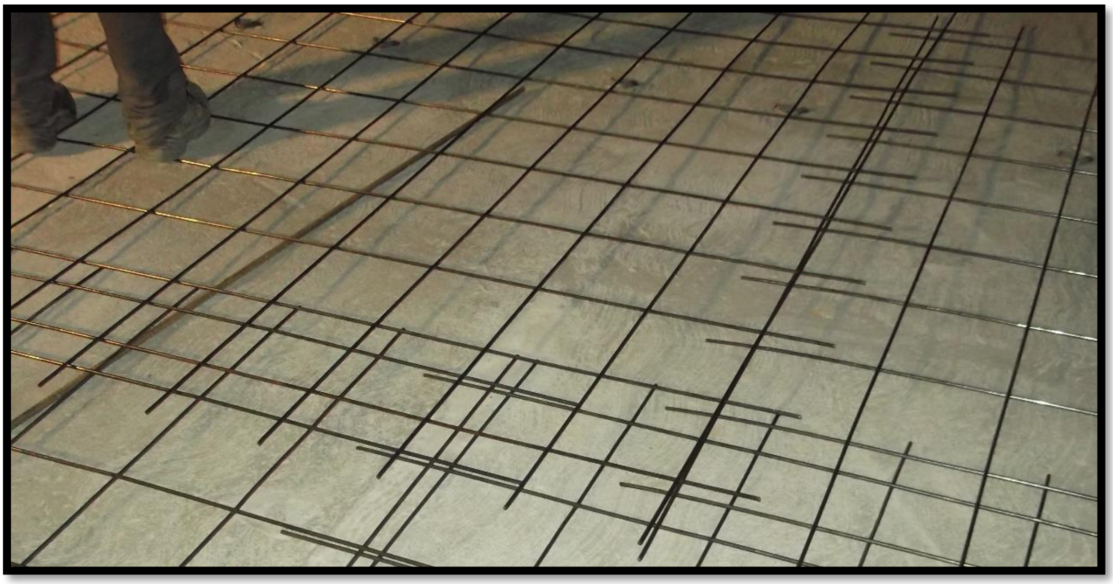

Figure 2-7: 6mm BRC mesh is used to reinforce the screed- before concreting (Fernando, 2016)

2.2.4. Junction Details

As far as precast concrete building systems are concerned, the structural continuity and connectivity is very important. Conventional in-situ cast concrete structures generally possess this property, since reinforcement bars will pass through each element with sufficient lap and anchorage. However, for precast building elements, this property can only be maintained if the joints are constructed properly.

To achieve the robust structure, 20mm or 25mm diameter reinforcement bars are embedded into 38mm diameter GI pipes, when GI pipes are cast within the beam and column as shown in the figure 8. Normal cement grout is sufficient for the bonding, since the embedment is about 500mm into the columns. A beam will rest on the column about 75-100mm to provide the space for the embedment (corbels). It makes it easy, for construction and the corbel aids to aid the shear transfer from the beam to the column.

Figure 2-8: A typical beam-column connection (Fernando,2016)

2.3. The precast panel system

Sandwich technology was considered as costly and advanced technology prior to 1960, and it was used completely for aerospace applications (Mugahed Amran, Abang Ali, Rashid, Hejazi, & Safiee, 2016). Later it was used to manufacture non-loadbearing cladding panels of buildings. Today, the application of precast concrete sandwich panels is considered as an accepted building system worldwide. These building systems has many advantages over conventional walling systems, such as speedy erection, high quality control, low maintenance cost and aesthetic appearance.

The precast panel system considered is based on foam concrete. This foam concrete has been obtained by mixing polystyrene beads to act as ultra-lightweight aggregate. The mixture is sandwiched with two 5mm thick cement fibre boards on either side, which helps to increase the flexural strength as well as final finish of the panels. Panels are manufactured to a size of 0.6m in width and 2.4m in height. The overall thickness could be 75 mm, 100 mm or 150 mm as shown in Figure 2-9. To maintain good connectivity between panels, tongue and groove arrangement has been used.

Figure 2-9: Foam concrete panels are manufactured in three thicknesses

2.3.1. The properties of EPS

Expanded polystyrene (EPS) is a low density, inert, hydrocarbon thermostatic (Ferrándiz-Mas, Bond, García-Alcocel, & Cheeseman, 2014). It is manufactured by adding a blowing or expanding agent to polystyrene, which is a vinyl polymer. It has variety of applications due to its ultra-light weight, exceptional thermal insulation and durability and extensively used as a packaging and thermal insulation material. However, the waste generated from EPS usage is problematic, since EPS is having an indefinite lifespan. Therefore, these wastes cannot be disposed with natural decaying. The need of reuse and recycling of these material is a globally accepted (Ferrándiz-Mas et al., 2014).

EPS has chemical resistant properties, when exposed to acids and alkalis (Ferrándiz-Mas & García-Alcocel, 2013). However, when it is exposed to concentrated acids, organic solvents and saturated aliphatic compounds EPS can dissolve easily (Ferrándiz-Mas et al., 2014). Complete combustion of EPS in an atmosphere with sufficient oxygen produces carbon dioxide (CO_2) and water. However, in an environment with limited oxygen supply, the combustion products are mainly carbon monoxide gas (CO) and carbon particles (C) (Ferrándiz-Mas et al., 2014). Thermal conductivity coefficient of expanded polystyrene is about 0.03 W/mK (Aciu, Manea, Molnar, & Jumate, 2015).

The biggest attraction of EPS is its light weight properties. 96-98% of the volume of EPS beads contains trapped air (Aciu et al., 2015). It results in the density of EPS is to be lower as 10-30 kg/m^3 (Xu, Jiang, Xu, & Li, 2012). Therefore, EPS can be a lightweight aggregate in foam concrete and mortar. However, the hydrophobic properties of EPS can create problems in these mixtures. In the EPS based concrete, the bond between the cement paste and light weight EPS beads is weak, since EPS does not absorb water in concrete fresh state. This could lead to segregation in the concrete. Researches have suggest that replacing some amount of cement with ultra-fine particles like fly ash or silica fume or using bonding additives like water-emulsified epoxies and aqueous dispersions of poly-vinyl propionate, can support to eliminate this problem (Babu & Babu, 2003).

Embodied energy of EPS is very high compared to the other materials. A study done in Spain has taken it as 105.5 MJ/kg (OECD/IEA, 2005) and another study done in Greece has taken it as 80.76 MJ/kg (Anastaselos, Giama, & Papadopoulos, 2009). An article published on Energy Plus International web site, Razvan Enescu has taken the embodied energy of EPS as 104.04 MJ/kg. (arch. Razvan Enescu, 2012) According to ICE database embodied energy value of EPS is 88.6 MJ/kg and it was selected for this study (Hammond & Jones, 2006).

The size of the EPS beads has a greater effect on the density and the strength properties of the light weight concrete mixture. Studies have shown that the smaller size beads leads to higher compressive strength in the concrete than larger ones (Fernando, 2016). Therefore, mechanically recycled should give lower compressive strength for the concrete mixture than the raw EPS. The reason is, the size of raw EPS beads is 1-3mm in diameter and the mechanically recycled EPS beads are about 3-5mm in diameter.

Figure 2-10: Expanded polystyrene beads

2.3.2. The mix used for foam concrete

The mix used to produce these panels are given in table 1. The main intention of preparing this mix has been reducing the weight of the manufactured panels while retaining sufficient strength for non-loadbearing applications. So, the normal density of the mix is in the range of 600-700kg/m^3. Also, 50% of the EPS used is from mechanical recycling of used polystyrene boards. The panel manufacturing facility is located in an area, where such waste polystyrene boards are abundant, mainly from the industrial zone nearby.

Table 2.1: Mix proportions used (*(Fernando, 2016)*

Material	**Content (kg/m³)**	**By Weight**
Cement	380	41.4%
Sand	136	14.8%
Water	282	30.7%
EPS	22	2.4%
Fly ash	98	10.7%

Even though the cement quantity of this mix is at a considerable level, compared to that, the sand use is notably low. Having low sand content is really beneficial in a country like Sri Lanka, in terms of financially as well as environmentally, because excessive river sand mining has resulted in many environmental problems near almost all rivers in the country. (Pereira & Ratnayake, 2013; Piyadasa, 2011) By using fly ash in the mix, further lowers the amount of cement usage. Also, there are several benefits associated with the strength characteristics of the product, as well as in sustainable aspect in the production work, by using fly ash in the mix. (Rofa & Supriya, 2015) Use of materials like fly ash reduces the embodied energy and embodied carbon of concrete mixes. (Kuruscu & Girgin, 2013)

The other important aspect of the mix is the use of EPS, with 50% of recycled content. Since EPS has a high embodied energy, replacing a part of it with recycled EPS will drastically reduce the embodied energy of the mix. The environmental harms which can caused by materials can be reduced by using recycled materials. (Petrov, 2011)

2.4. Life cycle energy of a building

Environmental degradation and global warming caused by greenhouse gases are two of the highly discussed topics in modern era. Buildings are largely responsible to this scenario due to the fact of over 40% of energy and material consumption globally. (Devi & Palaniappan, 2014) For the manufacturing of building materials, millions of tons of building materials are extracted each year through mining. Manufacturing and processing of these materials and products, transporting them and assembling in to buildings, all these require significant amount of energy. And material and energy consumption of a building does not stop there. Operation of a building- including heating/cooling, lighting and usage of different equipment in the building, regular maintenance, refurbishments and final demolition, all these activities consume millions of kilo watts of energy. With the increase of global population, these requirements could only be expected to grow in numbers. To fulfil this ever-increasing demand, power plants are producing more and more greenhouse gasses at their operation. Therefore, when a new building or a building system is introduced, it is highly beneficial to assess the environmental effect of it, throughout its life cycle.

Life cycle analysis is a globally accepted methodology to assess the environmental impact of a product through its life span-from cradle to grave. (Monteiro & Freire, 2012; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009) It can quantitatively evaluate the impact of a product based on different types of recognized impact categories. (Dong & Ng, 2015) When a building is considered as a product, LCA can be used to make important decisions, where environmental performance of the building can be improved. Most of the previous studies done in this sector have either focused on energy performance or the greenhouse gas emission of the considered dwelling.

Life cycle energy analysis (LCEA) can be easily conducted from LCA, following the guidelines given in ISO 14040. Mainly, life cycle energy of a building can be divided into two. Namely, embodied energy and the operational energy. LCEA can be used to quantitatively demonstrate the life cycle energy benefits of new system or a construction method. For example, the energy consumption of a house with new walling system.

2.5. Embodied energy analysis

Embodied energy of a product is usually divided into two; initial embodied energy and the recurrence embodied energy. But at certain occasions, embodied energy at the operation stage is also taken into account. (Manish K. Dixit, Culp, Lavy, & Fernandez-Solis, 2014) Initial embodied energy is the summation of energy to extract raw materials, process them, manufacture product components, transport them at different stages and assemble or install at a required location. Recurrence embodied energy includes the energy used at maintenance- repair-demolition and disposal of a product. Different definitions given to embodied energy are shown in Table 2.2.

Most of the studies done in embodied energy of buildings, have focused on the initial embodied energy of a product, due to uncertainty of the demolition and disposal stages.

Embodied energy analysis for a product is a complex and time-consuming process. The main reason for this is the two types of energy involved in a process; direct energy and indirect energy. (Roger Fay và Graham J.Treloar, 1998) When the energy consumed at each phase can be clearly definable and measurable, that energy can be considered as direct. For example, energy involved in transporting a product to a given location, can be easily calculated, if the fuel consumption of the vehicle is known. However, the energy involved in manufacturing of the product is not that easy to be measured. The reason is, it involves several upstream processes which support the manufacturing of the product. The energy involved in these processes is identified as indirect energy.

When buildings are concerned, embodied energy generally accounts for about 20%-40% of the total life cycle energy of the buildings. Total life cycle energy of a building is generally separately into operational energy and embodied energy. Operational energy is the energy used for heating, cooling, lighting and operating of appliances in maintaining the inside environment of a building. (Manish Kumar Dixit, Fernandez-

Solis, Lavy, & Culp, 2010) In extreme climate conditions operational energy can go up to 80%-90% of the total life cycle energy due to high amount of space heating and cooling demands. However, for countries like Sri Lanka, where most of the buildings are used as free running, the significance of operational energy reduces compared to embodied energy (Jayasinghe, 2011).

Table 2.2: Different definitions for Embodied Energy found in important literature

Author	Definition	Reference
Crowther	The total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings	(Manish Kumar Dixit et al., 2010)
Treloar et al.	Embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials).	(Manish Kumar Dixit et al., 2010)
Bousted and Hancock	"Embodied energy is defined as the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like. . ."	(Manish Kumar Dixit et al., 2010)
Baird	Embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building	(Manish Kumar Dixit et al., 2010)
Ding	Embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building.	(Cabeza et al., 2013)

2.5.1. Building materials and embodied energy

Embodied energy of building materials accounts the biggest contribution for the total embodied energy of a building. Generally, bricks, cement and steel are considered as the major contributors to the embodied energy. The reason is, they consume substantial amount of energy at extraction and their manufacturing process of those materials. Another factor is the high quantity used for the construction. Natural occurring materials like sand, aggregate has small amount of embodied energy. For those materials, the energy for extraction and processing are comparatively lower.

However, recycled materials have lower embodied energy than virgin materials in most of the cases. For example, virgin aluminium possesses an embodied energy close to 218MJ/kg but recycled aluminium has only about 29MJ/kg. Therefore, using recycled materials can significantly reduce the embodied energy of a building.

Substitution of materials for building products is another method of reducing the embodied energy from materials. A study done in Sri Lanka by Jayasinghe shows that the use of cement stabilized blocks and rammed earth as alternative walling materials for burnt clay brick wall and can significantly reduce total embodied energy (Jayasinghe, 2011). According to a similar study done by Reddy and Jagadish, some several alternative building materials for walls and roofs were highlighted. They had found that the soil cement blocks with 6% cement content will have 23.5% of embodied energy compared to burnt clay bricks. Similarly, hollow concrete block wall with 7% cement and steam cured blocks have 31.2% and 60.6% of energy content, with respect to burnt clay bricks (Venkatarama Reddy & Jagadish, 2003) . Bansel et al studied the effect of different building materials on the total embodied energy of buildings up to four stories and has found the hollow cement blocks gives the lowest value (Bansal, Singh, & Sawhney, 2014).

Several studies have highlighted that timber is the best alternative to reduce the embodied energy of buildings (Buchanan & Levine, 1999). Also, timber is considered as negative in carbon. The reason is they store carbon than emitted in their use. However, as a walling material, timber is not a common choice in Sri Lankan context.

2.5.2. Methods of embodied energy analysis

To calculate how much energy is required to produce building materials, several accepted methods are in use. Namely, process based analysis, input-output based analysis and hybrid analysis are three of the widely used methods. When detailed and comprehensive data is present for the particular industry, another method of analysis can be used, called statistical analysis. However, this method is not so popular due to lack of such data.

2.5.2.1. Process-based Analysis

Process-based analysis is one of the most widely used methods for the embodied energy analysis. This involves the systematic examination of the direct and indirect energy inputs to a process. Final production process of the building material is taken into account first, considering all possible direct energy inputs or sequestered energy of each contributing material. Then it works backwards as the energy of each contributing material or energy input needs to be ascertained. (Manish Kumar Dixit et al., 2010) It is similar to obtaining energy figures for each material.

Process based energy analysis has its own limitations because of the exclusion of many upstream processes as a result of truncation of system boundaries. The reason for this is the enormous efforts required to identify and quantify each small energy and product input of the complex upstream process. It is said that the magnitude of system incompleteness and error in process analysis is estimated to be as high as 50 percent and 10 percent respectively. (Manish Kumar Dixit et al., 2010)

2.5.2.2. Input-Output Analysis

Input/output-based analysis can be considered as relatively complete, since it can account for most direct and indirect energy inputs in the process of production of building materials. The economic data of money flow among various sectors of industry are used, in the form of input/output tables which are made available by the national government, thereby transcribing economic flows into energy flows by applying average energy tariffs. The Embodied Energy is calculated by multiplying the cost of the product by the energy intensity of that product expressed in MJ or GJ/$1000 and dividing it by $1000. (Manish Kumar Dixit et al., 2010)

It can capture that every dollar transaction, and hence every energy transaction, across the entire national economy. But the assumptions of homogeneity and proportionality across the economic sector, errors and uncertainty of economic data can make this analysis unreliable.

2.5.2.3. Hybrid Analysis

A hybrid analysis attempts to incorporate the most useful features of input-output analysis and process analysis by eliminating the fundamental errors. It starts with the readily available data for a process analysis. Sometimes it can go one stage more in the upstream where those energy data are usually the direct energy inputs of the final production stage and possibly the materials acquisition stages immediately upstream of that final stage. Then these values are substituted with the input-output method when it is difficult to achieve reliable and consistent information regarding complex upstream processes. (Manish Kumar Dixit et al., 2010)

Considering the availability of resources and availability of data in the Sri Lankan construction industry, process based embodied energy analysis is used in this research study.

2.6. Embodied carbon analysis

Similar to the embodied energy of a building, the typical embodied carbon is the amount of on dioxide equivalent (CO_2) or greenhouse gas (GHS) emissions associated with the non-operational phase of the building project which is cradle to gate. (Lockie & Berebecki, 2012; UK Green Building Council, 2015) However, carbon emissions occur in all different stages of a building's life cycle, which may be defined as (I) material extraction; (II) material processing and component fabrication; (III) construction and assembly; (IV) operation and service phase; and (V) end-of-life phase. (Akbarnezhad & Xiao, 2017) Also, considerable amount of CO_2 is emitted at the transportation activities between these phases. In European countries, buildings contribute to almost 50% of CO_2 emissions released to the atmosphere through the life cycle of the building (Li, Chen, Hui, Zhang, & Li, 2013) However, in India, construction industry contributes around 24% of CO_2 emissions of all the sectors. (Devi & Palaniappan, 2014) According to a report published by world bank in 2014, the carbon emission in Sri Lanka has been shown as 0.78 MT per person while the value in India is almost a double. (Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, 2014) However, to do a simple analysis on embodied carbon of building materials used, global values form published research work and databases have been used.

Embodied carbon is usually expressed in kilograms of CO_2 per kilogram of product or material. For example, the production of cement will directly contribute to the CO_2 emission which is around 0.73 kgCO_2/kg. (Hammond & Jones, 2006) However, the burnt clay bricks may have a low emission if part of the fuel for burning comes from bio-mass. For example, the ICE database gives a value of 2.43 kg CO_2/kg and a study done in India has given the value as 0.28 kg CO_2/kg. (Basu, Kumar Yadav, Kumar, & Bhushan, 2016) The ICE database value can be based on the burning of bricks using natural gas or similar non-renewable source and it can be the reason for this deficiency. Therefore, the value related to India has been used in this study, because the brick manufacturing in Sri Lanka is very close to the system used in India.

3. FIELD SURVEYS

3.1. General

The embodied energy involved in manufacturing can be obtained from literature and various other data bases. However, it is necessary to assure that such data is applicable to Sri Lanka. For this, embodied energy associated with manufacturing and transportation has been obtained using field surveys.

3.2. Precast pre-stressed beams and columns

Precast concrete beams and columns, both have similar manufacturing procedure. Generally, 6-8 beams or 10-12 columns are casted in one production line. Each consists of 8 prestressed strands and 6mm shear links are placed at 200mm interval. About 2-3 workers are involved in the whole manufacturing activities and the production is about 50-60 items per week, depending on the requirement.

Electrically operated machinery is used only for strand cutting. All other activities are done using human labour. One end of the strands is fixed and stressed from the other end following the normal stress procedure. However, unlike the common electrically operated hydraulic stressing machine, two manually operated hydraulic jacks are used to stress the strands. The elongation of the strands is measured and 2-3 strands are stressed together.

The casting bed is a levelled concrete floor. Form-oil is lightly applied on the bed, before fixing formwork. The formwork used at beams and columns are steel plates. The 6mm shear links at 200mm spacing is bound to the stressed strands. Plywood stopping boards are fixed at required locations to keep the size of beams/columns. Grade 40 concrete manufactured at Kandana, which is about 15km from the yard, is used for the concrete. 20mm porker vibrator is used for concrete compaction.

Stresses can be transferred to the concrete, once the strength of concrete is over 25N/mm^2. Usually after 1-3 days, strands are cut and elements are separated. For this work, they use electrical grinder which is about 2200W. The cutting operation usually takes a very small time. It was observed that within 30s of time 8-15 strands are cut.

After cutting the strands, beams/columns may have left at the yard for about 2 weeks for curing, which is usually done with water. With these collected information, the embodied energy calculation for beams and columns can be shown in Table 3.1 and Table 3.2.

3.2.1. Precast concrete slab panels

The manufacturing sequence of precast prestressed concrete slabs, studied under this research is similar to precast beams/columns discussed earlier. 65mm or 85mm thick slab panels are prestressed with 11 or 20 number of 5mm high tensile steel strands. The prestressing force is almost the same and the same method is used for stressing. The embodied energy calculation done for the manufactured slab panels are given in Table 3.3, with the details obtained from the field surveys.

Table 3.1: Manufacturing of pre-stressed beams (7 numbers of 350*150*4000mm)

Note: Transportation using trucks = *, ship = **, truck mixture= ***

Activity	**Quantity (kg)**	**Transport**			**Material**		**Construction**			**Total EE (MJ)**
		Distance (km)	**Waiting time (min)**	**EE of Transport (MJ)**	**EE per kg**	**EE of material (MJ)**	**Electricity (MJ)**	**Fuel usage (MJ)**	**EE at construction (MJ)**	
Apply foam oil	0.2	46*		0.0	40	8				8
Strand cutting	49	46* 8,000**		2 21	38	1,855	0.2		0.2	1,878
Installing T12 bars	49.4	46* 1,750**		2 5	20.1	993				998
Place shear links	25	46* 1,750**		1 2	20.1	496				499
Placing G40 concrete	3730	30***	60	2,375	1.13	4,215				6,590
Strand cutting							2		2	2
Total Embodied energy for beams										9,975

Table 3.2: Manufacturing of pre-stressed columns (7 numbers of 200*200*3000mm)

*Note: Transportation using trucks = *, ship = **, truck mixture= ****

Activity	**Quantity (kg)**	**Transport**			**Material**		**Construction**			**Total EE (MJ)**
		Distance (km)	**Waiting time (min)**	**EE of transport (MJ)**	**EE per kg**	**EE of material (MJ)**	**Electricity (MJ)**	**Fuel usage (MJ)**	**EE at construction (MJ)**	
Apply foam oil	0.2	46*		0.0	40	8				8
Strand cutting	49	46* 8,000**		2 21	38	1,855	0.2		0.2	1,878
Place shear links	23.8	46* 1,750**		1 2	20.1	478				481
Placing G40 concrete	3,629	30***	60	2,375	1.13	4,101				6,476
Strand cutting							2.3		2	2
Total Embodied energy for pre-stressed columns										8,845

Table 3.3: Manufacturing of pre-stressed slab panels (60*1000*4000mm)

*Note: Transportation using trucks = *, ship = **, truck mixture= ****

Activity	**Quantity (kg)**	**Transport**			**Material**		**Construction**			**Total EE (MJ)**
		Distance (km)	**Waiting time**	**EE of Transport (MJ)**	**EE per kg (MJ/kg)**	**EE of material (MJ)**	**Electricity (MJ)**	**Fuel usage (MJ)**	**EE at construction (MJ)**	
Apply foam oil	1.6	46*		0.0	40	64			0	64
Strand cutting	122	46* 8,000**		4 53	38	4,636	0.9		1	4,637
Placing G40 concrete	11,431	30***	180	3,135	1.13	12,917			0	15,452
Strand cutting							8.5		9	9
Total Embodied energy for pre-stressed slabs										20,162

3.2.2. Foam concrete panels

Unlike other precast elements in this precast system, the foam concrete sandwich panels are not prestressed. Instead the two cement fibre sheets at either sides of the panel increases the rigidity and flexural strength of the panel. Although panels are manufactured in 3 thickness variations, 100mm and 150mm panels were given priority in data collection, since they are more suitable thickness sizes for residential buildings. 75mm panel is better suited for partitioning of spaces.

In manufacturing of these panels, special formwork has to be used. The formwork is made out of lightweight aluminium at this instance. Equal tongue and groove arrangement of the panels are maintained by this formwork. Individual formworks are vertically stacked in a steel frame, separated by cement fibre sheets on either side. One steel frame can hold up to 18 number of 100mm panels or 12 number of 150mm panels.

Polystyrene beads as a virgin material, are imported from china. Usually, they are less than 1mm in diameter and requires expansion before using in the mix. For this purpose, a boiler is used to produce steam, which is used to expand the polystyrene beads in a separate machine. The boiler uses fuel oil l and expansion machine uses some amount of electricity at its operation. Since 50% recycled EPS is also in use, those boards brought as waste material from nearby factories has to be crushed. A small machine is used to crush these boards which uses about 1kWh per 10kg of EPS crushed. However, no expansion is required for these beads, since they are already expanded.

A special mixture is used to mix, cement-sand-fly ash- EPS together. The mixture used at Ekala factory has a separate mechanism for loading of material. Therefore, it has several motors with different capacities and functions. Quantifying the power consumed at each small operation is not practical. The only other method to calculate the power consumed at manufacturing stage of the panels is by recording the electrical utility meter at the time of machine operation. This enables quantifying the electricity consumption of all the activities happening at the factory, at the time interval of the record. It was made sure that no other major activity uses electricity at the time of manufacturing these panels. Therefore, the meter readings can be use directly related to electricity consumption of the concrete mixture.

Compaction work is done by hand and no machinery involves at manufacturing of foam concrete panels, other than mentioned above. So, using these data, the embodied energy can be calculated in the following manner.

Table 3.4: EE of transportation of materials to the factory

Material	Quantity (kg)	Transport Distance (km)	Vehicle Used	Embodied Energy (MJ)
Cement	750	115	25T Truck	115
Fly ash	220	126	25T Truck	37
Sand	304	25	25T Truck	10
EPS (virgin)	25	26	7T Truck	17
		8,000	Container ship	11
EPS (recycled)	25	10	25T Truck	8
Cement Fibre Sheet	348	26	25T Truck	12
		1,750	Container ship	33
Total EE at transportation of materials				243

Table 3.5: EE of materials for producing 18 number of 100mm thick EPS panels

Material	Quantity (kg)	Energy Intensity (MJ/kg)	Embodied Energy (MJ)
Cement	750	4.9	3,675
Fly ash	220	0.1	22
Sand	304	0.08	24
EPS (virgin)	25	88.6	2,215
Cement Fibre Sheet	348	10.4	3,619
Total EE of materials used			9,555

Average electricity usage for one batch of EPS panels = 5kWh

Therefore, the total electrical energy usage at manufacturing stage = 5×3.6 = 18MJ

Here 1 kWh is taken as 3.6MJ.

The total embodied energy of manufacturing 18 number of 100mm foam concrete panels =243+9,555+18 = 9,816 MJ

3.2.3. Plywood manufactured at Gintota

There are several plywood manufacturers in Sri Lanka and Gintota plywood is one of the oldest and most popular brands in Sri Lanka. Their factory located at Gintota was considered for quantify the embodied energy of plywood manufactured in Sri Lanka.

Most of the machineries in this factory are operated from the steam power, which are produced by massive two boilers fuelled by debris of the plywood production. The timber logs, which are used to manufacture plywood are brought from various parts of the country using trucks as the mode of transport. At the factory, the logs are sorted and cut into required sizes which are then called as “block”. These blocks are peeled using sharp blades to produce one sheet of veneer. These are dried in steam ovens. At the next stage, dried veneers are glued and stacked one another at in to the required thickness and apply pressure in heated conditions. After cutting these sheets, final plywood production process completes.

This factory daily processes about $50m^3$ of timber daily to produce roughly 400-500 plywood sheets per day. Very few machineries are operated using electricity. Fork lifts, loader and peelers are powered by diesel.

However, the embodied energy of timber is a small quantity. Therefore, the contribution for the total embodied energy of plywood is only 9%. A whopping 70% is represented by the chemicals used at the production process. The glue, which consist of urea formaldehyde, wheat powder and ammonia is largely responsible for this high embodied energy. One plywood consists of nearly 4kg of glue.

The embodied energy of plywood production is given below.

I. Electricity Usage

Table 3.6: Monthly Electricity usage of the factory

Month	Units (kWh)	EE (MJ)
Mar-15	289	1,040.4
Apr-15	288	1,036.8
May-15	224	806.4
Jun-15	307	1,105.2
Jul-15	282	1,015.2
Aug-15	266	957.6
Sep-15	270	972.0
Oct-15	238	856.8
Nov-15	242	871.2
Dec-15	292	1,051.2
Jan-16	276	993.6
Feb-16	263	946.8
Mar-16	278	1,000.8

Therefore, average monthly electricity energy consumption of the factory = 973MJ

II. Diesel usage

Operations inside the factory

For loader and poke lift = 60 liters/day

For 6 peelers = 240 liters/day

Therefore, total energy consumption in terms of diesel fuel for factory operations

= 300×.832×45.71×25 (density of diesel is taken as 832 kg/m^3 and energy is 45.71 MJ/kg. (OECD/IEA, 2005) 25 working days for a month is considered here)

= 285,230 MJ/month

Transportation of logs

Table 3.7: Monthly diesel consumption for the lorries which transport logs

Month	**Distance**		**Total Diesel (l)**
	Lorry with 3.5km/l consumption	**Lorry with 5km/l consumption**	
Jan-16	22,522	4,326	7,300
Feb-16	15,364	3,425	5,075
Mar-16	19,406	6,114	6,767

Average diesel consumption for transportation of logs per month = 6,381 liters/month

Therefore, total energy consumption in terms of diesel fuel for factory operations

= 6,381×.832×45.71 (density of diesel is taken as 832 kg/m^3 and energy is 45.71 MJ/kg)

= 242,674 MJ/month

Therefore, total energy usage in terms of diesel per month = 285,230+ 242,674

= 527,904 MJ/month

III. Timber

Average processed timber quantity =51 m^3/day

Embodied energy of timber = 0.3 MJ/kg

Total EE of processed timber =51×0.3×640×25 (density of timber is taken as 640 kg/m^3 and factory operates 25 working days per month)

=244,800 MJ/month

V. Other materials used

- *Oil (D40)* = 50 liters/month

  = 50×38.7 MJ/month (EE of D40 is taken as 38.7 MJ/kg from ICE database)

  = 1,935 MJ/month

- *Glue*

Table 3.8: Embodied energy of Glue

Material	Daily Consumption (kg)	EE coefficient (MJ/kg)	EE per month - 25 working days (MJ/month)
Urea formaldehyde	750	70	1,312,500
Wheat Powder	130	15	48,750
Ammonia	700	23.8	416,500

Total embodied energy of other materials used

=1935+1,312,500+48,750+416,500

= 1,779,685 MJ/month

Therefore, total embodied energy to produce plywood = {Electricity +Diesel +Timber + Other materials} = 2,553,363 MJ/month

= 102,134 MJ/day

Average daily production of plywood = 400 number of 12mm plywood boards

Therefore, EE of plywood $= \frac{102,134}{400 \times .012 \times 1.22 \times 2.44 \times 700}$

= <u>10.2 MJ/kg</u>

3.2.4. Quantify the energy used at transportation

Transportation is an essential component to complete any activity. Especially in the construction industry, nothing is possible without proper transportation of people, materials and finished products. In fact, transportation is so important, that more than 90% of the embodied energy of some products consists of transportation energy (eg. Sand). From extraction of raw materials to installation of finished products in a house, numerous transportation activities are done. Therefore, quantification of all these activities are not practical. However, it is very important to identify and consider the major transportation activities while calculating the embodied energy.

Embodied energy at transportation mainly comes from burning the fuel in a vehicle. For the same vehicle, the fuel consumption for transporting a fixed load (say 1 metric ton) for a given distance (say 1 km) depends on various other parameters. The speed of vehicle, road condition, driving nature of the driver, road traffic, tire pressure is some of them. However, many of these can't be predicted with sufficient confidence without large data set. In a small country like Sri Lanka, it is very difficult to collect such a large amount of data, for similar type of vehicles, with the high diversity of vehicles and operation conditions.

Therefore, data collection was recorded for vehicle type, engine capacity, maximum carrying capacity and fuel consumption. Most of these data were collected from the interviews with relevant drivers and operators. Average fuel consumption data for the vehicles considered are listed below in Table 3.9. Using the values in the Table 3.10, the calculations for transportation energy has been simplified.

Table 3.9: Average operation efficiencies of commonly used vehicles at construction activities

Vehicle	Load capacity	Type of fuel used	Fuel consumption	
			Idle running	Operating at full capacity
Truck	7 ton	Diesel	-	2.5 km/litre
Truck	25 ton	Diesel	-	2 km/litre
Lorry	750 kg	Diesel	-	16 km/litre
Backhoe Loader (JCB)	0.5 m^3 bucket	Diesel	-	4 litre/h
Fork Lift	3.5 ton	Diesel	-	2.4 litre/h
Truck Mixture	7 m^3	Diesel	0.17 litre/min	2 litre/km

Table 3.10: Average energy consumption of the considered vehicles in the study

Vehicle	Energy Consumption	Unit
25 Ton truck	0.76	MJ/(t*km)
7 Ton truck	2.17	MJ/(t*km)
750kg mini truck	3.20	MJ/(t*km)
Backhoe loader	114.00	MJ/h
Fork lift	90.40	MJ/h
Truck Mixture	66.50	MJ/km
Container ship	0.054	MJ/(t*km)

For ships, the fuel consumption data varies with different parameters like the speed, weather condition, size of the ship and many other. Literature was used to obtain a general energy consumption value for transportation of 1 ton of load using a ship. (MacKay, 2009)

3.3. Summary

Field surveys were meant to collect data from the real-world activities, so that the research work is more related to the Sri Lankan conditions. Various field visits helped to collect data to quantify the embodied energy of precast building elements as well as plywood. To quantify the embodied energy of transportation activities, vehicle fuel consumption data was also collected. These data are used to calculate the embodied energy of buildings which are discussed in the next chapters.

4. EMBODIED ENERGY OF A SINGLE STOREY HOUSE: CASE STUDY 1

4.1. General

Single storied houses are the dominant type of residential buildings in Sri Lanka. According to the Department of Census and Statistics, about 85.7% of the total housing in the country are single storied housing units. (*Census of Population and Housing 2012*, 2012) Also, it shows that about 53.2% of the housing units are constructed out of brick and 33.8% are constructed with cement blocks. So, it is beneficial to compare the embodied energy of these conventional housing systems with new foam concrete panelled system, which can shed light on the effect of using each type of building material.

Therefore, embodied energy analysis of a single storey house which is about 70 m^2 of floor area was conducted based on the process analysis method. It is a two bedroomed house with a single bathroom and a pantry as shown in the Figure 4.1 & Figure 4.2. This type of small houses are usually built for the low income families or as post-disaster housing usually funded by the government or various non-government organizations (Jagoda, n.d.). Standardization, low cost and fast construction are common requirements for such houses. This situation is ideal for precast EPS foam concrete panel houses to be used as walling material of these houses. The foundation material of the house is rubble masonry. Ground floor of the house is made of concrete and on top of that ceramic floor tiles laid as the finishing material. Windows, doors, and the roof frame is made out of timber, while Zinc/alum sheets are used as the roofing material. Roof insulation is provided by an 8mm thick expanded polyethylene layer I n between the roof and the ceiling. Ceiling is out of plywood boards. Being a small house, the ceiling is to be constructed with the roof to improve the interior space. Roof angle is 14 degrees. Eave height was taken as 8 feet or 2400mm.

Both 100mm and 150mm thick EPS foam concrete sandwiched wall panels were considered for two houses constructed according to the plan given in Figure 4.1. For the comparison, same house plan is used to calculate embodied energy of a hand moulded burnt clay brick house and a cement sand hollow block house. Wall thickness of the burnt clay brick house is taken as 225mm while the cement sand block wall has a thickness of 150mm.

For the comparative study, the different materials quantities under each house have been determined. Then, it was further divided into constituent materials. For example, the embodied energy of brickwork has been determined separately for bricks and mortar, further divided into cement and sand. The reason for this approach is to take into account the transportation energy requirement accurately since the distance transported would be different for individual materials. For example, it is 145km for cement and 65km for bricks. However, there are certain materials which the quantities are the same for all three housing systems. For example, the roof is constructed with timber structure, thatched with zinc-alum sheets for all the houses considered. Which inevitably gives the same embodied energy value for the zinc-alum sheets for all the houses considered.

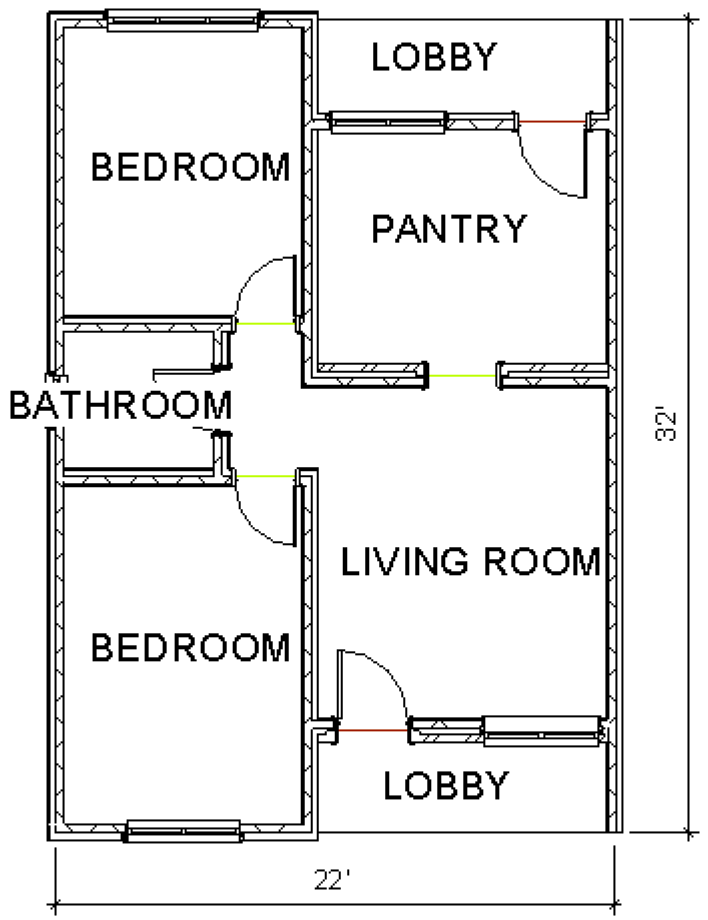

Figure 4-1: Plan view of the single storey house

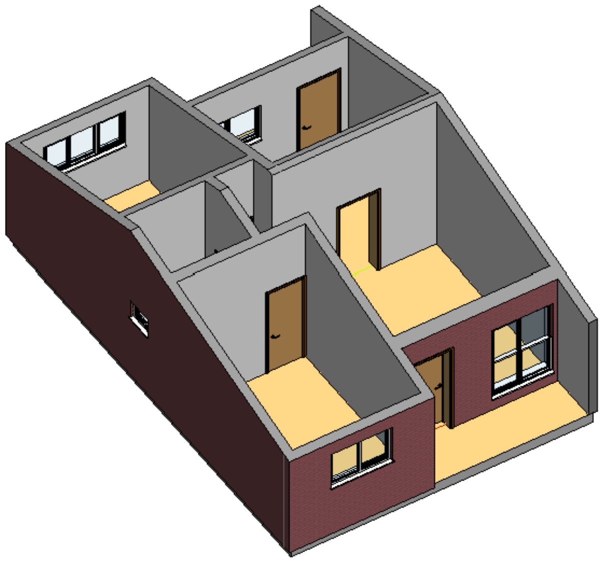

Figure 4-2: 3D model of the single storey house

4.2. Embodied energy of materials and elements

Building materials accounts for the largest share of embodied energy of a building. For the comparative study, the material quantities under each item has to be determined. When a building is considered as a product, from the start of the construction work with site clearing, different materials are involved at different activities until all finishing the work is completed. In quantifying these materials, the following approach was used for each element.

4.2.1. Mortar

For foundation work, masonry walls and plastering work, 1:5 cement sand mortar was used. As mentioned above, transportation of sand is from Manampitiya and cement is from Holcim cement factory located at Puttalam. For 1m^3 of mortar, 300kg of cement and 1500kg of sand is in used. The embodied energy of mortar for one cubic meter was calculated as following.

EE of cement	= 300×4.9	=1470MJ
EE of sand	=1500×.08	=120MJ
EE of transport	=300×0.19+1500×.31	=522MJ

EE for mortar	=1470+120+522	=2112MJ/m^3
EE of mortar with 5% wastage= 2112*1.05		=2218MJ/m^3

4.2.2. Concrete

The usage of concrete in these single storey houses is in limited quantity. However, when there is, Grade 30 concrete is used for all the applications. The composition of the mix was. 380kg of cement, 711kg of sand, 1283kg of coarse aggregate and 160kg of water. Transport energy for 1kg of cement is 0.19MJ/kg. For coarse aggregates, it is 0.32MJ/kg and for sand it is 0.45MJ/kg. Therefore, the embodied energy of Grade 30 concrete was calculated as,

EE of 380kg of cement	= 380× (4.9+0.19)	= 1933MJ
EE of coarse aggregate	=1283× (0.11+0.32)	= 552MJ
EE of sand	=771× (0.08+0.45)	= 377MJ
Total EE of concrete	=1933+552+377	= 2862MJ

4.2.3. Rubble foundation

The foundation of the house is constructed with random rubble masonry with 1:5 cement sand mortar. For 1m^3 of rubble masonry, 1.35m^3 of rubble and 0.3-0.4 m^3 of mortar is required. 1m^3 of cement sand mortar consists of about 300kg of cement and 1500kg of sand. This gives us a value of 2554MJ/m^3 of embodied energy for mortar with 5% wastage is considered. Considering the embodied energy co-efficient of rubble is 0.1MJ/kg and bulk density is 1860kg/m^3,

EE of 1.35m^3 of rubble	= 1.35×1860×0.1	= 142MJ
EE of transportation of rubble	=1.35×1860×0.24	= 602MJ
EE of 0.47m^3 of mortar	= 0.35×2218	= 776MJ
Total EE of 1m^3 of rubble work	= 142+602+776	= 1520MJ

4.2.4. Brick Masonry

For the house constructed with 225mm brick masonry, the embodied energy calculation was done as following. The size of the brick is 220mm×105mm×65mm which is the standard brick size in Sri Lanka. Hand moulded burnt clay bricks are manufactured in Dankotuwa area and transported via 25 Ton truck to the site. So the transportation energy was 0.09MJ/kg. The embodied energy of a brick is taken as 1.2 MJ/kg, based on literature as, mentioned before. And about 0.045m^3 of mortar is required for 1m^2 of brickwork.

No of blocks per 1m^2 of brickwork = 125Nos

Weight of a brick = 3kg

EE of bricks per 1m^2 of brickwork = (125×3) × (1.2+0.09) = 484 MJ/m^2

EE of Mortar per 1m^2 of brickwork = 0.045×2218 = 100MJ/m^2

EE of 1m^2 of brickwork = 584MJ/m^2

4.2.5. Block Masonry

For the construction of walls out of block masonry, 390mm×190mm×150mm cement sand blocks are used with 10mm mortar joints. 1:5 cement sand mortar is used for the joints and about 0.02m^3 of mortar is required for 1m^2. Since the blocks are considered to be manufactured in Pita Kotte area, a transport distance of 15km was assumed from the factory to the construction site. It costs 0.06 MJ/kg of transport energy for blocks. Manufacturing energy per block was calculated based on details of a block making machine with a maximum production capacity of 800 block per 8 hour shift. It has two motors with 3hp. So the production energy can be calculated per single block based on these data. (1hp = 0.746kW and 1kWh = 3.6MJ) Therefore, the embodied energy for 1m^2 of block work was calculated as following.

Calculation of the embodied energy of one 390mm×190mm×150mm hollow block can be given as following.

Table 4.1: Embodied energy of a cement- sand block

Material	Weight (kg)	EE of material (MJ/kg)	EE at transportation (MJ/kg)	EE per block (MJ)
Cement	0.944	4.9	0.19	4.8
Sand	11.55	0.08	0.08	4.3
Manufacturing energy per block				0.08
Total embodied energy of a block				9.18

No of blocks per 1m^2 of blockwork = 12.5Nos

Weight of a block = 13kg

EE of blocks = (12.5×9.18+12.5×13×0.06) = 124 MJ/m^2

EE of Mortar = 0.02×2218 = 44MJ/m^2

EE of 1m^2 of blockwork = 168MJ/m^2

4.2.6. Septic Tank and soakage pit

The septic tank and soakage pit is constructed with burnt clay bricks for all three houses. The size considered was 3m×2m×1.5m. Therefore, the area of brickwork is 22.24m^2. 50mm concrete cover requires 0.22m^3 of grade 30 concrete and 36kg of steel for the reinforcement of T10 bars at 200mm spacing. Grade 15 concrete is used in the bottom, which requires 0.17m^3 of concrete. So, the embodied energy calculation is as following.

EE for brickwork = 22.2×584 = 12,965 MJ

EE of grade 30 concrete = 0.22×2,862 = 629 MJ

EE of grade 15 concrete = 0.17×2,165 = 368 MJ

EE of steel =36×42.4 = 1,526 MJ

Total EE of septic tank and soakage pit = 15,488MJ

4.2.7. Roof

The roofs of the houses are constructed in similar manner, with timber frame and zinc-alum sheets for the covering. 12mm plywood is used for the ceiling while the roof insulation is provided by an 8mm thick expanded polyethylene layer in between the roof and the ceiling. To calculate the embodied energy of the roof, material usage was quantified for the whole roof structure. Different embodied energy figures were allocated for hard wood and soft wood, as given in ICE database. The embodied energy for zinc-alum sheets were not available in literature and had to calculate based on the material quantity used.

0.46mm zinc-alum sheet considered in this analysis consists of a 0.42mm thick steel sheet coated by a mixture of aluminium, zinc and silicon (Diamond, 2004). The composition of the coating is 55% aluminium, 43.5% zinc and 1.5% silicon by weight. The weight of the coating for square meter is 0.2kg while the whole sheet weighs 5.78kg/m^2 (Diamond, 2004). Therefore, the embodied energy was calculated as following.

Table 4.2: Embodied energy calculation for 1m^2 of zinc-alum sheet

Material	Quantity (kg)	EE coefficient (MJ/kg)	EE per 1m^2 of sheet (MJ)
Steel	5.58	42	234.4
Aluminium	0.11	236.8	26.0
Zinc	0.087	53.1	4.62
Silicon	0.003	2,358	7.07
Total EE for 1m^2 of a zinc-alum sheet			272

Per 1kg of sheet embodied energy can be taken as 272 / 5.78= 47MJ/kg. However, by assuming 10% of increase of energy due to transportation and 7% increase due to production process, the total embodied energy for 1kg of zinc-alum sheet was taken as 55MJ/kg.

Embodied energy of roof was calculated as shown in the Table 4.3.

Table 4.3: Embodied energy of roof the single storey house

Material	Quantity (kg)	Wastage (%)	EE coefficient (MJ/kg)	EE at transportation (MJ/kg)	Total EE (MJ)
Zinc-alum sheets	628	5	55	0.47	38,076
Plywood (12mm)	856	5	12.5	0.17	11,382
2*2 wood	308	5	3.54	0.13	1,187
2*4 rafters	1,223	5	4.23	0.13	5,599
1*9 valance board	279	5	4.23	0.13	1,278
4*6 beams	480	5	4.23	0.13	2,197
Insulation	49.3	0	126.4	0.47	6,254
Total embodied energy					65,973

4.3. Embodied energy of transportation activities

Transportation activities are very important in quantifying the embodied energy of building construction. As shown in Chapter 3, energy consumptions of transport activities of several commonly used vehicles were calculated, based on the data collected from field surveys.

For each activity at the construction stage of the house, the nature of the transportation involved was considered. For example, for the block walled house, blocks are bought from a manufacturer from nearby area. (The factory located within 15km as shown in 4.2.5) For that the vehicles used was the 7 Ton truck. Cement and Sand required for the manufacturing of blocks are transported from Puttalam and Manampitiya respectively. The preferred vehicle class is 25Ton truck considering the transportation distance and mass production requirement of blocks. The transportation requirement for labour is not considered in this analysis.

4.4. Results of the analysis

The embodied energy analysis done for the building system is presented in this section under two main topics. The total embodied energy analysis for the aforementioned house with three types of building systems and an individual material usage analysis for the same building. The later was used to estimate the embodied carbon of the three types of buildings. Though the 100mm thick eps foam concrete panels are much suitable for the single storey house construction like this, the 150mm panel also included to check the effect of the increased panel size on embodied energy.

4.4.1. Total embodied energy

The total embodied energy for each item has been calculated for the house under consideration. This is presented in Table 4.4. For example, the extraction and backfill involves the operation of a backhoe loader for 8 hours and also the transportation of soil for back filling. It is considered that this is common in the all three houses irrespective of the walling materials.

The foundation of all three houses are constructed with random rubble masonry work. It was found that the random rubble masonry can contain about 1520MJ of embodied energy per cubic meter. Cement sand mortar of 1: 5 mix proportion used in foundation work. Hence, transportation of materials is largely responsible for the high embodied energy of random rubble masonry. Similarly, many other items could be common. The difference comes with the walling material and the plaster. However, Table 6 shows the impact of such a change on the overall embodied energy of a house. When converted to per square meter values, the cement sand block house gives an embodied energy value of 3.02 GJ/m2. As far as the embodied energy is concerned, the cement sand block house appears the most attractive. The foam concrete panel house with 100mm thick panels also could come closer with 3.46 GJ/m2. The 150mm thick wall panel house would have a higher embodied energy and it is 3.68 GJ/m2. However, the burnt clay brick house has the highest amount of embodied energy per square meter, with 4.03 GJ/m2.

Table 4.4: Total embodied energy of single storey houses

		Embodied Energy (MJ)			
		Brick Masonry	Block Masonry	Foam Concrete Panel	
				100mm	150mm
Excavation	Excavation and back-filling	6,931	6,931	6,931	6,931
Foundation	Rubble Work	15,486	15,486	15,486	15,486
	Plinth Plaster	714	714	714	714
Superstructure	Ground floor concrete	9,036	9,036	9,036	9,036
	Walls	92,316	26,688	64,646	78,913
	Lintel	2198	2198	0	0
Roof	Roof with ceiling	65,973	65,973	65,973	65,973
Finishing	Doors & windows	5,760	5,760	5,760	5,760
	Plastering	6842	6842	0	0
	Tiling	14,981	14,981	14,981	14,981
	Painting	16,355	16,355	16,355	16,355
MEP work	Electrical Work	4,045	4,045	4045	4,045
	Plumbing & sanitary	5,908	5,908	5908	5,908
	Septic tank and soakage pit	15,469	15,469	15469	15,469
Total Embodied Energy		264,554	188,097	217,833	232,366
Embodied energy per square meter (GJ/m2)		4.03	3.02	3.46	3.68

4.4.2. Contribution of individual materials

The embodied energy analysis done for individual materials used for the three building systems yielded the results given in Table 4.5. The calculation was done for the major contributing materials without the transportation energy and installation energy at the site as mentioned in the previous chapter.

The largest contributor to the embodied energy of the brick walled house is burnt clay bricks, which is about 30% of the total embodied energy. Cement contributes about 12% and zinc/ alum sheets contribute close to 14% to the total EE. Plywood, timber, paints, and ceramic tiles, all contribute approximately similar amount, which is about 4-5%. Apart from these materials, there is no significant contribution from other materials.

When it comes to cement sand block house, the contribution from cement and zinc/ alum sheets have gone up to 18% of the total EE. Plywood, timber, paints, and ceramic tiles are about 6%-8% of total energy, mainly because the total embodied energy of the block walled house is less than of the brick house.

When it comes to the cement quantity used, the eps wall panelled house is prominent compared to the other two types. It is about 17% of the total EE. Paints and cement fibre sheets (used in the sandwiched wall panels) contribute about 7%, while EPS, timber, plywood and ceramic tile, all contribute close to 6%.

Table 4.5: Contribution of individual materials to the embodied energy

Building Materials		Burnt Clay Brick House		Cement-Sand Block House		100mm Foam Concrete Wall House		150mm Foam Concrete Wall House	
		Weight (Kg)	EE (MJ)	Weight (Kg)	EE (MJ)	Weight (Kg)	EE (MJ)	Weight (Kg)	EE (MJ)
1	Cement	6,729	32,971	7,385	36,186	7,942	38,914	10,160	38,914
2	Sand	26,458	2,117	43,946	3,516	11,966	957	12,708	1,016
3	Coarse Aggregate	6,094	670	6,094	670	5,073	558	5,073	558
4	Bricks	67,842	81,403	8,348	10,017	8,348	10,017	8,348	10,017
5	EPS (Virgin)	0	0	0	0	148	13,080	221	19,531
6	Steel	121	5,099	121	5,099	84	3,515	84	3,515
7	Ceramic Tiles	1,248	11,235	1,248	11,235	1,248	11,235	1,248	11,235
8	Paints	111	16,032	111	16,032	113	16,276	113	16,276
9	Putty	58	306	58	306	58	306	58	306
10	PVC	61	6,448	61	6,448	61	6,448	61	6,448
11	Zinc/Alum Sheets	628	36,280	628	36,280	628	36,280	628	36,280
12	Timber	3,025	12,594	3,025	12,594	3,025	12,594	3,025	12,594
13	Plywood	899	11,232	899	11,232	899	11,232	899	11,232
14	Cement Fibre Sheets	0	0	0	0	2,060	15,998	2,060	15,998

4.4.3. Embodied carbon analysis of the building materials used

The material quantification of the previous analysis was used to estimate the embodied carbon for the three building systems and the results are given in the Table 4.6. From the carbon emission point of view also, the cement sand block house has performed as the best. The foam concrete precast panel house of 100 mm or 150 mm comes closer.

Even with a much favourable carbon emission value of bricks, the house that uses the brickwork has got the highest emission.

Table 4.6: Carbon emission from building materials used in the case study (Carbon Coefficients based on ICE database)

		Carbon Coefficients ($KgCO_2/Kg$)	Carbon Emission ($KgCO_2$)			
			Burnt Clay Brick House	Cement Sand House	100mm Foam Concrete House	150mm Foam Concrete House
1	Cement	0.73	4,912	5,391	5,797	7,417
2	Sand	0.0048	127	211	57	61
3	Coarse Aggregate	0.0048	29	29	24	24
4	Bricks	0.28	18,996	2,338	2,338	2,338
5	EPS (Virgin)	2.55	0	0	376	565
6	Steel	1.37	166	166	115	115
7	Ceramic Tiles	0.74	924	924	924	924
8	Paints	2.42	269	269	274	274
9	Glass	0.86	34	34	34	34
10	PVC	2.56	156	156	156	156
11	Zinc/Alum Sheets	1.522	956	956	956	956
12	Timber	0.46	1,392	1,392	1,392	1,392
13	Plywood	0.81	728	728	728	728
14	Cement Fibre Sheets	1.09	0	0	2,246	2,246
Total			28,689	12,593	15,411	17,228

4.5. Discussion

When compared with cement sand blocks and brickwork, it can be stated that the form concrete precast panel house can perform reasonably well. Hence, it can be promoted as a mainstream building material considering its advantages like saving the construction time and the need for less labour for construction. The availability of the panels in different thicknesses will allow the use of it in single storey houses relatively easy while meeting various requirements that may occur due to aesthetics, slenderness effects, sound insulation needed, etc.

5. EMBODIED ENERGY OF A TWO-STOREY HOUSE: CASE STUDY 2

5.1. General

Precast building constructions are not uncommon in Sri Lanka. 1st application of precast concrete in Sri Lanka, has been recorded in 1949 in Colombo port. In mid-1950's, the technology was introduced for the building construction in Sri Lanka under the influence under Dr. A.N.S. Kulasinghe (Weerasri, 2007). Today, with the involvement of private sector, new precast systems and technologies are being used for building construction. Faster construction and good quality control are two of the main advantages of precast buildings. It is a good solution for the limited space available at the construction site as well, where it is difficult to store materials in the site. In this context, residential buildings out of precast concrete elements is becoming increasingly popular in urban areas of Sri Lanka. In this study, one of such precast concrete system is studied to quantify the embodied energy (EE) of a two-storey house constructed using the system.

The precast building system studied consists of a precast pre-stressed beam-column-slab system with EPS foam concrete wall panels. For constructing the house shown in Figure 5.1 and Figure 5.2, in Pita Kotte Area, all the precast concrete items had been produced in Ekala. The study done for the structural performance of these foam concrete panels had shown that these panels have more than enough flexural strength and compressive strength to withstand the loading of a two-storied structure. Therefore, 150mm thick foam concrete panels are also considered in this study to be used as a comparative alternative house construction method with load bearing walls. The two-storied house consists of 191 m^2 of floor area with a space for a single car and a roof terrace. Individual pad footings for the columns has been used as the foundation and along walls rubble foundations have been used with plinth beams. For the load bearing structure, random rubble masonry foundation with plinth beams were used, since the soil condition of the area is hard laterite. As described in Chapter 2, the slab has been constructed with precast pre-stressed slab panels with a 50mm concrete screed on top. As many of the urban houses, the roof of this particular house was constructed with a timbre structure, thatched with cement fibre sheets with a timber ceiling.

For both brick walled house and block walled house, in-situ tie beams were used at the edge of the slab and for the 150mm foam concrete house also same type of beam was used even though the slab was constructed pre-cast. For all the houses staircase was considered to be an in-situ cast concrete one. MEP works were considered to be same for all 4 types while finishers were different due to the plastering requirement of block work and brick work.

5.2. Embodied energy of materials

Building materials accounts for the largest share of embodied energy of a building. For the comparative study, the material quantities under each item has to be determined. Then, it was further divided into constituent materials. For example, the embodied energy of brickwork has been determined separately for bricks and mortar, further divided into cement and sand. The reason for this approach is to take into account the transportation energy requirement accurately since the distance transported would be different for different materials.

5.3. Embodied energy of transportation activities

Since the land selected does not differ from the study done for the single-story house, the transportation energy does not differ much for the vehicles used. Precast concrete slab panels, foam concrete wall panels, columns and beams, all are manufactured in Ekala and have to be transported using truck- ideally a boom truck to easy loading and unloading purpose. All other materials will be the same as mentioned in the single-story house construction details.

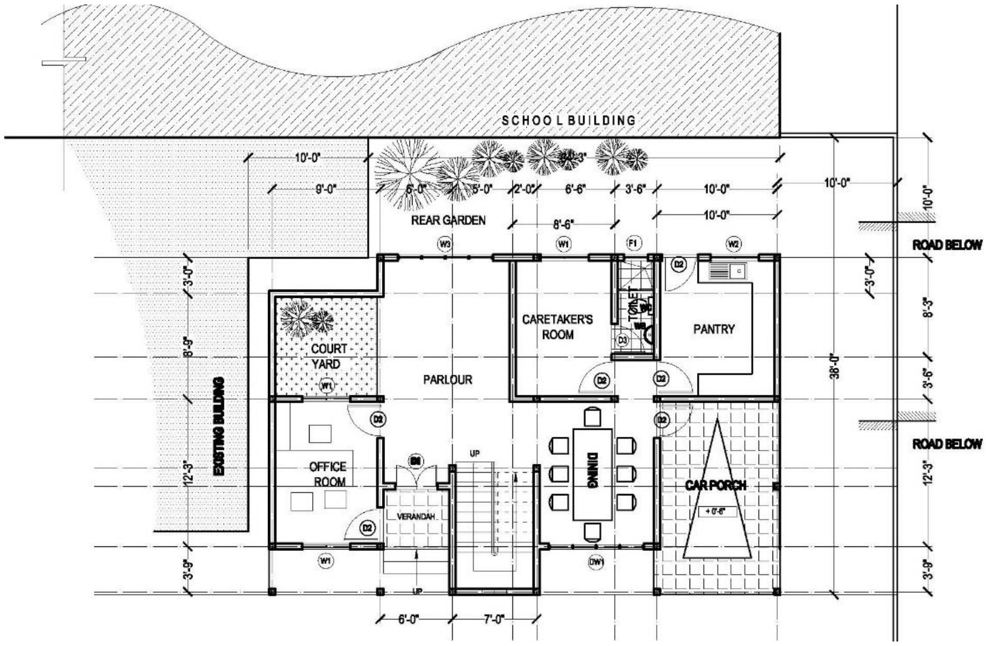

Figure 5-1: Ground floor plan of the house

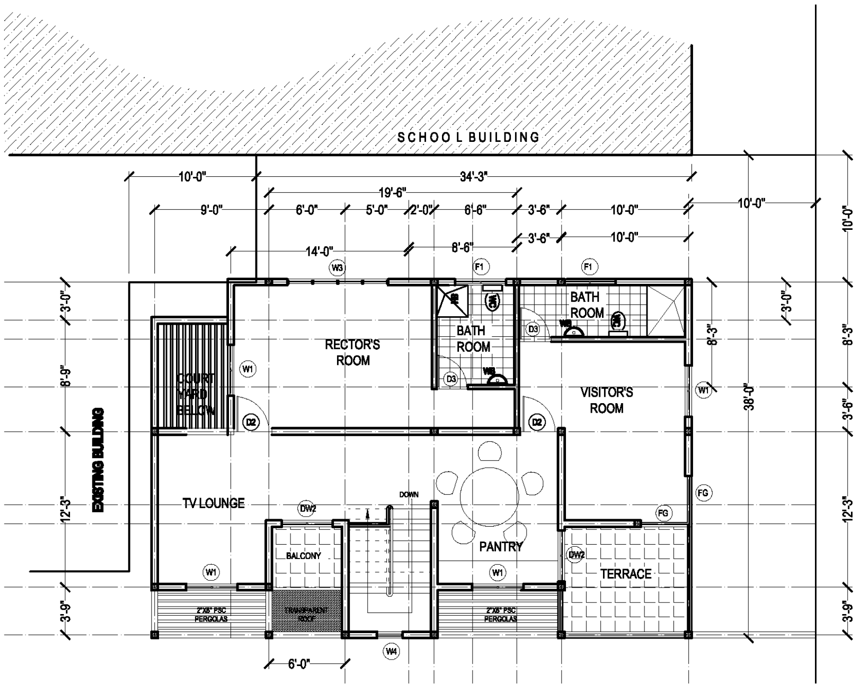

Figure 5-2: 1st floor plan

5.4. Results of the analysis

5.4.1. Total embodied energy

As mentioned in the previous sections, the brick walled house and 150mm foam concrete panelled house were constructed with load bearing walls while others were frame structures with concrete columns and beams. However, those beams and columns used for the 100mm foam concrete walled house were precast elements, while all of them are constructed in-situ for the block walled house. The embodied energy analysis done for the two-storey house yielded rather different results in terms of the total embodied energy, compared to the single storey house with the comparison of 150mm panelled house.

Up to the foundation completion stage, both block walled house and 100mm foam concrete panelled house have almost the same amount of EE due to the similarities of the foundation. However, due to the absence of using concrete for the bases of foundation, the brick house and 150mm foam concrete panelled house have less amount of EE compared to the other two. The precast tie beams of the 100mm foam concrete house is reduced mainly due to the smaller section size and less reinforcement requirement. Other three uses same type of in-situ tie beams have same value for the EE of that element.

There is a significant difference in EE of the columns used for block walled house and precast columns of 100mm foam concrete panelled house. Another advantage of foam concrete panelled walls is ability to provide smaller openings like doors without lintels. Therefor lintels were only used on top of large windows. However, for the larger lintels in 150mm panelled walls, the values go slightly higher due to the higher width of the wall.

Roof and MEP work are all the same for 4 houses and there is no change for the EE values. However, smooth flat finish of panelled walls does not require many finishing touches while the requirement of plastering the walls of brick and block houses increase the EE for the finishing work. Even though the painting work required for the panelled houses is slightly less than the other two, it was assumed same EE for painting for all 4 houses.

As shown in table 5.1 final results of the analysis show that the brick walled house has the highest amount of EE, which is 4.5 GJ/m^2. It is also higher than the value obtained from the single storey brick house which was 4.06 GJ/m^2. This indicates that the added floor has increased the embodied energy of the EE per square meter of area. The main reason for this, is the use of higher volume concrete in the two-storey house than the single storey house. 100mm foam concrete panelled house has higher amount of EE than the 6" block masonry walled house, which are 3.64 GJ/m^2 and 3.51 GJ/m^2, but these values are almost the same amount. Comparatively, those have 19% and 22% EE saving with respect to the brick masonry house respectively. However, the interesting finding is the 150mm foam concrete panelled house has a EE 4.02 GJ/m^2. It is about 11% reduction of EE compared to the brick house. These results are easily visualized in the chart given below (figure 5:3).

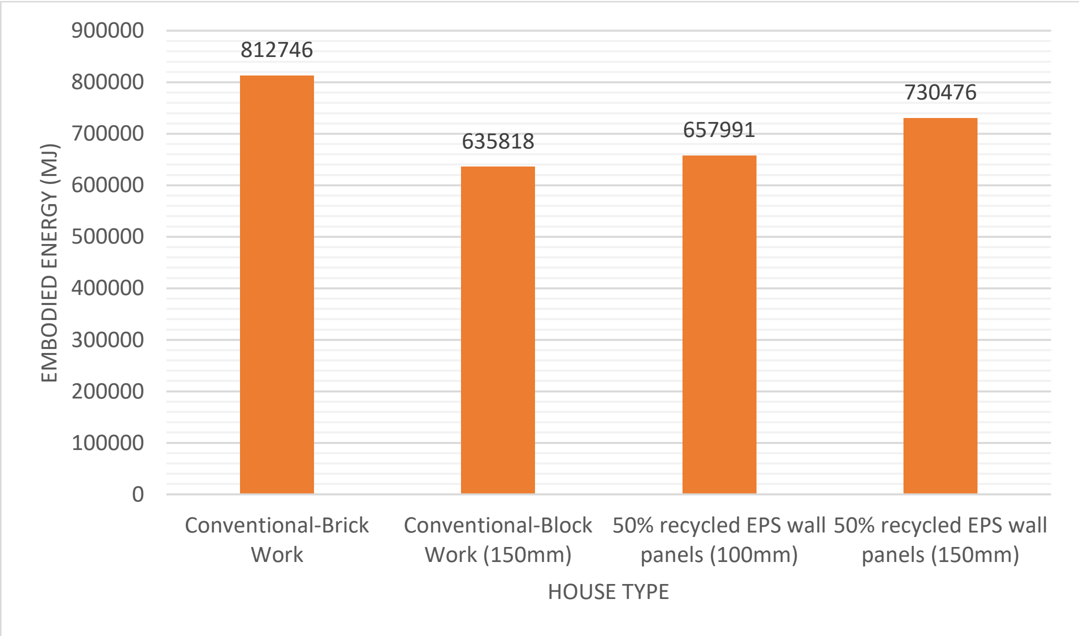

Figure 5-3: Comparison of the total embodied energy of the four houses

Table 5.1: Total embodied energy of the two-story house

		Embodied Energy (MJ)			
		Brick Masonry	Block Masonry	Foam Concrete Panel	
				100mm	150mm
Excavation	Excavation and backfilling	9,158	9,158	9,158	9,158
Foundation	Rubble Work	69,347	10,507	10,507	69,347
	Column Bases	-	34,093	34,096	-
	Plinth Beam	32,342	32,342	31,630	28,523
	Plinth Plaster	1,388	1,388	1,388	1,388
Superstructure	Tie beams	62,241	62,241	40,192	52,369
	Ground floor concrete	12,874	12,874	12,874	12,874
	Columns	-	25,642	17,383	-
	Walls	248,538	71,851	166,458	218,227
	Slab	77,953	77,953	60,154	60,154
	Staircase	10,808	10,808	10,808	10,808
	Lintels	3,479	2,342	926	1,390
Roof	Roof with ceiling	62,496	62,496	62,496	62,496
Finishing	Doors & windows	11,314	11,314	11,314	11,314
	Plastering	22,200	22,200	-	-
	Tiling	63,557	63,557	63,557	63,557
	Painting	53,909	53,909	53,909	53,909
MEP work	Electrical Work	10,467	10,467	10,467	10,467
	Plumbing & sanitary	22,511	22,511	22,511	22,511
	Septic tank and soakage pit	29,976	29,976	29,976	29,976
Total Embodied Energy		804,557	627,629	649802	718,468
Embodied energy per square meter (GJ/m2)		4.50	3.51	3.64	4.02

Table 5.2: Contribution of Individual materials to the Embodied Energy

	Building Materials	Burnt clay brick house		Cement-sand block house		100mm EPS wall panels house		150mm EPS wall panels house	
		EE (MJ)	Contribution	EE (MJ)	Contribution	EE (MJ)	Contribution	EE (MJ)	Contribution
1	Cement	152,745	18.8%	117,975	18.6%	184,378	28.0%	172,557	26.2%
2	Sand	8,461	1.0%	5,269	0.8%	2,952	0.4%	4,324	0.7%
3	Aggregate & Rubble	14,896	1.8%	7,671	1.2%	8,131	1.2%	12,497	1.9%
4	Main Walling Material	207,649	25.5%	49,013	7.7%	35,216	5.4%	52,823	8.0%
5	Steel	118,206	14.5%	118,206	18.6%	59,887	9.1%	54,065	8.2%
6	Ceramic Tiles	63,103	7.8%	63,103	9.9%	63,103	9.6%	63,103	9.6%
7	Paints	52,018	6.4%	53,961	8.5%	52,018	7.9%	52,018	7.9%
8	PVC	12,265	1.5%	12,265	1.9%	12,265	1.9%	12,265	1.9%
9	Timber	6,517	0.8%	6,517	1.0%	24,719	3.8%	24,719	3.8%
10	Cement Fibre sheets	31,295	3.9%	32,785	5.2%	91,293	13.9%	91,293	13.9%
	Total Embodied Energy	812,746	82.1%	635,818	73.4%	657,991	81.2%	539,664	82.0%

5.4.2. Contribution of individual materials

The materials used in each housing type was quantified for the ease of analysing the embodied energy. For example, in a brick wall, walling materials were separated as cement, sand, burnt clay bricks and water (which was neglected due to very small embodied energy). For the cement sand block house, this separation of walling materials could go further, by separating the constituents of the cement sand blocks. However, for the easiness of comparison that extensive quantification of materials was not done and the embodied energy for cement, sand blocks were presented as a single unit in the analysis. By this way, three walling materials can be easily quantifiable. The results are presented in Table 5.2.

According to the calculations done for the three houses, materials contribute around 80% of the embodied energy of a two-storied building. In the block walled house, this contribution was found to be 73.4% which is the least. For the burnt clay brick house, the maximum contribution to the embodied energy has been done with the walling materials- specially form bricks. It is about 25% of the total embodied energy of the house. Cement and steel also contribute a substantial amount while paints and ceramic tiles contribute approximately equal amount of to the total embodied energy.

In the block walled house, these major contributing material changes in a small amount, largely due to the less amount of embodied energy required for manufacturing of cement sand blocks. Therefore, the main contributors to the embodied energy are cement and steel, where both contributing about 18.6% of the total embodied energy of the house. However, it is noticeable that the cement quantity used in the cement sand block house is less than the quantity used in the burnt clay brick house (neglecting the cement quantity used for the blocks), and the main reason for this can be the least amount of mortar joints. Ceramic tiles, paints and cement sand blocks, together they contribute close to 27% of the total embodied energy.

The foam concrete panelled houses have identical characteristics when the usage of materials is considered. However, the differences in material quantity due to the thickness of the wall panels and usage of steel and concrete resulted in the differences in the values presented in Table 5.2. Even though the thickness of 150mm panel is higher, there is a notable reduction in cement usage of the two buildings. The main reason is, 100mm EPS panelled wall house is a concrete framed structure, but the 150mm wall panelled house is a load bearing design. Therefor concrete used for the 150mm wall panelled house is less and it has resulted in the reduction in cement usage. However, the higher thickness of the panels has resulted in higher amounts of EPS usage and, the contribution of the main walling material has been increased from 5.4% to 8% of the total embodied energy, when wall panel thickness is increased by 50mm. In all three houses, cement fibre sheets are used for the roof. The noticeable increase in the contribution of this material to the total embodied energy at foam concrete panelled houses is due to the cement fibre sheets, which used to sandwich these panels.

2.6.1. Embodied Carbon Analysis

The results of the embodied carbon analysis done are given in the table 5.3. Only the major materials used in this construction work have been considered in the analysis. And the results are not dramatically different from embodied energy analysis because, the highest and the lowest values of the housing types are not changed. The burnt clay brick house has the highest amount of embodied carbon, which is 93695kg of carbon dioxide. The cement sand block house has only 43150kg and it has the least amount of carbon dioxide per unit floor. However, the interesting result is from the two-foam concrete panelled houses. Despite thick panels are being used for the walls, 150mm foam concrete house has less amount of embodied carbon than 100mm panelled house. Again, the main reason for this is the difference in the considered design type. The 100mm panelled house is a concrete framed structure, but the 150mm house is a load bearing type. Therefore, this result is different from the results embodied energy analysis, which explained at 2.5.2.

Table 5.3: Results of embodied carbon analysis

Material		Carbon Coefficients (kgCO2kg)	Carbon Emission (kgCO2)			
			Burnt clay brick house	Cement sand house	100mm Foam concrete house	150mm Foam concrete house
1	Cement	0.73	22,756	17,576	27,469	25,708
2	Sand	0.0048	508	316	177	259
3	Coarse Aggregate	0.0048	650	335	355	545
4	Bricks	0.28	48,456	3,607	3,607	3,607
5	EPS (virgin)	2.55	0	0	1,014	1,520
6	Steel	1.37	3,856	3,827	1,953	1,764
7	Ceramic Tiles	0.74	3,891	3,891	3,891	3,891
8	Paints	2.42	874	874	874	874
9	Glass	0.86	111	111	111	111
10	PVC	2.56	296	296	296	296
11	Timber	0.46	2,998	3,016	2,805	2,805
12	Plywood	0.81	5,863	5,863	4,018	3,254
13	Cement Fibre sheets	1.09	3,436	3,436	9,568	10,429
Total			93,695	43,150	56,138	55,065

5.5. Discussion

The embodied energy analysis and the embodied carbon analysis done for the two-storied house with 1910 ft2 area, has shown almost identical results for the aforementioned building system with precast foam concrete wall panels and precast beam-column-slab system. The cement sand block house has the least amount of EE and has the least amount of embodied carbon. And the burnt clay brick house has the highest amount of EE and the highest amount of embodied carbon out of three building systems. However, the results embodied energy analysis and embodied carbon analysis is slightly different from the 100mm precast foam concrete panelled house and the 150mm precast foam concrete panelled house. For the considered 13 materials, the embodied carbon of the 150mm house is better with less amount of carbon while the 100mm panel has slightly higher value. But, in terms of the embodied energy of the buildings, the 100mm panelled house has the least amount of EE compared to the 150mm building system.

6. CONCLUSIONS AND RECOMMENDATIONS

Precast building systems are becoming more and more popular in the modern world due to their time saving constructability and cost effectiveness. While the whole world is discussing about the preservation of natural resources and sustainability in the construction industry, it is important to analyse the building systems for their environmental performances as well. Embodied energy and embodied carbon analysis are two of such methods to analyse the impact on the environment.

The precast building system studied in this research consist of pre-stressed concrete beams, columns and slabs, which is mainly targeted on the residential buildings, not more than 3 stories high. For the same system, walls are constructed using precast foam concrete panels, which are made out of 50% of with recycled EPS. Due to the simple and straightforward connection of the beam-column and slab construction and interlocking tongue and groove arrangement of the foam concrete panels has improved the constructability and provided with sufficient strength for the residential house construction. However, with the availability of material and distance of transporting the finished elements and energy used in installing those can determine the financial benefits as well as the environmental cost of this system. This research was mainly targeted at identifying the environmental impact of this particular system with the conventional housing methods of Sri Lanka.

EPS foam concrete panels are a novel construction alternative to the conventional housing methods. Houses made out of 100mm or 150mm EPS foam concrete panels have outperformed the houses constructed with burnt clay bricks, in terms of embodied energy and embodied carbon. Also, they closely match with the cement sand blocks in this aspect, even though the houses out of cement sand blocks have the edge. However, with the requirement of less labour, speedy construction and comparatively low cost, EPS foam concrete panels are a better alternative to the conventional house construction methods.

The foam concrete panels use the comparatively high amount of cement with their foam concrete mix and the cement fibre sheets. Even though this is a considerable disadvantage in terms of material usage with high embodied energy, the consequences are balanced with the usage of 50% recycled EPS.

Transportation energy of materials and manufactured products can have a considerable effect on the embodied energy and cost of the constructed houses. The case studies done for this research were located in Pita Kotte area, which is less than 50km from the manufacturing plant of these precast elements. Therefore, the results are not valid for constructions done far away.

Constructing a building for the residential purpose and calculating the energy up to the finishing stage is straight forward. To get the comprehensive idea about the performance of the building system, operational stage of the house is also important. In the operational stage, results can be affected by various factors like, no of occupants, the location and of the house, lighting and machinery usage, many other factors. Therefore, to do this study, sufficient case studies should be able to be done. Since this is a new building system, operational stage of these precast houses can be studied in a separate study, when the system is more popularized.

The data collected for vehicle efficiencies can vary with so many factors, but some general details are collected in this study. It can be useful to categorize the different vehicles with their common payload capacities, and conduct a more expansive survey, so that the details collected can be used in other research work.

The method used for this study was process based embodied energy analysis, which is very labour intensive. So, small processes and minor contributors to the embodied energy of the house have been neglected, due to the difficulties in quantification. There are no input-output tables developed for the energy consumption of Sri Lanka. Due to that reason input-output embodied energy analysis or the hybrid analysis (which is more advanced and accurate) cannot be used. Researching on the energy demand for various industries in Sri Lanka, and developing the input-output tables for the country, can make the embodied energy analysis and life cycle energy analysis more common in the decision making processes and more accurate studies can be done.

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