EMBODIED ENERGY, EMBODIED CARBON AND COST ANALYSIS FOR THE ROOFING MATERIALS AVAILABLE IN SRI LANKA.

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ABSTRACT

World population is rising day by day. Due to the increment of population, the demand for all the needs including foods, clothes, shelter etc. are also being increased. Therefore, escalating the production of various sectors is a must to meet these needs of the growing population. Most importantly, the increment of population has urged for new developments including factories, houses, apartments and various other construction works to facilitate their needs. Therefore, construction industry has become one of the significant industries to any country in the world. Nevertheless, it reasons for the environmental pollution due to carbon related emissions and due to the usage of tons of nonrenewable energy sources for it's day to day activities. Therefore, the researchers all around the world are focusing to reduce these since human needs should be fulfilled while saving the environment for the future. As a result of that, lots of new things have been introduced to the construction industry. Nevertheless, almost all of them are costly. Most importantly, being a developing country, cost effective sustainable solutions are really essential for a country like SL in reaching towards a sustainable goal. Nevertheless, there are minimum number of researches (Energy and Carbon) which have been conducted for the SL context in terms life cycle perspective. Further, roof element has not yet been studied in terms of Embodied Energy and Embodied Carbon perspective.

Therefore, this research aimed to identify the importance of Embodied Energy and Embodied Carbon and to analyze the roofing materials available in SL in terms of Embodied Energy, Embodied Carbon and Cost (initial and maintenance). There, (1) To identify the significance of Embodied Energy and Embodied Carbon throughout the life cycle of construction (2) To analyze the roofing materials available in Sri Lanka, in referring of Embodied Energy (3) To analyze the roofing materials in terms of Embodied Carbon and Initial and Maintenance Cost, were implemented as objectives to achieve the aim of this research. Here, the first objective was completely fulfilled through literature review and expert interviews. Work studies and documentary reviews were adopted to fulfill the second and third objectives.

After collecting data and analyzing them, it was found that conventional clay tile is the best (least EE & EC material), asbestos sheet (second best), automated clay tile (third best) and concrete (highest EE & EC material) is the worst in terms of EE & EC. Further, asbestos sheet is having lowest initial and maintenance cost and conventional clay tile, automated clay tile and concrete are having initial and maintenance cost values increasing accordingly. Moreover, the researcher has introduced a procedure/work sheet to find out the best roof material in terms of Embodied Energy, Embodied Carbon and initial and maintenance cost. Eventually, the developed work sheet can be adopted to analyze the alternative / newly invented roofing materials to analyze them in accordance with the same parameters.

Key words -: *Embodied Energy, Embodied Carbon, Building life cycle, Roof, Life Cycle Assessment*

I dedicate this piece of work to my beloved parents and brother………………..

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This successful research outcome was not only a result of an individual effort; many people's contribution was there. Hence, I would like to thank each and every one who gave their valuable support on many circumstances and to all who shared their wisdom and professional experience to make this work a success.

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LIST OF ABRIVIATIONS

Abbreviation	Description
BOQ	Bill of Quantities
EC	Embodied Carbon
EE	Embodied Energy
GHG	Green House Gas
LCA	Life Cycle Assessment
OC	Operational Carbon

CHAPTER 1

1.0 INTRODUCTION

1.1 Background

Global population is rising 1.05% per annum and it has estimated that average increment in population is 81 million per year (Department of Economic and Social Affairs- United Nations, 2020). Shelter, clothes and nutrition are three main basic needs of humans (Kopsov, 2019). Rising population has made a significant demand for basic human needs (Cilluffo & Ruiz, 2019). This excessive demand is urging the governments of each country to increase the production so as to facilitate the civilians (Peterson, 2017). Therefore, new factories, housing schemes, power plants, etc. are being constructed day by day (Kopsov, 2019). Most importantly, lots of resources are consumed for construction works and therefore construction industry has become a main exploiter of natural resources (Dixit, Fernandez-Solis, Lavy, & Culp, 2010). Moreover, significant amount of energy is also consumed for construction works and it puts the biosphere at risk (Hammond & Jones, 2008). When it was 2007, building related energy usage was responsible for 29% percent of global energy consumption (Han et al., 2013).Without stopping from using energy, building sector has become so cruel to the environment by becoming the largest single contributor for GHG emission (Hakkinen, Kuittinen, Ruuska, & Jung, 2015). In answering these situations, new regulations have been implemented to reduce the energy usage and carbon emissions from the operations of buildings (Han, et al., 2013).In case of building construction, the total life cycle energy consumption is made up of two components. They are Operational energy (OE) and Embodied Energy (EE) (Cabeza et al., 2013).

EE can be defined as the summation of direct or indirect energy requirements related with the life cycle of a product (McAlinden, 2015). It is better to go through an example to understand the concept of EE. In considering a brick wall, its EE (from mining to end of the construction) is the energy needed to make the bricks, bring them to the site, lay them, plaster and paint the wall (Haynes, 2013). In similar to EE there is a concept called OE as well.

OE is the energy required for a building during its operational works like heating, cooling, run appliances and lighting (Haynes, 2013). It is really essential to distinguish both EE and OE for a better life cycle assessment (McAlinden, 2015). Then, there are few main methods of EE analysis and they are process analysis , input/output analysis and hybrid analysis (Yohanis & Nortan, 2002). Next, it has found that EE is reasoned for Embodied Carbon(EC) as well (Dixit, Fernandez-Solis, Lavy, & Culp, 2010).

Embodied Carbon is the emission of carbon dioxide or carbon dioxide equivalent gases (CO2e) which are emitted due to non-operational works of the building (Gronvall et al., 2014). In similar to OE there is a term called Operational Carbon (OC) as well. It refers to the emissions (CO_2 and CO_2 equivalent gases) from operational activities of buildings including lighting, cooling, etc. (Kang, Kim, Kim, Cho, & Kang, 2015). International Energy Agency (IEA) has revealed that according to the current situations CO_2 emissions would be doubled by 2050 (Zhang & Wang, 2016). Further, it was found that more CO_2 is released from building materials like concrete, brick, steel than wood (Gustavsson & Sathre, 2006). Therefore, it is highly essential to discuss and take precautions towards EC in building life cycle.

Stages of building life cycle consist of varies activities and they are raw material extraction, bring them to the site, energy use for construction works, maintenance, repair and replacement of materials (Chastas, Theodosiou, & Bikas, 2016). Moreover, Gronvall et al., (2014) have mentioned a bit similar but more clear life cycle of a building. According to them, the activities that come under those stages are raw material extraction, transportation of raw materials to the factory, manufacturing of products, transportation of finished products to the site, construction of the building, maintaining and renovation of the building and ultimately disposal of materials. Furthermore, Monteiro, Fernndez, and Freire, (2016) mentioned that EE and EC are significant components of the life cycle of construction.

In describing the significance of EE and EC, until recently , it was assumed that OE is higher than EE and now it has been revealed that Embodied Energy accounts for a massive quantity of life cycle energy (Cabeza, et al., 2013).Crawford and Treloar,(2003) stated that EE contained in a building is 20-25 times of the annual OE needs for a building. In analyzing more and more, modern knowledge over EE encourages to reduce the EC emission as well (Sartori & Hestnes, 2007). Moreover, construction sector of India is responsible for 22% of annual Carbon emissions (Cabeza, et al., 2013). It evident that EC is even similarly significant as much as EE.

1.2 Problem statement

In considering EE use in building construction it accounts 30%-100% of total life cycle energy of residential buildings (Haynes, 2013). It emphasizes that EE is responsible for a huge portion of energy in building life cycle. Therefore, it is really essential to study over the EE related with buildings and find strategies to minimize that energy component. Moreover, tons of CO_2 and other greenhouse gases are emitted to the environment from day to day activities of construction industry. Then, cities responsible for 70% of energy consumption and CO_2 emissions, they occupy 3% of earth's land though (Haynes, 2013). These figures imply that, it was highly essential to identify the impact of these emissions. But still the studies towards EE and EC were at developing stage. Some researchers around the world had done their researches regarding this area for the construction industry. Further, all most all the researchers have touched the construction phase only and there were very less number of researches which had focus the total building life cycle. Moreover, there were very few researches regarding EE and EC in Sri Lankan context even for the construction phase. These portrait that there is a research gap in this area and therefore, it was necessary to do a research in order to fill that gap. Furthermore, doing a research in this area has become a must which is urgent due to the scarcity of nonrenewable energy sources and increment of tons of bad effects as a result of massive emissions daily.

1.3 Aim

To identify the significance of Embodied Energy and Embodied Carbon and to analyze the roofing materials available in SL in terms of Embodied Energy, Embodied Carbon and Cost (initial and maintenance).

1.4 Objectives

1. To identify the significance of Embodied Energy and Embodied Carbon throughout the life cycle of construction.
2. To analyze the roofing materials available in Sri Lanka, in referring to Embodied Energy.
3. To analyze the roofing materials in terms of Embodied Carbon and Initial and Maintenance Cost.

1.5 Scope and limitations

Embodied Energy and Embodied Carbon analysis for the roofing materials were conducted for the permanent roofing materials available in Sri Lanka. As per census statistic data, clay tile, asbestos and concrete are the permanent roofing materials. Therefore, they were considered for this study. Moreover, demolition phase was excluded from this life cycle analysis, due to the unavailability of demolition data. Furthermore, cost parameter was included to this study since cost covers a significant role in construction materials. Therefore initial and maintenance cost was included for the study. Then in referring to the expert interviews, expert interviews had to be limited to twelve, since there were very less number of experts available in SL in terms of EE and EC.

1.6 Methodology

1. A comprehensive literature survey was carried out regarding EE and EC within the building life cycle through journals, articles and books.
2. Twelve semi structured expert interviews were conducted to validate the literature findings, to identify the recent status of this subject area within construction industry of SL and to distinguish the best energy and carbon analysis method to conduct a separate case study analysis.
3. A case study was carried out for calculating EE, EC and initial and maintenance cost values of four alternative roof materials.

a) Data for calculating EE and EC values were collected from various places (e.g.: clay tile, asbestos sheet, manufacturing places, etc.) through work studies.

b) Desk study was adopted to find EE and EC intensity values of some materials, which were not able to find though process analysis (e.g.:- EE value of diesel is 35.9 MJ/L).

c) A documentary review was done in order to gain cost details regarding the construction of the roof element from each of the selected roofing material (conventional clay tile, automated clay tile, asbestos sheet and concrete roof) for the research.

1.7 Key Findings

- Embodied Energy covers a considerably higher portion of life cycle energy consumption of a building.
- Embodied Carbon cover a significant amount of life cycle emissions of a building.
- Awareness towards the Embodied Energy and Embodied Carbon in Sri Lankan construction industry is at primary stage.
- Conventional clay tile is the least emitting roof material and asbestos sheet, automated clay tile and concrete emit accordingly.
- Conventional clay tile consumes least Embodied Energy and asbestos sheet, automated clay tile and concrete consumes accordingly.
- Asbestos sheet is having the least initial and maintenance cost and conventional clay tile, automated clay tile and concrete are costlier accordingly.

1.8 Chapter breakdown.

Chapter 01: Introduction

This chapter consists of a brief background for the research with problem statement, aims and objectives, scope and limitations and research methodology.

Chapter 02: Literature Review

This chapter consists of a comprehensive literature survey regarding the Embodied Energy and Embodied Carbon concepts and their significance within the building life cycle.

Chapter 03: Research Methodology

This chapter previews the methodology for the research and explains the methods that used for both data collection and data analysis.

Chapter 04 : Data Analysis and Research Findings

This chapter includes the findings of research through expert interviews and a case study with a comprehensive analysis of gathered details from above mentioned interviews and the case study.

Chapter 05: Conclusion and Recommendations

This chapter concludes the research with conclusion, recommendations and approaches for further research.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 General

This chapter aimed the existing literature towards the research area and to emphasize the research problem by highlighting the existing research gap. Therefore, this chapter consists the existing literature gained from journals, books, etc. towards this subject area. Starting from broader view of “Global population growth” the key concepts of Embodied Energy and Embodied Carbon have been discussed accordingly. After discussing all the necessary sub topics, a summary of the total chapter has been given at the end. Thereby this chapter fulfilled the literature review and helped to complete the first objective.

2.2 Global Population Growth

It is expected that global population will reach 11 billion margin by 2100 (Cilluffo & Ruiz, 2019). Most importantly, global population was 1 billion in 1800 and it has reached up to 7 billion within 215 years and figure 2.1 emphasizes the increment of world population with the time being (Department of Economic and Social Affairs-United Nations, 2020).

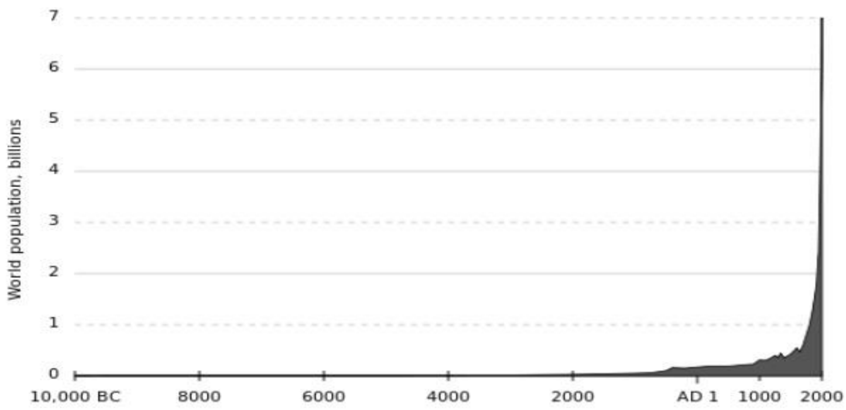

Figure 2. 1 World population growth

Source: (Department of Economic and Social Affairs- United Nations, 2020)

This rising population has been identified as a global problem (International Labour Organization, 2017). Humans have three main basic needs as nutrition, clothes, shelter (Kopsov, 2019). Nevertheless, rising population demands more of these resources to cover their necessities, for instance it is predicted that 70% more food would be necessary by 2050 (Max-Neef, 2010). Most importantly, each government is bound to fulfill the basic needs of their civilians and is trying their best come up with various developments to facilitate them (Peterson, 2017). There, the experts from Construction Industry Institute have estimated that due to increment of global population, world construction will increase in next 100 years than past 2000 years (Alfredo, Nguyen, Jacob, & Dean, 2016).

2.3 Construction Industry

Construction industry is a significant industry to any country and by 2018 its contribution to the GDP of Sri Lanka was 7.1 (Central Bank of Sri Lanka, 2019). Construction industry diversifies as various developments including buildings, roads, irrigation, airports, harbours, etc. Nevertheless, buildings cover 0.18 % of construction works per annum in global context. Moreover, abundance of materials are consumed for the construction works daily (Cabeza, et al., 2013). Since these materials should be extracted, manufactured and transport, massive energy consumption is all-around (Ham-mond & Jones, 2008). Without stopping from consuming massive amount of energy, construction results for the unwanted emissions like greenhouse gases and puts the biosphere at risk (Urege- Vorsatz, et al., 2007). Intergovernmental panel on climate change emphasizes (through their fourth assessment report -2007) that 30% of the annual GHG emissions are due to construction related works (Akbarnezhad & Xiao, 2017). Therefore, energy usage and emissions due to construction related works have been discussed by upcoming sub sections accordingly.

2.4 Energy related with construction.

Energy most commonly categorizes into two types as primary and secondary ("Energy Efficiency Trends in Canada 1990 to 2013," 2013). The primary energy (potential energy) is defined as the intrinsic energy in a product or a resource (Liu et al., 2012). Secondary energy refers to the forms of energy which are transformed from primary energy sources through energy transformation procedure (Li & Colombier, 2009). Electricity which is transformed from primary energy sources such as coal, natural gas, raw oil, etc. can be pointed out as an example for secondary energy (Dincer, Midilli, Hepbasli, & Karakoc, 2010). Nevertheless, Energy consumed within the total building life cycle is basically combined with two energy components (Dixit et al., 2010). According to the authors, they are Operational Energy and Embodied Energy. There, Operational Energy can be defined as the energy consumes for the operational activities of the building like lighting, heating, cooling etc. (Huang, Krigsvoll, Johansen, Liu, & Zhang, 2017). Since Embodied Energy is a main component of our study, it is better to have a comprehensive study on Embodied Energy.

2.4.1 Embodied Energy

There is no any hesitation that energy is included in all the things we use from clothes to foods, machines, vehicles and houses etc.(Alwan & Jones, 2014). Basically, the energy associate with raw material mining to manufacturing the products, transport them to the site, construction works and to the end of it's life can be defined as the Embodied Energy of building life cycle (Ciravoglu, 2005). Moreover, Reddy and Jagadish (2003) also has defined it in similar manner and according to them, Embodied energy is the energy consumed by processes associated with the total production of a building, from mining and manufacturing, through transport and other functions. After distinguishing Embodied Energy, better to have a look towards emissions related with construction.

2.5 Emissions related with construction

Intergovernmental panel on climate change emphasizes (through their fourth assessment report -2007) that 30% of the annual GHG emissions are due to construction related works (Akbarnezhad & Xiao, 2017). Furthermore, it is expected that, GHG emissions related with building life cycle would be doubled within next 20 years (BUILDINGS AND CLIMATE CHANGE: Summary for Decision Makers, 2009). Most importantly, carbon related emissions of a building can be categorized into two as Embodied Carbon (EC) and Operational Carbon (OC) (Purnell, 2011). Operational Carbon refers to the carbon related emissions which release to the atmosphere due to the operational works (throughout the building life cycle) like lighting, heating, cooling, etc. (Darby, Elmualim, & Kelly, 2011). Similar to Embodied Energy, since Embodied Carbon is also a main component of this study, it has been discussed in detail within next sub topic.

2.5.1 Embodied Carbon

Embodied Carbon (EC) refers to the sum of fuel based Carbon emissions and non-fuel related (due to the processes) Carbon emissions within the life cycle of a building (Moncaster & Symons, 2013). Not only that, but also the author states that this includes emissions due to mining of raw materials, manufacturing the products, assembly and transportation of them, maintenance and replacement and ultimately demolition and disposal of them at the end of the life span. Furthermore, Lockie and Berebecki, (2012) has defined the Embodied Carbon in a similar manner and according to them the energy consumption (Embodied Energy) during the process of mining (extraction of raw materials) to demolition of the products (buildings) result for carbon related emissions (Embodied Carbon). Further, author states that it does not include the carbon emissions due to some operational works like cooling and lighting within the use phase of the building. Moreover, CO_2e is used as a measurement to measure the impact of gases comparing to Carbon dioxide (Gronvall et al., 2014). Greenhouse gases and their potentials are mentioned within the table 2.1.

Table 2. 1 Greenhouse gases and their potentials.

Greenhouse gas	**Potential**
Carbon dioxide	1
Methane	25
Nitrous oxide	298
Sulfur hexafluoride	22800
Perfluorocarbon	7390 - 12200
Hydrofluorocarbon	124 - 14800

Source : (Lockie & Berebecki, 2012).

In describing the above table for example lets consider methane. "Methane has a global warming potential of 25 and it means that 1 kg of methane has the same impact on climate change as 25 kg of carbon dioxide" (Lockie & Berebecki, 2012). Therefore, according to the author, 1 kg of methane is represented from 25 kg of CO2e. As it is, CO2 equivalent of other mentioned gases are also can be taken from table 2.1. Moreover, employers all around the world have commenced to consider about Embodied Carbon measurements and it's minimization due to it's significance (Lockie, 2013). Therefore, the significance of Embodied Carbon and Embodied Energy have been discussed within the next sub topic.

2.6 Significance of Embodied Energy and Embodied Carbon.

In past a massive effort has been done to minimize the Operational Energy of a building, assuming that Operational Energy is extremely higher than Embodied Energy (Wallbaum, Ostermeyer, Salzer, & Zea Escamilla, 2012). Nevertheless, recent researches have proved that Embodied Energy component also significantly high in comparing to Operational Energy of a building (Cabeza, et al., 2013). Furthermore, in supporting this, low energy buildings of Swedish have pointed out that initial Embodied Energy even of a home (one family sized) responsible for nearly around 40% of the building's whole life cycle energy over period of 50 years (Thormark, 2002).

Moreover, Embodied Energy of a building is approximately 20-25 the energy need for Operational purposes of a building in Australia (Crawford & Treloar, 2003). Not only that, but also, according to the author Embodied Energy accounts 13% to 19% of Operational energy of an office building of 50 years life span. Furthermore, the Embodied energy of a building can represent up to 40% of life cycle energy use of residential buildings (Dissanayake & Jayasinghe, 2015). All these evidences emphasize the significance of Embodied Energy competitively to Operational Energy and figure 2.2 shows the variation of Operational and Embodied Energy within the life cycle of an office building.

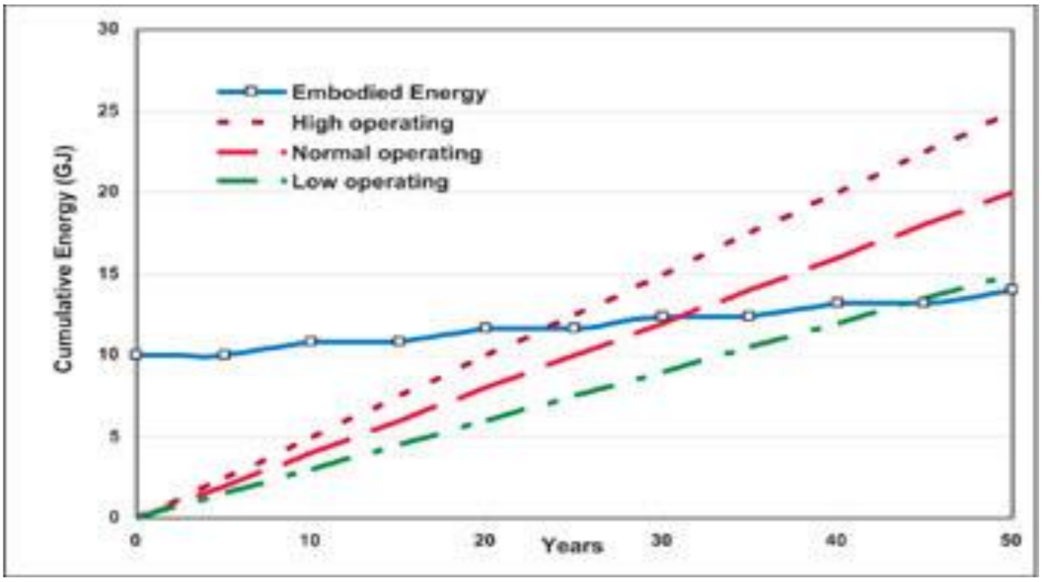

Figure 2. 2 Summation of life cycle energy of an office complex.

Source : (Ciravoglu, 2005).

According to the figure above, the Embodied Energy of a building is a significant multiple of the annual operating energy consumed, ranging from around 10 year typical dwellings to over 30 year office buildings (Ciravoglu, 2005). Moreover, according to the author it changes when the life span is more than 40 to 50 years.

Most importantly, it is assumed that the temperature of the world will increase 1.5 - 4.5 degrees of Celsius when it reaches to the end of this century (ZHAO & MA, 2015). According to the authors Intergovernmental Panel on Climate Change has pointed out that this is happened since the quantity of CO_2 doubles. It has found that buildings account for nearly 30% of the global greenhouse gas emissions (Biswas, 2014). Furthermore, almost a quarter of all global CO_2 emissions are due to energy usage of buildings (Monahan & Powell, 2011). Basically, it is assumed that Operational Carbon quantity is higher than the Embodied Carbon quantity of building life cycle (Kang, Kim, Kim, Cho, & Kang, 2015). Nevertheless, EC has been identified by the Green Building Councils of both USA and Australia as a significant measurement that can affect the life cycle of the buildings (Lockie & Berebecki, 2012). Further, according to Kang et al., (2015) the Operational energy component has been reduced with the time due to some technology related efforts like energy efficiency techniques in heating and air conditioning . Therefore, the EC component is relatively increased in considering the overall carbon emission within the total life cycle. It is shown in figure 2.3.

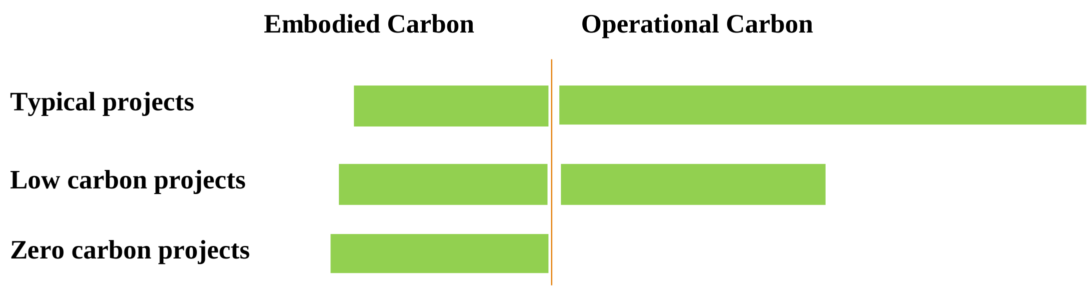

Figure 2. 3 A comparison of EC and OC with the project type.

Source: (Lockie & Berebecki, 2012).

In analyzing the above figure, it is obvious that the portion of EC is being increased in comparing to the total Carbon emissions of construction projects (with the introduction of new rules and regulations) (Lockie & Berebecki, 2012). Therefore, when it comes from typical projects to zero – carbon projects Operational Carbon component has decreased to zero and significance of Embodied Carbon has posed. Furthermore, it is really tough to minimize these carbon emissions with the neglection of Embodied Carbon and it has become a vital reason to go for Embodied Carbon analysis to find strategies of minimizing Embodied Carbon (Gan, Cheng, Lo, & Chan, 2017). In analyzing Embodied Energy and Embodied Carbon, it is necessary to identify the stages of building life cycle (Haynes, 2013).

2.7 Stages of building life cycle.

According to Pomponi and Moncaster, (2016) whole building life cycle can be categorized into following stages and they are product stage, construction stage, use stage and end of life stage. Furthermore, all these stages include energy consumption processes within the building life cycle and they are mentioned below accordingly (Pomponi & Moncaster, 2016). According to the authors, raw material supply, transport and manufacturing the products are relevant to the product stage. Next, construction stage consists of the transportation of manufacturing products to the site, on and off site transportations and construction or installation processes. Then use stage includes use, maintenance, repair, refurbishment and replacement of the building. Ultimately, end of life stage encompasses demolition, transportation of demolished things, recycling of waste and disposal of those materials. Moreover, Lockie, (2013) also has categorized the building life cycle in same manner for the assessment of energy and carbon emissions. Nevertheless, Ramesh et al., (2010) have categorized the building life cycle in a different manner. There the stages of building life cycle are manufacturing phase, use phase/operational phase and demolition/end life phase (Ramesh et al., 2010). According to the authors manufacture phase includes mining of raw materials, production and transportation of building materials and installation and construction of the building and renovation of the building. Next, Use phase/operational phase includes the operational activities like lighting, heating ventilation and air conditioning etc. Ultimately, demolition phase includes demolition of the building, transportation of dismantled materials, recycling and disposing them. In analyzing the above mentioned stages of all three authors it seems that all the energy consumption activities/processes within the building life cycle are same, categorization of stages are bit different though. Since the total of the mentioned energy consumption processes/activities (eg-: mining the raw materials, transporting the manufacturing products, etc.) are same in all the phase categorizations of the life cycle. Therefore, selecting any of them is okay. Due to the easiness and clearness of the reader, stages (manufacturing stage, construction stage, operational stage and end life stage) that pointed out at the beginning of this sub topic were considered for this research. Furthermore, the selected stages and the processes/activities relevant to those are shown in figure 2.4.

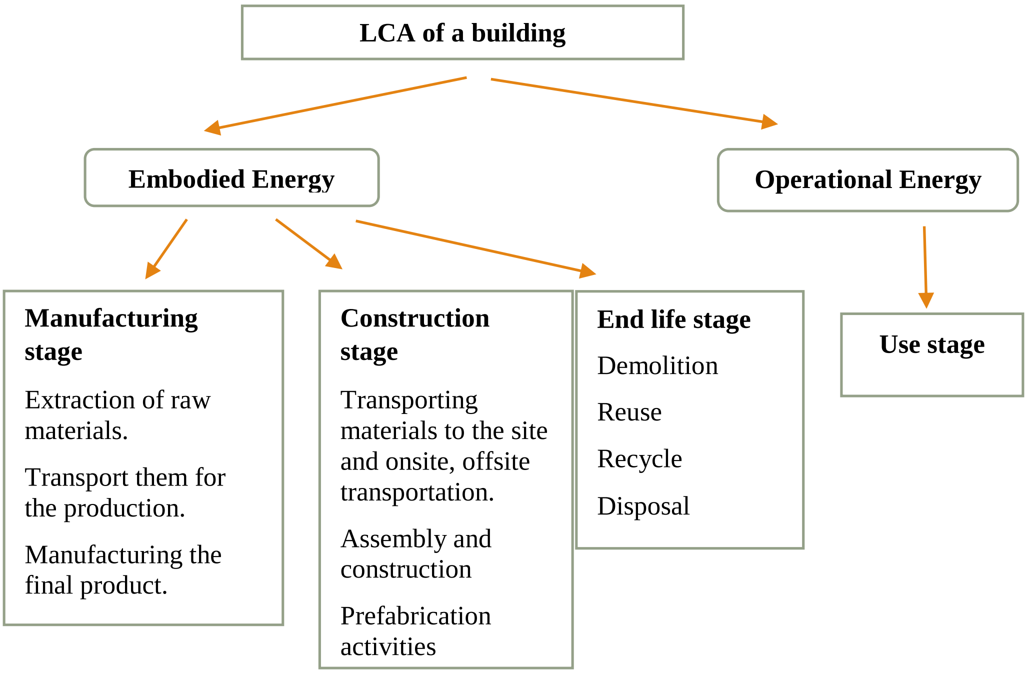

Figure 2-4: Stages / phases of building life cycle.

Source :- (Pomponi & Moncaster, 2016).

In analyzing the above figure, all the energy consumption/emission related processes/activities mention under those stages account for the life cycle energy (Operational and Embodied energy) and life cycle emissions (Operational and Embodied emissions) (Crawford, 2012). Therefore, after distinguishing the stages it is necessary to identify the Embodied Energy and Embodied Carbon analysis methods.

2.8 Embodied Energy and Embodied Carbon analysis.

Literature suggests that determination of Embodied Energy is difficult and no standard methodology is available to estimate the energy level of building materials (Verbeeck & Hens, 2010). Moreover, most importantly there is no generally accepted analysis method available to compute Embodied Energy/Embodied Carbon accurately and consistently and as a result wide variations in measurement figures are inevitable (Hammond & Jones, 2008). According to Cabeza, et al., (2013) databases/ inventories are used for all these analysis methods. Furthermore, Embodied Energy analysis of a building or any product depends on several parameters (Dissanayake & Jayasinghe, 2015). According to the author number of stages or processes/activities of the building life cycle consider for the analysis is one of them. Then, geographical location of the study is also important, because the climate conditions, material properties, transport distances and methods, and many other parameters can change depending on the location of study (Dixit et al., 2010). Furthermore, according to the authors source of data, age of data, completeness of data and technology of the manufacturing process can also have an impact on the analysis. Ultimately, the method use for Embodied Energy/Embodied Carbon analysis also can affect a lot for the outcome (John, Treloar, Arch, & Arch, 1998). In accordance with the author basically there are three Embodied Energy/Embodied Carbon analysis methods. They are Input – Output analysis, Process analysis and Hybrid analysis. Hybrid analysis has again divided into another two sections. They are Processed based Hybrid analysis and Input – Output based Hybrid analysis (John et al., 1998). It is better to go through these analysis methods in detail manner.

2.8.1 Input- Output analysis.

Input-output analysis is a crucial Embodied Energy/Embodied Carbon analysis method because it comprises a comprehensive framework (John et al., 1998). Mainly this analysis portraits the relationship of the varies sectors of economy and their monetary transactions (HENDRICKSON & HORVATH, 1998). Further, an input – output based analysis could account for most direct and indirect energy inputs in the process of production of building materials and thus is considered relatively complete (Dixit et al., 2010). Furthermore, this analysis uses a system approach to model the flows of products between the sectors of an economy (John et al., 1998). Moreover, according to the authors there are four energy supply sectors in the Australian economy and they are 'coal, oil and gas', 'petroleum, coal products', 'electricity supply' and 'gas supply'. Every other sector purchases energy directly from at least one of these energy supply sectors (John et al., 1998). The great advantage of this method is data completeness of system boundaries since entire economic activities of a nation are represented (Menzies et al., 2007). However, when the direct energy section of a product is high, Process analysis is really suitable (Lenzen & Treloar, 2006).

2.8.2 Process analysis

The process analysis method (also called conventional or traditional method) is the oldest and still most commonly used method life cycle analysis of buildings and it includes activities such as extraction , transportation, manufacturing, use , recycling, disposal (Menzies et al., 2007).In considering process analysis it aims a specific product or sometimes a service (Lenzen & Treloar, 2006). Process based energy/carbon analysis has its own limitations because of the exclusion of many upstream processes as a result of truncation of system boundaries (Dissanayake & Jayasinghe, 2015).The magnitude of system incompleteness and error in process analysis are estimated to be as high as 50 percent and 10 percent respectively. (Dixit et al., 2010). Moreover ,in order to overcome the issues in both Process and Input – Output analysis, Hybrid analysis has introduced (Poyry, Saynajoki, Heinonen, Junnonen, & Junnila, 2015).

2.8.3 Hybrid analysis

Most importantly, hybrid analysis is suggested to result in more complete and accurate assessments (Poyry et al., 2015). Not only that but also, even in a situation where the relevant process data are not available , this analysis is useful and most importantly results can be gained quickly (Acquaye, 2010). The main disadvantage of this technique is the risk of double- counting (Menzies et al., 2007).

- Processed based hybrid analysis.

  The basis of this Process-based hybrid analysis lies in the assumption that the main disadvantage of I/O analysis (aggregation and proportionality of monetary values of sectors) can be compensated by defining the inputs into the main processes (Menzies et al., 2007). However, complex materials , which involve more than one material, could pose problems for this method (Dixit et al., 2010).
- Input – Output based hybrid analysis

  This method uses conventional Input-Output analysis data as the starting point (Menzies et al., 2007). Furthermore, according to the author single items or groups of data in the Input – Output matrices are substituted with process analysis data. Dixit et al., (2010) state that input – output based hybrid analysis is considered complete and nearly perfect in the life cycle analysis of buildings.

Due to the simplicity and ability to find data, process analysis is most commonly used (Gunawardena, 2013). One of the main requirements of the input-output method is the energy usage at various sectors of the economy and comprehensive data of them tough to find in Sri Lanka (Dissanayake, Jayasinghe, & Jayasinghe, 2017). Hence the use of input-output method is not possible. Hybrid method is a combination of process method and input-output method. Therefore, hybrid method also cannot be used due to lack of data , since it is a combination of input-output method and the process analysis method (Dissanayake et al., 2017). Furthermore, in considering the resource and data available in Sri Lankan construction industry, process analysis is better(Dissanayake & Jayasinghe, 2015).Therefore, in considering these things and the outcome of expert interviews (refer chapter-4), process analysis was selected for this research. After selecting the Embodied Energy/ Embodied Carbon analysis method it is better to go through the Embodied Energy analysis of building materials.

2.9 Embodied Energy analysis of building materials

Materials use in buildings are mainly concrete, wood, bricks and sandstone (Cabeza, et al., 2013). Each building material consumes energy and releases GHG emissions during its production (Dumani, 2009). Furthermore, the environmental sustainability of building materials is really important (Dimoudi & Tompa, 2008). According to the author, this is because the choice of building materials determines the energy required for the construction of buildings as well as other environmental implications. Having different Embodied Energy intensity values for different materials is also a reason for it and Embodied Energy intensities of some construction materials are shown in table 2.2.

Table 2. 2 Energy intensity values of some construction materials.

Materials	Energy intensity(MJ/kg)	Source
Aggregate	0.11	SL
River sand	0.08	SL
Alluminium	1.55	SL
Cement	4.9	ICE
Cement motar	2.55	SL
Ceramic tiles	12	ICE
Bricks	2.3	SL
Steel	35.1	IND

Source : (Dissanayake & Jayasinghe, 2015).

Above table is a composition of few data bases and it can be used to calculate Embodied energy of building materials (Dissanayake et al., 2017). Here, the Embodied Energy of 1kg of aggregates has estimated through the work studies of diesel (fuel) usage and electricity usage of crusher plants (Dissanayake & Jayasinghe, 2015). Therefore, according to the table 2.2, it is consumed 0.11 MJ/kg of energy to make aggregates. It is needed to keep in mind that this energy component is only for the extraction and manufacture of aggregates, it doesn't represent the whole energy component of aggregate, that represent the energy consumption from mining to transportation of manufactured aggregates to the construction site (Reddy & Jagadish, 2003). If those extraction of aggregates are mined and manufacture manually (without using fuel and electricity) energy intensity value becomes 0 MJ/kg. This is proved since energy in a stone block is 0 MJ (Reddy & Jagadish, 2003). Furthermore, above table has stated that the energy intensity of cement is 4.9 MJ/kg. Moreover, it is known that cement is produced from natural products like sea shells. Therefore, energy intensity of cement represents the energy consumes in mining those natural products, bringing them to the cement factory and manufacturing cement from those mined materials (Reddy & Jagadish, 2003).

Then, it is needed to consider the Embodied energy in transportation of manufactured materials (finished product) and it includes the transportation of the product to and within the site (Dissanayake et al., 2017). Table 2.3 shows the energy consumption of some of the vehicles commonly use in construction.

Table 2. 3 Commonly use vehicles within a site and their energy consumption.

Vehicle	**Energy consumption**	**Unit**
25 Ton truck (while operating)	0.76	MJ/(t*km)
25 Ton truck (idle)	15.21	MJ/h
7.5 Ton truck	2.08	MJ/(t*km)
750kg mini truck	3.17	MJ/(t*km)
Container ship	0.054	MJ/(t*km)

Source : (Dixit et al., 2010).

The energy consumption values mentioned in above table are estimated with the work studies done (Dissanayake & Jayasinghe, 2015). It is better to go through an example in order to know the way of calculating the energy usage at transportation (Dissanayake et al., 2017). Lets assume, cement (weight of the cement bags are 750kg) is transported by using a 25 ton truck over a distance of 115 kms. Then the Embodied Energy incur for this work is 0.76 MJ/(t*km) ×0.750 t ×115 km = 65.5 MJ (Dissanayake et al., 2017).

After considering the Embodied Energy related to the transportation of building materials next step is to consider the Energy component of these materials within the construction. For small scale constructions, the energy usage at construction is minimized, since most of the work is labour intensive and machinery usage is minimized (Dissanayake & Jayasinghe, 2015). Nevertheless according to the author, at in-situ building construction, a concrete mixture is mainly used and grinders, bar-cutters, arc- welding plant, and electrical drill like equipments are also used. Therefore, the quantification of energy for different activities should be done through work studies (Dissanayake et al., 2017).

Next, it is needed to consider the Embodied energy of building materials within the use phase. A large variety of materials are being used in building construction and some of them have a life span less than of the building’s (eg -: paints) (Ramesh et al., 2010). According to the author, they are replaced with the time due to that reason. In addition to this, buildings require some regular annual maintenance. The energy incurred for such repair and replacement needs to be accounted during the entire life span of the buildings (Haynes, 2013). That energy is called Recurrent Embodied energy and according to Ramesh et al.,(2010) it can be expressed in following manner.

$$EE_r = \sum m_i.M_i \left[\left(L_b/L_{mi} \right) - 1 \right]$$

EE_r = Recurring Embodied Energy of the building , L_b = Life span of the building , L_{mi} = Life span of the material, m_i = Quantity of building material , M_i = Energy content of material per unit quantity.

Ultimately, it is needed to consider the Embodied energy of building materials within the Demolition phase (End life phase). Fay et al.,(2000) say that the Embodied Energy savings from recycling or reusing demolished materials should be attributed to the next user, not to the demolished building. Moreover, the energy required to demolish the building is generally considered to be very small compared to the rest of the life cycle energy (Bekker, 1982). Furthermore, it is confirmed by Crowther,(1999) and according to the author the energy associated with this demolition stage of a building represents less than 1% of the building's life cycle energy requirement. Therefore, the Embodied Energy component of demolition phase can be neglected within the building life cycle. After analyzing Embodied Energy within the building life cycle it is highly essential to find Embodied Carbon within the building life cycle as well.

2.10 Embodied Carbon of building materials within the building life cycle.

It has found that some building materials like concrete and aluminum are accounted much more for the carbon emissions within the life cycle of the building (Akbarnezhad & Xiao, 2017). Nevertheless, authors state that the effect for the emissions from some materials is negligible. Therefore, it is essential to distinguish the elements which affect more or less for the carbon related emissions (Lockie & Berebecki, 2012). Table 2.4 shows the elements of a building which affect more for the carbon related emissions.

Table 2. 4 Elements of the building that affect a lot for the carbon related emissions.

Component of the building	**Carbon critical elements**
Substructure	Foundation
	Retaining walls of Basement
Superstructure	Frame
	Upper floors
	Roof
	Stairs and ramps
	External walls
	Windows and external doors
	Internal walls and partitions
Internal finishes	Wall finishes
	Floor finishes
	Ceiling finishes

Source : (Lockie & Berebecki, 2012).

In analyzing the table 2.4, it is needed to keep in mind that these elements should be measured with its net quantity **(**e.g. area that covers by the doors and windows should be deducted in measuring the area of external walls) (Lockie & Berebecki, 2012). However, carbon critical elements of various types of buildings are quiet tough to distinguish (VICTORIA, PERERA, & DAVIES, 2015). Further, according to the authors it is also assumed that the hierarchy of carbon critical elements might change from building to building with some sort of changes. Next, lets consider the Embodied Carbon of materials at each stage of the building life cycle.

2.10.1 Product stage (manufacturing stage).

As previously discussed (under the sub section - stages of building life cycle) manufacture stage includes the processes/activities called raw material extraction, transport them to the factory, manufacture the products. Therefore, Embodied Carbon within the manufacture stage means the Carbon emissions from these processes/activities (Zhang & Wang, 2016). It is better to go through and example to understand it and lets consider a brick. Embodied Carbon emissions from a brick within these processes (activities within the manufacturing phase) can be stated as below (Lockie, 2013).

- Embodied carbon emissions within these processes/activities (kg CO_2e) = {Weight of a brick(kg)* Embodied Carbon factor of a brick (kg CO_2e/ kg)}

Here, carbon emissions within the transportation also can be gained in a similar manner.

- Embodied carbon in transportation (kgCO_2e) = distance from the manufacturing place to the store (km) * fuel consumption (liter/km) * carbon conversion factor of fuel (kg CO_2e/liter).

These Embodied Carbon factor (kg CO_2e/ kg) values are taken from published (existing) data bases (Lockie & Berebecki, 2012). It is needed to keep in mind that Embodied Carbon factor of the brick represents, the carbon emissions at mining of raw materials for bricks, transport them to the brick manufacturing place, manufacturing of bricks (Lockie, 2013). Furthermore, a research by the UK government (2010) has shown that this stage is the second most significant area of carbon emissions from the entire life cycle of a building (after the operational emissions) (Akbarnezhad & Xiao, 2017). Then lets consider the carbon emissions within the construction phase.

2.10.2 Construction phase

Embodied carbon of this phase means the carbon emissions during the construction processes and other onsite, off site transportation works (Zhang & Wang, 2016). Lockie and Berebecki, (2012) has given an example to understand it properly. Lets assume, 4,500 kWh of electricity was consumed during the construction phase. Carbon conversion factor of electricity is 0.6 kgCO_2e/kWh. Then carbon emissions from electricity usage is (4,500 kWh * 0.6 kgCO_2e/kWh) = 2700 kgCO_2e. Anyhow, this example covers only a small part of emission within the phase of construction. After analyzing the carbon emissions within construction phase, use phase can be analyzed.

2.10.3 Use phase

It is essential to repair, replace, refurbish the buildings within their operational phases and these activities reason for the carbon related emissions (Zhang & Wang, 2016). (refer sub topic 4.4.5.4 for more clarifications). Furthermore, similar to Operational

Energy a term called Operational Carbon also meets within the use phase (operational phase) and it is needed to distinguish both Embodied and Operational Carbon clearly. Operational Carbon means the Carbon emissions associated with the energy consumption (operational energy) for the operational works of a building like lighting, cooling etc. (Lockie, 2013). Moreover, Lockie and Berebecki, (2012) have given an example to understand the Embodied Carbon within this stage. Lets assume that the tiles of an office should be replaced every 10 years time and the life span of the building is 60 years. Here, in replacing tiles for every 10 years time, existing tiles should be removed and new tiles should be brought to the place and fixed (replacing is done manually- assumption). Energy is consumed in these processes and carbon emissions are also happened. Therefore,

- Carbon emissions in replacing tiles (kg CO2e) = {number of replacements (60/10) * floor area (m^2) * carbon conversion factor of tiles (kgCO2e per m2)} +{ carbon emissions within the transportation of materials}.

Relevant conversion factors can be gained from published databases (Dissanayake et al., 2017). Then, it is needed to consider Embodied Carbon within the End life (demolition) phase.

2.10.4 End life phase.

Basically, end of life emissions include the emissions due to the demolition, transportation of demolished things, waste processing and disposal of the waste (Gronvall et al., 2014). This is evident by Zhang and Wang, (2016) and according to them Embodied Carbon within the demolition phase means the Carbon related emissions associated with demolition, materials/waste transportation, processing and disposal. Furthermore, it is advised to neglect the emissions within the demolition phase, if there is no any planned schedule for the demolition process (Lockie & Berebecki, 2012). According to the author, difficulty of gathering data is also a reason for this. If relevant data is available , Embodied Carbon within this stage also can be calculated similar to other stages (VICTORIA et al., 2015). After knowing about the Embodied carbon within the building life cycle, it is needed to search for strategies in minimizing energy usage and carbon related emissions.

2.11 Strategies to reduce the Embodied Energy of buildings.

The environmental impact of building materials is caused during their whole life cycle (Unalan, Tanrivermis, Bulbul, Celani, & Ciaramella, 2016). It is very important to select the lowest environmental impact building products for the construction processes (Chen, Burnett, & Chau, 2001). The low carbon and low Embodied Energy materials (which are used for the construction) are really essential in reaching towards a sustainable environment (Alwan & Jones, 2014). That overview urges the designers to decide what materials are suitable in terms of sustainability perspective (Chastas et al., 2016). Actions that can be taken in reducing Embodied Energy within the life cycle are mentioned below.

- Adopting for the alternative materials with low Embodied Energy content(Dixit et al., 2010).
- Reducing the material quantity which is used in the construction process (McAlinden, 2015). According to the author it reasons for the minimization of Embodied Energy usage.
- Designing the buildings by allowing them to reuse and deconstruction. (McAlinden, 2015). Moreover, according to the author, reusing the materials at the end of the life span of a building reasons for energy savings.
- Designing the buildings by allowing them to adopt for any of the purpose in future with minimum changes to the building (McAlinden, 2015).
- Waste minimization- it has found that nearly around 120 million tons of waste are generated within a year from construction industry (Langdon, 2009). These waste are responsible for 22% of Embodied Energy in whole construction (Hammond & Jones, 2008).
- Constructing buildings which are having an excellent energy efficiency (Pacheco-Torgal, Faria, & Jalali, 2013).

In order to reduce the carbon related emissions of construction it is significant to care the embodied energy that is Embedded in materials and the process (McAlinden, 2015). This leads for the concept of Embodied Carbon.

2.12 Strategies of reducing Embodied Carbon emissions within the building life cycle.

Numerous researches have been conducted all around the world to investigate various strategies with the expectation of reducing the Embodied Carbon of buildings (Akbarnezhad & Xiao, 2017). There are various things that can be done in order to minimize these carbon emissions and they are mentioned in detail below.

- Going for alternative building materials.
  It has been found that nearly around 47% of GHG emissions (within the manufacturing phase) can be removed with the replacement of fly ash, recycled aluminum and recycled steel (Biswas, 2014). In supporting this Damgaard, Larsen, and Christensen, (2009) also utter that the substitution of new aluminum with recycled aluminum, reasons for the reduction of GHG emissions in a large amount.
- Reusing and recycling are motivated through the designing procedure of the construction to reduce the wastages (Lupisek et al., 2015). With the minimization of waste and adopting for both reusing and recycling, energy usage for these processes can be reduced and it results for the minimization of carbon emissions as well (Lockie & Berebecki, 2012).
- Due to the higher usage of nonrenewable energy, GHG emission also has become high. Therefore, no other option other than using renewable energy (De Wolf, Pomponi, & Moncaster, 2017).
- Designing the building by allowing it to use for any of the purposes with minimum changes (Su & Zhang, 2016). It really helps to reduce the energy usage for the processes (future refurbishments) and in other words it reasons to minimize the Embodied Carbon in refurbishment processes (Lockie & Berebecki, 2012).
- Adopting for the use of systems and products with long life spans (Zhao, Wang, Zhang, Liu, & Ahmad, 2016). According to the authors due to this long period of the life span both maintenance and refurbishments become less. It reasons for the minimization of Carbon related emissions.

Similarly, lots of other strategies are implemented and investigating for the betterment of the world in recent years and it has become a good practice to have energy related measurements (eg -: energy audits) with sustainability consultants for the construction projects (Gronvall et al., 2014). Anyhow, it has become a must to find solutions in reducing both Embodied Energy and Carbon for the betterment of the future generation.

2.13 Literature model.

The literature model was created with the findings of literature review. Overview of that literature model is shown in annexure as appendix C. In analyzing that model, it starts with a specific simple question, "What is meant by Embodied Energy and Embodied carbon?". The answer is given through the findings of the literature review. Next, importance of both Embodied Energy and Embodied Carbon is discussed. Significance of them is emphasized through the quotations from few authors. After discussing the importance of both Embodied Energy and Embodied Carbon, the stages of building life cycle are identified and Embodied Energy and Embodied Carbon within those stages are analyzed. Process analysis, Input output analysis and Hybrid analysis are used for this analysis. The outcome of this analysis leads for the strategies of minimizing both Embodied Energy and Embodied Carbon.

2.14 Summary.

Chapter two was mainly focused on identifying the existing literature on this research area. The literature over the relevant subject area was gathered through local and foreign researches, books, conference papers and other reliable sources. Initially, it was found that the global population is increasing rapidly and it has made a massive demand for the basic human needs. Therefore, all the governments in the world are focusing to increase their developments to facilitate the human needs. Therefore, it has increased the construction works as well. Moreover, construction reasons for massive use of energy sources and emit tons of gases to the environment. Therefore, there is an increasing awareness towards the reduction of excessive energy usage and emissions associated with construction. Most importantly these have urged the researchers to study the concepts of EE and EC within the building life cycle. The energy associated with raw material mining to demolition excluding the operational works of the building is referred to as Embodied Energy and the carbon related emissions associated with the same processes is known as Embodied Carbon. Moreover, as it was found from literature EE and EC are significant throughout building life cycle and there are very less number of researches available in Sri Lanka towards these two concepts. After emphasizing the significance of EE and EC, the stages of building life cycle were identified. As per the existing literature, majority of the authors have categorized the building life cycle into four stages as manufacturing stage, construction stage, operational stage (use stage) and demolition stage. Further, energy usage and emissions within the building life cycle is not depend on the stage categorization and it is a constant value for the considered life cycle boundary. Next, both EE and EC within those stages were discussed in detail. Ultimately, the strategies use in reducing both EE and EC within the prevailing construction industry were discussed and model was created as a summary of literature findings. The next chapter has described the research methodology of this research.

CHAPTER 3

3.0 RESEARCH METHODOLOGY

3.1 General.

After completing the literature chapter, research methodology was described within this chapter. Research methodology is a systematic way to solve a problem. It explains a way to carry out the research as it reaches the expected output. There, the research process was explained first. Basically, it talked about the overall procedure of the research and the way of conducting the research. Next, this chapter addressed the research design which was consist of the research approach as well as the research technique. Data collecting techniques and data analysis techniques came to the stage as the next steps. Eventually, conclusions and recommendations were made with the outcome of the analysis. All the steps that come under research methodology were described in detail below.

3.2 Research Design.

Yin, (2009) utters that research design is a systematic process which consists the way of planning and executing the research and ultimately solving the research problem. Furthermore, according to the author, research design is a systematic procedure which helps to reach from 'here' to 'there', where 'here' is the identified research problem and 'there' means the answer found for it (Yin, 2009). In considering the research design of this research, the researcher investigated the significance of Embodied Energy and Embodied Carbon within the building life cycle by conducting expert interviews and a case study for the roofing materials available in Sri Lanka. In analyzing more and more, Saunders, Lewis, and Thornhill, (2009) declare that in order to attain aims and objectives of a research through the research design, both research approach and techniques should be identified well.

3.3 Research Approach

Basically there are three research approaches as, quantitative, qualitative and mixed approach (Creswell, 2007). In considering Quantitative research method it maximizes the objectivity and generalize the findings (Harwell, 2011). Moreover, numerical data are concerned more comparing to descriptive data under this method (Sibanda, 2009). Saunders, Lewis, and Thornhill, (2009) explained that, qualitative research approach allows the researcher to assess opinions, behaviors and find new relationships. According to Harwell (2011) the mixed method combines the quantitative and qualitative methods and ultimately bridges the differences of those two methods. In peeping to Embodied energy and Embodied Carbon it was a novel concept to the Sri Lankan construction industry. Therefore, the ideas of the experts in the industry were really productive in fulfilling the research objectives. Bricki and Green, (2007) denote that, if the researcher requires the experience of people and their different perspectives, then qualitative research should be selected. Nevertheless, when seeking the significance of both EE and EC of roofing materials within the building life cycle, it was needed to calculate the EE and EC values of the roof element (within each phase of the life cycle) in order to come to a conclusion through those results. For that, quantitative approach was also essential. Therefore, in considering all the above facts it was better to go for mixed approach for this research. After selecting the best approach, the next step was to study the research techniques.

3.3.1 Research Techniques/Methods.

According to Thurairajah, Haigh, and Amaratunga, (2007) both data collection and data analysis are included in Research techniques. Basically, a number of data collection and analysis techniques are used in researches and it depends on the type of research (Saunders et al., 2009).

3.3.1.1 Data collection techniques

In accordance with Harrell and Bradley, (2009) there are six types of data collection methods and they are survey, interviews, focus group, observation, data extraction and secondary data sources. In accordance with this research, first of all qualitative data was collected from twelve experts in this research area and quantitative data relevant for the calculation of EE, EC and cost (initial and maintenance) values of roof element were gained through a case study. Further, work studies, observations, desk study, questionnaire survey were used to gather data for this case study. These methods and the type of data collected were discussed in detail below.

Expert Interviews

Basically, there are three types of interviews as structured, semi-structured and unstructured (Macdonald & Headlam, 2011). They have described in detail below.

- Structured Interviews- A group of specific questions prepared according to systematic way.
- Semi-structured Interview- Except following specific questions, a framework is followed here.
- Unstructured Interviews- Rather than following predetermined questions or a framework just continue the interview according to the situation.

As it was mentioned earlier EE and EC was a new as well as a comprehensive area. Therefore, going for unstructured interviews without having predetermined procedure and predetermined questions was quiet immaterial. Next, it was needed to have predetermined questions (specific) to clarify the validity of the literature findings. Not only that, but also in order to have the opinions of the interviewees towards the topic other than the literature found, questions within the scope of the research topic were also prepared. Therefore, semi – structured interview method was selected to conduct the expert interviews of this research. Furthermore, interviews can either be carried out over the phone, through emails or face to face (Harrell & Bradley, 2009). For this research, twelve interviews were conducted in face to face manner and one was conducted via email. After conducting the interviews, a case study was carried out.

Case study

Case study gives a researcher to examine the data in a close manner and in most cases, this study covers a specific area (Zainal, 2007). Most importantly, this life cycle embodied energy and embodied carbon analysis were limited to permanent roofing materials of residential buildings. In accordance with the census statistic data clay tile, asbestos sheet and concrete are the permanent roofing materials use for residential purposes (Department of Census and Statistics, 2019). Therefore, a process analysis for these permanent roofing materials Conventional Clay Tile – (406.5 mm x 254 mm), Modern (Fully Automated) Clay Tile –(310 mm x 307 mm), Asbestos Sheet (2.5 m x 1.09 m) and Concrete-125 mm thick slab) was conducted for their life cycles.

Most importantly a house model was used for the calculation of EC values of the roof within each phase across the life cycle. Ministry of Housing and Samurdhi department of Sri Lanka has designed and developed a low cost house model and has constructed these houses all over the country. In accordance with this research, a case study was conducted for a base house model (situated in Katubedda, Colombo area). Plan view of that house model is shown within the figure 3.1.

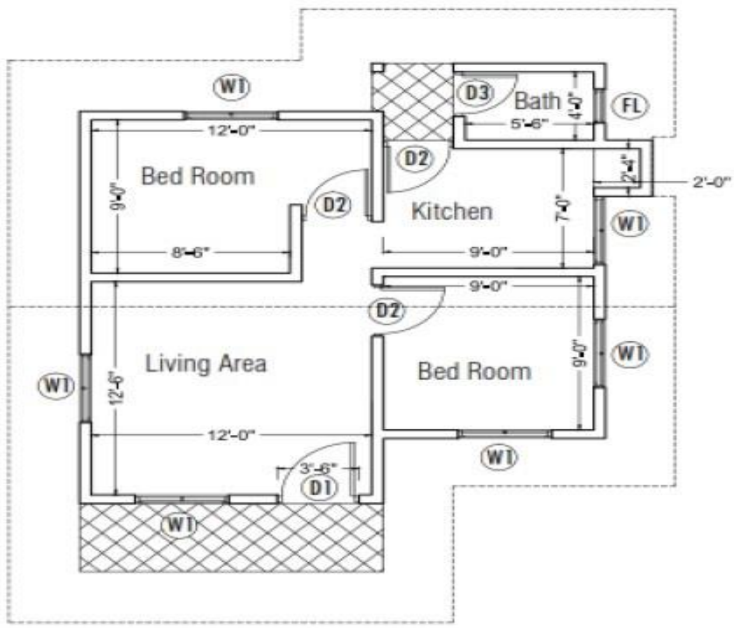

Figure 3. 1 Plan view of the model house.

Source: (Udawatta and Halwatura, 2017)

This model house was used for the calculation of EE, EC values of that roof element within the roof's life cycle, and to calculate the initial and maintenance cost values of it as well. This was done for the comparison of these four roofing types in terms of

EE, EC and initial and maintenance cost. Then, the methods used for the collection of details for the case study were described under the same heading which is “case study”.

- Work studies.

  In order to collect data for the calculation of EE and EC values of roofing materials within their life cycle, it was needed to visit raw material mining places, product (e.g: clay roof tile) manufacturing places and needed to observe the transportation methods and the transportation distance of these as well. Therefore, work studies and relevant observations were needed to collect these details.

- Desk study

  Desk study is a method of collecting data through secondary sources like journals, books, annual reports and other published documents (Dawson, 2002). Other than for the literature survey, data was collected through this study since those data were needed for the calculation of EE and EC values of the roofing types. In explaining this further, some EE and EC intensity values (refer table 2.1) had to be gained from existing databases for some EE and EC calculations due to the difficulty of calculating those intensity values from process analysis (e.g. :- if a vehicle can travel 50 kms from one diesel liter and if it has already travelled 20 kms, in order to calculate the EE incurred with the transportation, energy intensity value of diesel (35.9 MJ/L) is needed).

- Documentary review

  In order to gain some data for the case study, a documentary review was also done. In explaining this further, since the researcher has considered roof materials for his case study, it was needed to know cost details and the quantities of material for the calculations of initial and maintenance cost values for the roof. Therefore, norms and rate breakdowns of all four roof materials were gained from four C1 contractors and an average value gained from them was considered for the calculations. After knowing about the methods of collecting data, analyzing methods of those collected data were discussed next.

3.2.2.2 Data analysis techniques

After collecting data, data analysis should be carried out (Saunders, Lewis, & Thornhill, 2009). Therefore, next vital step was to analyze the data which were collected.

Content analysis

This analysis was carried out in order to analyze the data collected from expert interviews. There, the data collected were analyzed comparing with literature findings. Furthermore, all the data were analyzed manually. Next, the analysis method which was used for the analysis of case study data was discussed.

Analysis of case study data.

After collecting the data regarding the roof materials within the case study, relevant EE, EC and cost calculations were done. Moreover, a house model was adopted for the calculations of EE, EC and initial and maintenance cost. Ultimately, table 3.1 was prepared out of the outcomes gained from the calculations.

Table 3. 1 Arrangement of the collected data regarding the selected roof types.

Roofing type	Initial & Maintenance cost (Rs.)	EE within the life cycle (MJ)	EC within the life cycle ($kgCO_{2e}$)
Eg: Conventional Clay tile Automated Clay tile Asbestos Concrete			

By using the table 3.1 it was capable of analyzing the alternative roofing materials in terms of initial and maintenance cost, Embodied Energy and Embodied Carbon (as highest, lowest and medium). Next, best material was selected by giving a rank. For the selection of the best material following procedure was adopted.

EE, EC and initial and maintenance cost are three different perspectives and there was no any link between each of these three parameters. In analyzing it further, which parameter should receive the priority is depend on the client. For an instance, if one client wants to finish his or her project with a minimum cost, then he or she will definitely give a higher weightage to the initial and maintenance cost other than the EE and EC. Nevertheless, if someone considers more about environmental friendliness through his or her project then he or she will give a higher weightage for EE and EC than the initial and maintenance cost. Therefore, it was needed to emphasize that the researcher hasn't introduced a black and white output (eg :- conventional clay tile is the best) and here the researcher has introduced a procedure to find the best material by giving relevant weightage. Therefore, best way to deal with this was to give equal weightage (marks) to all three parameters and it is shown in table 3.2.

Table 3. 2 Marks given for the parameters.

Parameter	**Lowest**	**Second Lowest**	**Third Lowest**	**Highest**
EE	4	3	2	1
EC	4	3	2	1
Initial & Maintenance Cost	4	3	2	1
Total	12	9	6	3
Rank	**1**	**2**	**3**	**4**

In accordance with table 3.2, if any alternative (roof type from selected four roofing types) gets 9 marks then it is the best in terms of EE, EC and initial and maintenance cost perspectives. If any alternative gets 3 marks it becomes the worst in terms of these perspectives. In accordance with these, the ranking of the roofing materials was done. Nevertheless, if any of the two alternatives get equal marks, then both of them has to be considered separately and ranked them through a further categorization by considering the priority of the client. For more clarification of the reader it was explained by using an example. Lets assume, conventional clay tile received two marks for EE, two marks for EC and one mark for initial & maintenance cost (worst in terms of initial and maintenance cost). Then, if modern clay tile received one mark for EE, one mark for EC and three marks for initial and maintenance cost, both conventional clay tile and modern clay tile have taken equal marks. Therefore, next step is to rank these two. Same procedure can be followed for that. If client considers more about cost, then automatically modern clay tile comes to the top since it is having the lowest cost (according to the example, modern clay tile has received 3 marks and conventional clay tile has received only one mark). Therefore, once again it was needed to emphasize that the researcher has introduced a procedure to follow. The user of that process can replace the given marks (weightages) with relevant marks (weightages) and get the relevant output. After identifying the ranking procedure of roofing types, research process was discussed.

3.4 Research Process.

Research process consists of several steps which have arranged in a sequential manner to carry out an effective research (Saunders, Lewis, & Thornhill, 2009). Research process of this research has shown in figure 3.2.

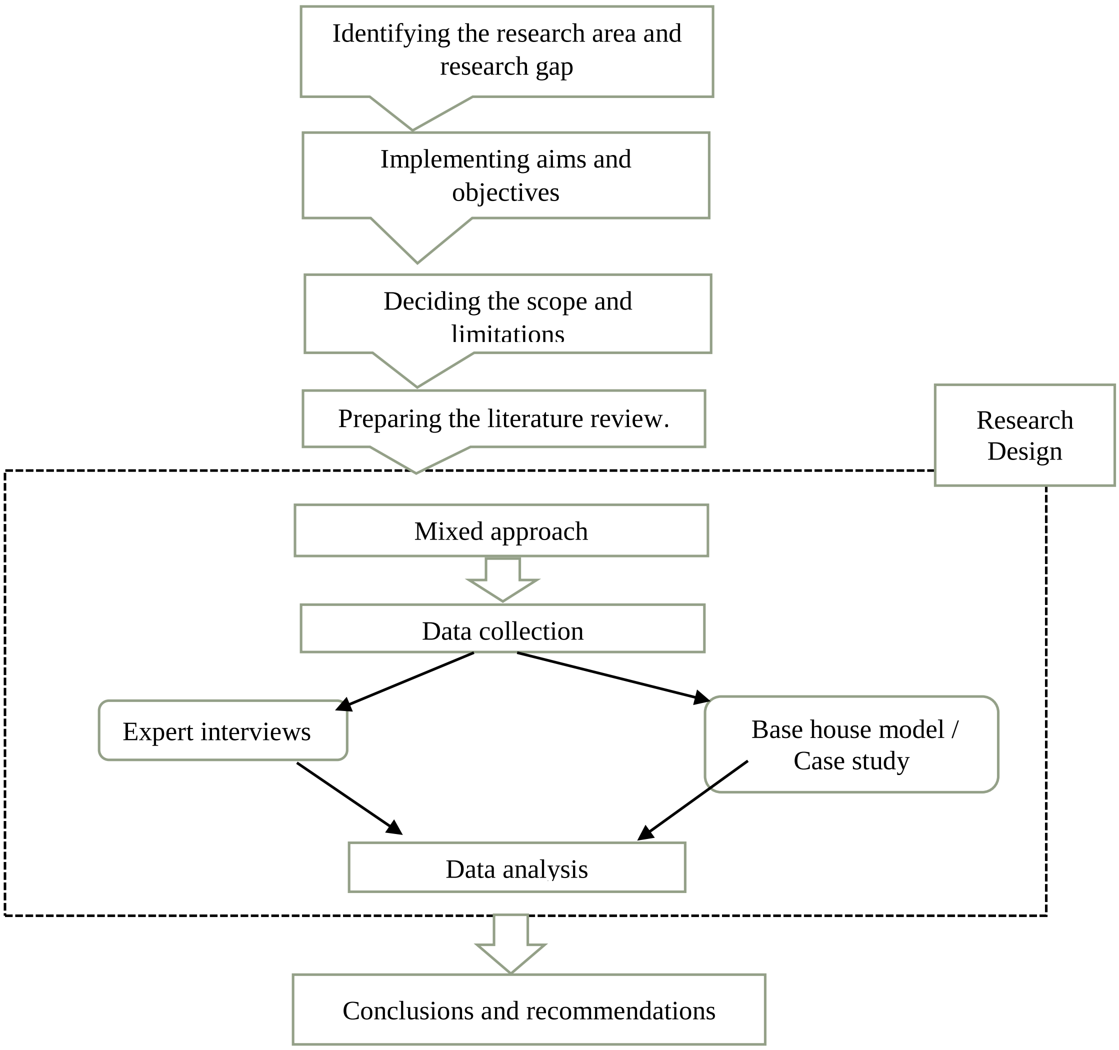

Figure 3. 2 Research process.

In explaining the steps of figure 3.2, first step (identifying the research area) has represented the activity of selecting a topic (subject area) for the research and carrying out a simple study over the selected area. Next, an existing research gap was identified under the research problem and aim and objectives, scope and limitations were implemented in order to carry on the research as well as to overcome the research problem. Then, a background study and the literature survey was done accordingly by using the secondary data sources like journals, books, internet, etc. After end of all these a crucial step, research design was begun. Briefly, this was a strategic plan of collecting and analyzing collected data in order to reach for the aim and objectives of the research. Research design process mainly includes two sections called data collection and data analysis. Both of them were discussed in detail within next chapter.

Furthermore, the calculation procedure of EE and EC of roofing materials that comes under the data analysis was discussed. Then, as the next step, with the outcome of research design, conclusion and recommendations were made. Conclusions and recommendations were mentioned under the topic number 5 and there the limitations for this research and further studies can be done were discussed.

3.5 Summary.

This chapter explained how the research problem was solved. In order to solve it properly, a proper research process was discussed throughout the chapter. With the expectation of solving the research problem by achieving the aim and objectives of the research, mixed research approach. Since EE and EC is a novel topic to the SL construction industry, in order to know the current status of these subjects, to validate the literature findings expert interviews were conducted and they were analyze through content analysis. Moreover, a case study analysis was conducted based on a model house to calculate the EE, EC and initial and maintenance cost values of selected roof materials for the study. The next chapter has discussed the research findings of this study.

CHAPTER 4

4.0 RESEARCH FINDINGS AND DISCUSSION

4.1 General

This chapter has shown the findings of the research and have analyzed them in a detail manner. In considering the findings of the research, they were basically belong to two sections called expert interview findings and case study findings. After pointing out the findings they were analyzed.

4.2 Expert interviews

Expert interviews were really essential for this research mainly due to two reasons. First of all it was needed to validate the literature findings since there were lots discrepancies between various literature sources. Next, "Significance of Embodied Energy and Embodied Carbon within the building life cycle" was one of the novel topics to the Sri Lankan construction industry. Therefore, before doing a case study analysis it was essential to know the current status of this subject in Sri Lanka and the capability of collecting data. After introducing the reasons, the researcher has moved to the objectives that covered from those interviews.

4.2.1 Objectives of expert interviews.

There were some objectives of expert interviews and they were in lined with the research objectives as well. Recognizing the significance of EE and EC was the first one and this was covered through literature review as well. Next one was to identify the building life cycle stages and EE and EC within those stages. Most importantly, these two objectives have in lined with research objectives. Therefore, it was expected to validate the findings of literature review regarding these objectives through expert interviews. Final objective of the expert interviews was to investigate the current status and the progress of EE and EC in Sri Lankan construction industry. After going through the objectives, it was better to know the experts who were interviewed for this research. It has been mentioned in detail within the subtopic 4.2.2.

4.2.2 Details of respondents.

"The significance of Embodied Energy and Embodied Carbon within the building life cycle" was a novel topic to Sri Lanka. Therefore, all most all the experts in this research area were university lecturers (since they are doing some researches regarding this subject area) and there were very limited number of experts from the industry. Nevertheless, total number of experts from both industry and universities were also limited since this is a novel area to the construction industry of SL. Therefore, level of experience was not considered in selecting interviewees and total number of interviewees were limited since there were less number of experts. Table 4.1 has shown the details of the interviewees in detail manner.

Table 4. 1 Details of the interviewees.

Interviewee	Designation	Experience in expertise area	Working environment
A.	Senior Lecturer	10 years	Academic
B.	Professor	13 years	Academic
C.	Architect	5 years	Industry
D.	Engineer	8 years	Industry
E.	Professor	15 years	Industry
F.	Senior lecturer	5 year	Academic
G.	Quantity Surveyor	4 years	Industry
H.	Quantity Surveyor	5 year	Industry
I.	Engineer	6 years	Industry
J	Architect	4 years	Industry
K	Senior Lecturer	7 years	Academic
L	Senior Lecturer	3 years	Academic

When conducting the interviews, a prepared questionnaire was given to the experts and they were free to answer for the questions with their own views. As it was mentioned under sub topic 3.2.2.1 these interviews were conducted in both face to face manner (all others except H) and via mail (only H). Furthermore, whole questionnaire was prepared with questions that cover the importance of Embodied Energy and

Embodied Carbon, building life cycle stages and Embodied Energy, Embodied Carbon within those stages and ultimately the current status and the most suited method to analyze Embodied Energy and Embodied Carbon for Sri Lankan construction industry. After collecting data from experts (interviewees) a comparison between the literature findings and the information gained from the experts were discussed in detail.

4.3 Findings of expert interviews.

Here, the findings of expert interviews were presented within the tables (refer the expert interview findings) in accordance with each objective of the interview Most importantly, for the better clarification both Embodied Energy and Embodied Carbon sections were discussed within the same table. All three objectives of expert interviews and their findings were mentioned under each sub topic accordingly.

4.3.1 Identifying the importance of Embodied Energy and Embodied Carbon.

Significance of Embodied Energy and Embodied Carbon was discussed in detail manner within the literature chapter and table 4.2 was prepared by including both literature and interview findings. In order to analyze the views of the experts (interviewees) effectively, their response for each of the finding was mentioned in front of the relevant finding. It would give a clear over view to the reader about the general idea of most of the experts. All these things were clearly mentioned within the table 4.2. Most importantly, table 4.2 includes a column named “interview findings” and it represents the ideas which came to the stage through interviewees’ itself. There, “√” mark has been used to interpret the interviewees who raised the same or similar idea to the interview finding. If he or she didn’t raise anything, a blank space () was kept and if someone didn’t agree or raised something completely different to that “x” mark was used.

Table 4. 2 Findings regarding the significance of EE and EC.

Heading	Literature Findings	Interview findings	A	B	C	D	E	F	G	H	I	J	K	L
<u>Embodied Energy</u> Embodied Energy of a building.	Embodied energy of a building is the energy consumed by all of the processes associated with raw material mining to demolition (Ciravoglu, 2005).	EE is the summation of energy exerted in all the processes (excluding OE).	√	√	√	√	√	√	√	√	√	√	√	√
		EE is the total amount of energy embedded to the system.	√	√	√	√			√			√		
Significance of Embodied Energy	• EE of a building is 20 -25 of its operational energy need. • EE of a building can represent up to 40% of life cycle energy of a building.	EE component is larger than the OE component in SL.	√			√		√		√	√		√	√
		Reduction of EE leads way to the reduction of total life cycle energy component.			√	√	√		√	√	√	√		
<u>Embodied Carbon</u> Embodied Energy of a building.	EC refers to sum of fuel related Carbon emissions and non-fuel related (due to the processes) Carbon emissions within the life cycle of a building (Moneaster & Symons, 2013).	EC refers to carbon related emissions from raw material mining to end of life.	√	√	√	√	√	√	√	√	√	√	√	√
		EC includes CO_2 equivalent gases (CH4, SF6) as well.	√	√	√	√	√		√		√		√	√
Importance of Embodied Carbon	• CO_2 quantity will double at the end of this century. • Buildings account for 30% of GHG emissions. • EC measurement and its mitigation is a part of minimizing building life-cycle impacts.	EC component is comparatively high in SL.			√	√	√		√	√		√		
		Minimizing EC affect a lot for the reduction of life cycle emissions.	√	√		√	√	√	√	√	√	√		√

Table 4.2 has clearly shown a comparison between the literature findings and the findings gained from interviewees. There, the Embodied Energy section has stated at the beginning and Embodied carbon section has mentioned then.

Briefly, all the experts had a similar kind of view regarding Embodied Energy of a building. Further, in comparing it with the literature findings it seemed that the idea gained from the experts was coincide with what literature had mentioned. Next, as the experts said in comparing with Operational Energy, EE component is really significant for a country like SL. Simply because, space heating is not necessary and less air conditioning is used in Sri Lanka comparing to other countries. Therefore, according to the experts, if it is capable of controlling EE component, it will lead to a massive energy saving. After discussing the significance of EE, EC section was discussed.

All the experts except F, H, I and J mentioned something called CO_2 equivalent gases. There they said, it is needed to consider not only CO_2 but also CO_2 equivalent gases (CH_4, SF_6 etc.) under Embodied Carbon. Literature also had pointed out this in same manner. Then, in considering the significance of Embodied Carbon, as experts uttered, since Embodied Energy is higher than the Operational Energy in Sri Lankan buildings, Embodied Carbon component also higher comparing to Operational Carbon component. The reason is EC component depends on the EE portion. Next, the second objective of expert interviews was discussed.

4.3.2 Identifying the stages of building life cycle and Embodied Energy, Embodied Carbon within those stages.

In accordance with the literature basically there are four main life cycle stages use for the analysis of EE and EC. Table 4.3 was prepared by including both literature and interview findings regarding these life cycle stages. Most importantly, table 4.3 includes a column named "interview findings" and it represents the ideas which came to the stage through interviewees' itself. There, "√" mark has been used to interpret the interviewees who raised the same or similar idea to the interview finding. If he or she didn't raise anything, a blank space () was kept and if someone didn't agree or raised something completely different to that "x" mark was used.

Table 4. 3 Findings regarding the building life cycle stages and EE, EC within those stages.

Heading	Literature Findings	Interview findings	A	B	C	D	E	F	G	H	I	J	K	L
Stages of building life cycle.	• Manufacturing phase • Construction phase • Operational phase • Demolition phase	Same stages which have been mentioned within literature findings.	√	√	√	√	√	√	√	√	√	√	√	√
		Intention of the phase categorization is for the easiness and clarity of the calculations.	√	√		√	√		√		√	√	√	
Embodied Energy and Embodied Carbon analysis methods.	• Process analysis • Input-output analysis. • Hybrid analysis.	Process analysis, input-output analysis and hybrid analysis.	√	√	√	√	√	√	√	√	√	√	√	√
		Process analysis is most suited for SL, rather than using only published database values for calculations.	√	√	√	√	√	√	√		√	√	√	√
Strategies of reducing EE within the building life cycle.	• Using alternative building materials with low Embodied Energy content. • Minimizing the quantity of materials use for the construction process. • Minimizing waste.	• Design a building as it can change for any purpose.		√		√	√		√		√	√		
		• Using materials with high durability.	√	√		√		√		√	√	√	√	
		• Reduce the transportation distance.	√	√	√	√	√	√		√				
Strategies of reducing EC	• Alternative materials can be adopted. • Using more renewable energy types where necessary. • Design as it can reuse. • Minimizing the wastage.	• Design a building as it can change for any purpose.		√		√	√		√		√	√	√	
		• Using materials with high durability.	√	√		√		√		√	√	√		
		• Reduce the transportation distance.	√	√		√	√	√	√	√				

In analyzing the table 4.3, the stages of building life cycle were discussed first. Then, the EE and EC analysis methods were pointed out and the strategies of reducing both EE and EC were mentioned. Furthermore, according to the interviewees, all them were agreed with the categorization for the building life cycle mentioned within literature. Furthermore, experts, A and D added something to this. According to them, this categorization depends on the scope of the research. For an instance, if someone considers whole building life cycle for his or her study then stages from raw material extraction to demolition of the building should be considered. If someone's study is up to the construction phase then only the stages from raw material extraction to construction are accounted. Moreover, according to the experts A and D, this kind of categorization is done with the expectation of distinguishing the energy and carbon related activities precisely. For example, manufacturing phase includes following Energy and Carbon emission activities. Raw material mining, transport them to the factory and product manufacturing. Then, construction phase includes transportation of the products to the site and construction works. As the experts said it is easy to recognize the energy and carbon related activities due to this categorization. It automatically reasons for the accuracy of the calculations as well.

Next, all the experts uttered that it is better to go for Process analysis rather than using data base values only if someone hopes do an energy and carbon analysis. The reason is data bases have published by some other countries in the world and the researchers really don't know whether the processes had used within each of the phase are same with theirs' or not. Therefore, it is better to go for process analysis rather than using data base values of another country. If not energy and carbon values may completely different with the actual. Nevertheless, if the calculation results are not that much important to the outcome of the study then it is better to use the data base values since it is easy.

Then, in considering the strategies of reducing Embodied Energy and Embodied Carbon, few points were recalled by the experts other than the points which had been mentioned under literature findings. First one was using more durable materials. If the life time of the materials are high, then it is not necessary to replace them frequently and it reduces the energy and carbon emissions in replacements. Next, designing a building with an open plan to change the purpose of the building with the time (adaptability). By following this it is easy to change a place according to the intention. For example, some office buildings have constructed as they can use as shopping complexes with some tiny changes. This prevents the construction of a new building and in other words this minimizes the energy and carbon related processes (lots of energy and carbon related processes are accounted if a building is newly constructed). Ultimately, by minimizing the transportation distance even it is possible to reduce energy usage and carbon emissions. It is quiet obvious that fuel usage of a vehicle is inversed to the distance it traveled. Therefore, it is capable of minimizing the energy usage and carbon emissions by reducing the travelling distance. After discussing about the strategies of minimizing EE and EC, current state of this area was discussed.

4.3.3 Current state and progress of Embodied Energy and Embodied Carbon in Sri Lankan construction industry.

Both EE and EC was becoming a vital topic within the construction industry of SL and Table 4.4 was prepared by including both literature and interview findings regarding the current status and the progress of this topic within the country. Most importantly, same symbolization (√, () and x) was adopted to the table 4.4 as well.

Table 4. 4 Findings regarding the current status and the progress of the topic EE and EC within the construction industry of SL.

Heading	Literature Findings	Interview Findings	A	B	C	D	E	F	G	H	I	J	K	L
Current status and progress of Embodied Energy and Embodied carbon in Sri Lankan construction industry.	• EE of some walling materials • EE analysis of precast building system.	Green building rating system, UDA certificate system has implemented.		√		√	√		√		√	√	√	
		Energy and Carbon policies.	√		√	√	√	√	√	√	√	√		v

Most importantly, there are very less number of publications regarding Embodied Energy and Embodied Carbon in Sri Lanka and according to the view of experts there is a little awareness regarding these concepts within the construction industry of SL (regarding EE and EC) and it is being improved. Furthermore, according to the experts due to the huge cost that has to bear for adhering these concepts has become an obstruct for the practical usage of these within the construction industry. Nevertheless, new energy and carbon policies, green building rating systems and Urban Development Authority (UDA) certification system are being developed within the construction industry of Sri Lanka with the expectation of enhancing sustainable construction. Due to these, there is an increasing awareness within the construction industry towards sustainability. Anyhow, according to the view of experts, still the eye towards these two concepts (Embodied Energy and Embodied Carbon) in SL is at primary stage.

4.4 Case study

This case study was consist of the details gathered from work studies, databases which had published, and by a documentary review. Then, the collected information were presented in a detail manner within the next sub topics. Ultimately, collected details have analyzed and output gained from the analysis was discussed.

4.4.1 Objective of the case study.

The intention of this case study was to fulfill the second and third objectives. After knowing about the objective of the case study it is necessary to familiar with the case which was selected for this study.

4.4.2 Introduction about the case.

This case study focused permanent roofing materials available in SL. In accordance with the census statistic data clay tile, asbestos sheet and concrete are the permanent roofing materials use for residential purposes (Central Statistics Report, 2019). Therefore, a process analysis for these permanent roofing materials (Conventional Clay Tile – (406.5 mm x 254 mm), Modern (Fully Automated) Clay Tile –(310 mm x

307 mm), Asbestos Sheet (2.5 m x 1.09 m) and Concrete-125 mm thick slab) was conducted for their life cycles.

Most importantly a base house model was used for the calculation of EC values of the roof within each phase across the life cycle. Ministry of Housing and Samurdhi department of Sri Lanka has designed and developed a low cost house model and has constructed these houses all over the country. Therefore, this house model was adopted (Katubedda was considered as the site location) for the EC calculations by replacing its roof with above four roofing materials. Further, work studies were adopted in collecting data relevant for each process including the activities such as raw material mining, transportation of those raw materials to the factory, production process of roofing material, etc. Furthermore, some specific data which were difficult to gain through work studies (e.g. EC intensity of diesel = 2.68 kgCO2/L (Lockie, 2013)) were collected through documentary reviews.

After identifying the overview of the case study, work studies and their findings have pointed out within the next sub topic.

4.4.3 Work studies.

All most all the details needed for the case study in order to calculate Embodied Energy, Embodied Carbon values were gained through work studies. Further, Embodied Energy and Embodied Carbon values within the stages of life cycle depend on the transportation distance of relevant materials. The reason is the fuel is used for the transportation and when transportation distance increases, energy and carbon values are also increased. Therefore, for the betterment of the study (for minimizing energy, carbon and cost) nearest material available places to site (Katubedda area) were considered. For an instance nearest place of conventional clay tile manufacturing places to the selected site (Katubedda area) was Dankotuwa area. Furthermore, in order to maintain the accuracy of the calculations average of the values gained were taken into consideration. For an instance, lets consider the process of conventional clay tile. Examples for some key details collected from various places through work studies were mentioned within the tables of 4.5 and 4.6.

Table 4. 5 Details taken from clay mining places.

Details	Place A1	Place A2	Place A3	Average
Details gained from clay mining.				
Number of clay cubes can be mined and loaded by a dozer.	17 Cubes	13 Cubes	15 Cubes	15 Cubes
Number of diesel liters necessary for one hour work of dozer	7.5 Cubes	8.5 Cubes	8 Cubes	8 Cubes
Mixing of clay.				
Diesel consumption of the dozer for the work of around 15 minutes.	1.5 Liters	1.5 Liters	1.5 Liters	1.5 Liters

In considering the manufacturing of conventional clay tiles, it is started with mining clay. It was needed to gain details from clay mining places and the details related to mixing of clay for the EE and EC calculation of conventional clay tiles. Therefore, details were gained from few places as it was mentioned within the table 4.5 and considered an average value for the calculations. Then, it was needed to have relevant details from pug mill process in clay tile manufacturing, the details gained from pug mill process were mentioned within the table 4.6.

Table 4. 6 Details gained form clay tile manufacturing places.

Details	Place A4	Place A5	Place A6	Average
How long will it take to work with 3 cubes of mixed clay	8.0 Hrs	8.5 Hrs	8.5 Hrs	8.5 Hrs
Number of clay tiles (before burning) have to remove from 1000 tiles	150	200	175	175

In order to calculate the EE and EC values of conventional clay tile, average values related to pug mill process and tile forming process were needed. Therefore, the table 4.6 portraits some of the average values gained from those places. Similarly, average values were gained from most of the places to minimize the errors that cause from calculations.

Next step is to calculate the EE and EC values of roofing materials with the use of collected data. Since these calculations are very lengthy, EE and EC values of conventional clay tile were mentioned within this chapter and the other calculation sheets have been attached to the annexure.

4.4.4 Embodied Energy and Embodied Carbon calculation for selected roof types (for the study).

In considering the roof element of a building, it can be categorized into few stages within it's life cycle. In accordance with the literature chapter, manufacturing the roof materials (e.g. -: clay tiles, etc.), construction phase of the roof by using those materials, operational phase of the roof and demolition stage of the roof were the stages of the roof within it's life cycle. Nevertheless, as it was mentioned under limitations, demolition phase was neglected. Therefore, the EE and EC calculations were done for all other phases except demolition phase. Step by step calculations of Embodied Energy and Embodied Carbon of conventional clay tile was explained within the appendix A. Results of the analysis were discussed in detail since next sub topic.

4.4.5 Analyzing the EE and EC results gained for the roof element (by replacing alternative roof materials).

After calculating the EE and EC values of each of the roof material, following tables and graphs were prepared. Most importantly, table 4.7 has pointed out the EE values of each roof material within the selected system boundary.

Table 4. 7 EE values of selected roof materials.

Roof type	Manufacturing phase	Construction phase	Operational phase	Total EE
Conventional Clay tile	***1,261.39 MJ***	***586.16 MJ***	***0 MJ***	***1,847.55 MJ***
Automated Clay tile	***7,826.29 MJ***	***373.83 MJ***	***0 MJ***	***8,200.12 MJ***
Asbestos sheet	***5,171.03 MJ***	***108.25 MJ***	***0 MJ***	***5,279.28 MJ***
Concrete	***19,122.49 MJ***	***839.52 MJ***	***6,887.14 MJ***	***26,849.15 MJ***

In analyzing the table 4.7, it seemed that concrete roof (flat roof) includes the highest EE, Automated clay tile roof is the second highest, Asbestos sheet roof is the third and the conventional clay tile is the lowest. This data have been graphically shown below for more clarity (refer figure 4.1).

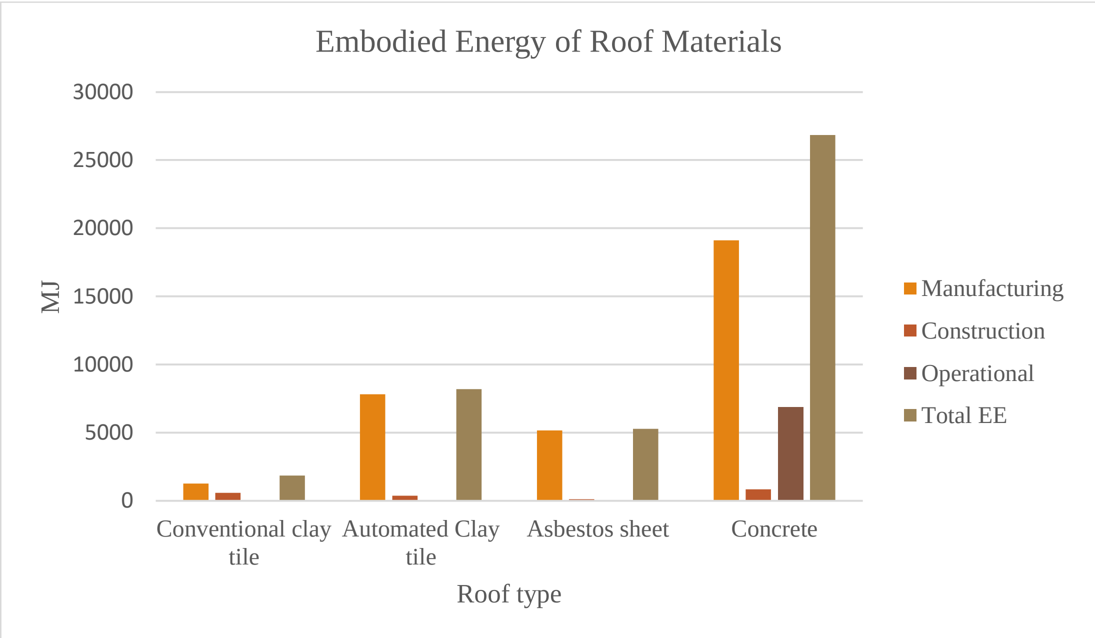

Figure 4. 1 Embodied Energy of Roof Materials

In accordance with the calculated values, it was obvious that concrete roofing is having the highest Embodied Energy within selected life cycle boundary for the study. While automated clay tile, asbestos roofing and conventional clay tile consume lesser energy accordingly. Using of high quantity of cement for concrete is the main reason for raising the Embodied Energy in concrete roofing (calculations point out that cement accounts for more than 50% of Embodied Energy of concrete roof within the manufacturing phase) comparing to other roofing types. Furthermore, LP gas is used to burn the clay tiles in automated process and as per calculations, its impact for Embodied Energy of one tile is also more than 50%. Therefore, it is possible to reduce Embodied Energy usage in automated tiles by replacing LP gas with another suitable fuel in burning process. In analyzing more and more, only concrete roofing is having Embodied Energy within the operational phase and it is due to the periodical (warranty period of most of the water proofing materials available in the market is 10 years, therefore it was considered as the replacement time gap for the calculation) replacement of waterproofing layer with protective screed on top of the roof slab. Nevertheless, since all other roofing materials are having more than 60 years of life span, recurrent Embodied Energy value of them are 0 MJ.

Next, total EC values of the selected roof materials (within the selected life cycle boundary) have been shown within the table 4.8 below.

Table 4. 8 EC values of selected roof materials.

Roof type	Manufacturing phase	Construction phase	Operational phase	Total EC
Conventional Clay tile	***156.12 kgCO2e***	***43.89 kgCO2e***	***0 kgCO2e***	***200.01 kgCO2e***
Automated Clay tile	***715.20 kgCO2e***	***27.99 kgCO2e***	***0 kgCO2e***	***743.19 kgCO2e***
Asbestos sheet	***655.92 kgCO2e***	***8.27 kgCO2e***	***0 kgCO2e***	***664.19 kgCO2e***
Concrete	***2,035.36 kgCO2e***	***83.40 kgCO2e***	***518.31 kgCO2e***	***2,637.07 kgCO2e***

In analyzing the table 4.8 it seemed that concrete roof (flat roof) includes the highest EC, Automated clay tile roof is the second highest, Asbestos sheet roof is the third and the conventional clay tile is the lowest. This data have been graphically shown below for more clarity (refer figure 4.2).

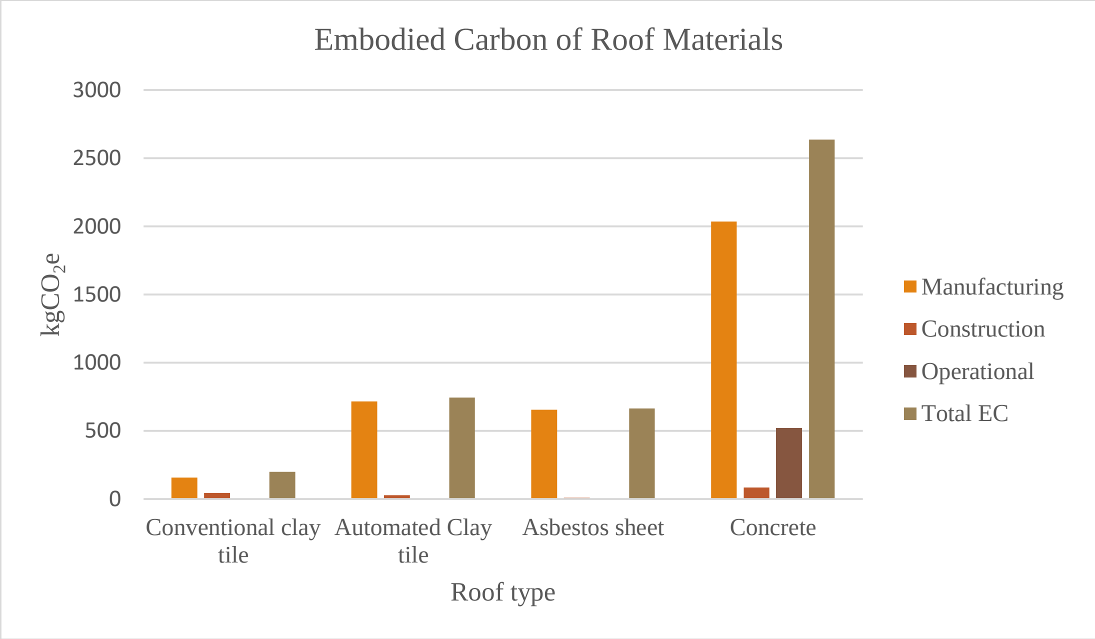

Figure 4. 2 Embodied Carbon of Roof Materials

In accordance with the calculated values, it was obvious that concrete roofing is having the highest life cycle embodied emissions while automated clay tile, asbestos roofing and conventional clay tile emit lesser accordingly. Using of high quantity of cement for concrete is the main reason for raising the embodied emissions in concrete roofing (calculations point out that cement accounts for 50% of Embodied Carbon of concrete roof within the manufacturing phase) comparing to other roofing types. Furthermore, LP gas is used to burn the clay tiles in automated process and as per calculations, its impact for Embodied Carbon of one tile is approximately 50%. Therefore, it is possible to reduce embodied emissions in automated tiles by replacing LP gas with another suitable fuel in burning process. In analyzing more and more, only concrete roofing is having Embodied Carbon within the operational phase and it is due to the periodical (warranty period of most of the water proofing materials available in the market is 10 years, therefore it was considered as the replacement time gap for the calculation) replacement of waterproofing layer with protective screed on top of the roof slab.

Nevertheless, since all other roofing materials are having more than 60 years of life span, recurrent Embodied Carbon value of them are 0 kgCO2e.

4.4.6 Initial and maintenance cost of selected roof materials for the study (conventional clay tile, fully automated clay tile, asbestos sheet and concrete roof).

In considering the construction stage, all most all the clients try to do their construction with a minimum cost. Therefore, cost has become a significant factor within the construction industry. In analyzing more and more, within the construction industry of SL, priority has given to the cost rather than the environmental friendliness. In considering the cost, initial cost is one of the most considered factors in constructing houses. Therefore, it was better to check the initial cost of these three roofing types. For the analysis of the initial cost of these roof materials, cost data were taken from four C1 contractors. Then an average price was considered as the initial cost. Table 4.9 has shown the summary of the cost data for all four roofing materials.

Table 4. 9 Initial cost of selected roof materials.

Roof type	**Contractor A**	**Contractor B**	**Contractor C**	**Contractor D**	**Average**
Conventional clay tile	Rs.475,000.00	Rs.490,000.00	Rs.460,000.00	Rs. 475,000.00	Rs.475,000.00
Automated clay tile	Rs.480,000.00	Rs.490,000.00	Rs.495,000.00	Rs.475,000.00	Rs.485,000.00
Asbestos	Rs. 395,000.00	Rs. 380,000.00	Rs. 350,000.00	Rs. 375,000.00	Rs.375,000.00
Concrete	Rs. 550,000.00	Rs.554.000.00	Rs.560,000.00	Rs. 555,720.00	Rs. 554,860.00

After calculating the initial cost of all four roof materials it was needed to calculate the maintenance cost of roof materials where applicable. Conventional clay tile, Automated clay tile, Asbestos sheets are having a life span of more than 60 years and the companies who are manufacturing these products even give a guaranty more than 60 years. Therefore, the maintenance cost is only applied for flat roof. There, a water proof layer (baralastic) is applied on top of the flat roof. Since, the warranty period of most of these water proof layers in the market are 10 years it was considered as the warranty period of this water proof layer. So, it should be replaced once in every decade. Following table 4.10 shows maintenance cost of each of the selected roof materials within the given life span.

Table 4. 10 Maintenance cost of selected roof materials.

Roof type	Maintenance cost
Conventional clay tile	Rs.0
Automated clay tile	Rs.0
Asbestos	Rs.0
Concrete	Rs. 2,698,445. 26

4.4.7 Ranking the roof types (selected for the study) in terms of EE, EC and initial and maintenance cost of them.

It was quiet obvious that EE, EC and initial and maintenance cost are three different perspectives and there was no any link between each of these three parameters. This point was evident by each of the experts even (experts who have discussed under the sub topic expert interviews). Furthermore, in order to rank these roof types it was needed to give a weightage for each of the parameters. Nevertheless, since there is no any link between each other the idea of the experts was to give an equal weightage for all three parameters. In analyzing it further, which parameter should receive the priority is depend on the client. For an instance, if one client wants to finish his or her project with a minimum cost rather than the sustainability, then he or she will definitely give a higher weightage to the initial and maintenance cost. Nevertheless, if someone considers more about environmental friendliness through his or her project then he gives a higher weightage for EE and EC than the initial cost. Therefore, here the researcher has introduced only a process and it depends on the clients' desire to decide what weightage should be given to the parameters according to the requirements of them. Given weights for each of the parameters were mentioned within table 4.11.

Table 4. 11 Weights (marks) of the parameters.

Parameter	**Lowest**	**Second Lowest**	**Third Lowest**	**Highest**
EE	4	3	2	1
EC	4	3	2	1
Initial and maintenance Cost	4	3	2	1

It is quiet obvious that if one product is having lowest EE, EC and initial and maintenance cost values then it is the best. Therefore, according to the table 4.10 if one gets 12 marks (maximum marks) it is ideal. Then, according to the total marks gained by each alternative a rank can be given. Therefore, the one gets the highest marks automatically becomes the first. Nevertheless, as previously mentioned this marking criteria (weightage) can be changed according to the requirements of the client. The results gained according to the marks stated under table 4.11 have shown within the table 4.12.

Table 4. 12 Ranking the roof types selected for the study.

Parameter vs roof	**Conventional Clay Tile**	**Automated Clay Tile**	**Asbestos sheet**	**Concrete (flat roof)**
Embodied Energy	4	2	3	1
Embodied Carbon	4	2	3	1
Initial and Maintenance Cost	3	2	4	1
Total marks	**11**	**6**	**10**	**3**

In analyzing the table 4.12 it was evident that conventional clay tile is the best as per the total marking criteria. Then, asbestos has posed as the second best as per the gained marks. Eventually, automated clay tile and concrete have gained third and fourth places accordingly.

4.4.8 Discussion over the results gained from the case study.

In considering the results mentioned under table 4.12 it was obvious that conventional clay tile was the most suitable roofing material in terms of the selected three roof materials. Since it received the rank one, there was no hesitation that it was the best (in terms of these parameters). Nevertheless, it is needed to emphasize that the gained values through the calculations can be slightly changed. In explaining it further with an example, demand for the conventional clay roof tile may increase and it may reason for the increment of the prices of conventional clay tiles in future. Then, it might not be the second cheapest among these three roofing materials. Therefore, while highlighting the gained output (for the current status) the researcher tried to introduce a procedure to find the best roofing material in terms of EE, EC and initial and maintenance cost. The person who use that procedure can reach for an unique output with the data input for the formulas of calculating the EE, EC and initial and maintenance cost values. Therefore, as the reader it is needed to focus on the procedure of selecting the best roofing material rather than the final output (e.g: conventional clay tile is the best in terms of EE, EC and initial and maintenance cost) gained from the calculations of this research.

4.5 Summary

This chapter analyzed the research findings while presenting them in a detail manner. In considering this chapter this has done a content analysis and a case study analysis regarding the suitability of roofing materials, with respect to the Embodied Energy, Embodied Carbon and initial and maintenance cost, in Sri Lankan construction industry. It was identified from the content analysis that the concern towards the Embodied Energy and Embodied Carbon within the construction industry of Sri Lanka is still within the primary stage. Moreover, the case study analysis was done by selecting four roofing materials (conventional clay tile, automated clay tile, asbestos and concrete) and conventional clay tile was posed as the best roofing material in terms of Embodied Energy and Embodied Carbon as least energy usage and emissions associated with. Moreover, asbestos was the best in terms of initial and maintenance cost and in considering all these three parameters, conventional clay tile is the best and asbestos sheet, automated clay tile and concrete were ranked accordingly.

CHAPTER 05

5.0 CONCLUSIONS AND RECOMMENDATIONS.

5.1 Conclusions

- Global population is increasing rapidly and the necessity of developments is also rising in order to facilitate the basic needs of the people.
- Construction projects have been increased all around the world and they reason for massive renewable and non-renewable energy consumption.
- Without stopping from using energy, construction reason for huge portion of global emissions.
- Building life cycle can be categorized into various stages and majority of the authors have used four stage categorization and those stages are manufacturing stage, construction stage, operational stage (use stage) and demolition stage.
- Irrespective of the stage categorization, life cycle Embodied Energy and life cycle Embodied Carbon is constant for the total life cycle.
- Embodied Energy covers a significant portion (20%-40%) of life cycle energy use of buildings.
- Embodied Carbon also covers considerable portion of life cycle emissions of buildings. Embodied Carbon becomes the decider in reaching towards a zero emission buildings.
- Reducing the transportation distance, using alternative building materials with less EE and EC, minimizing the processes, using alternative energy sources can be pointed out as strategies to reduce EE and EC.
- Researchers all around the world are focusing to reduce Embodied Energy and Embodied Carbon but there are less number of researches for total building life cycle.
- In referring to Sri Lankan context, very few number of EE and EC researches are available even for few stages of building life cycle.
- There is not an EE and EC database available for SL context.

- Process analysis, Input-Output analysis and Hybrid analysis are the three main Embodied Energy and Embodied Carbon analysis methods.
- Since we don't have Input-Output data in Sri Lanka (within the primary stage), Input-Output method is not suitable to use for EE & EC calculations in Sri Lanka. Further, since hybrid analysis is a combination of both Input-Output and Process analyses it is also not very suitable for Sri Lankan context. Therefore, Process analysis is the most suited to conduct an EE & EC analysis for SL context.
- Concern towards the Embodied Energy and Embodied Carbon in Sri Lanka within the construction industry is still at primary stage.
- In referring to roofing materials selected for the study, conventional clay tile is consuming least EE and asbestos sheet, automated clay tile and concrete consumes EE accordingly.
- Moreover, EC of all four roofing materials is also ranked similar to EE.
- In accordance with the initial and maintenance cost of all four selected roof materials, asbestos is the lowest and conventional clay tile, automated clay tile and concrete cost accordingly.

5.2 Recommendations.

It was better to start the recommendations from the place where the conclusions were ended. There the researcher has introduced a procedure while gaining (as the final result) the conventional clay tile as the best (in terms of EE, EC and initial and maintenance cost) from his calculations. Therefore, the researcher has come up with a procedure to analyze the roof materials in terms of EE, EC and initial and maintenance cost and he has developed a data sheet which can be used by any to calculate the EE, EC and initial and maintenance cost values of any roof material with their relevant inputs. Sometimes, after following the same calculation procedure even, the output (final EE, EC and cost values) might bit change due to the change of the travelling distances, travelling modes and some other processes. That's why the researcher has highlighted a procedure rather than the final output. Most importantly, this procedure can use as a guidance for the calculation of above parameters of any other building material as well.

Furthermore, while trying to do a similar kind of calculation (as the one that has shown under the analysis chapter of this research), it is compulsory to use process analysis (this has been highlighted in literature review), rather than using database values of published databases (by other countries of the world). Most frequently the processes which are used by some other countries in the world for manufacturing the products are totally different with the processes follow in Sri Lanka. Therefore, when doing a calculation with the use of those database values (published by some other part of the world), it may reason for some huge discrepancies between the actual and the calculated result.

5.3 Directions for further researches.

- Roof is a significant element of a building in terms of EE, EC and cost. Therefore, a similar kind of analysis can be conducted to find the suitability of another building element to the Sri Lankan construction industry (in terms of EE, EC and initial cost).
- Life cycle costing (LCC) is a good approach to find the suitability of the available alternatives. Therefore, a LCC analysis can be done for a building element by considering the alternatives available.
- Operational Energy and Operation Carbon analysis for this same element or any other element can be done as a separate research.

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7.0 APPENDICES

APPENDIX A

INTERVIEW GUIDELINE

Embodied Energy, Embodied Carbon and Cost Analysis for the Roofing Materials available in Sri Lanka.

1.0 General Information

1.1. Designation : ....

1.2. Experience-this research area(Years) : ....

1.3. Date of interview : ....

1.4. Venue : ....

1.5. Duration : ....

2.0 Embodied Energy

1. What do you mean by Embodied Energy?

   In accordance with the dictionary of energy, Embodied Energy is defined as " The sum of the energy requirements associated , directly or indirectly, with the delivery of a good or service" (Cleveland & Morris, 2009). It is better to go through an example to understand the concept of Embodied Energy. In considering a brick wall, its Embodied Energy is the energy needs to make the bricks, bring them to the site, lay them, plaster them and if necessary paint them within the life span of the wall (Haynes, 2013).

   Further explanations from the interviewee.

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2. Various authors have mentioned something called direct Embodied Energy and Indirect Embodied Energy. What are they? Could you please explain them by using an example?

   Further explanations from the interviewee

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3. What do you mean by Embodied Energy of a building?

   Embodied energy of a building is the energy consumed by all of the processes associated with the production of a building, from the acquisition of natural resources to product delivery, including mining, manufacturing of materials and equipment, transport and other functions related with it (Ciravoglu, 2005).

   Further explanations from the interviewee

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4. Lots of authors have talked about stages of building/ product life cycle . What is the best categorization of building life cycle in order to calculate Embodied Energy within those stages?

   Pomponi & Monacaster, (2016) have stated that the building life cycle in a different manner. According to the authors whole building life cycle consists with following stages and they are product stage, construction process stage , use stage, end of life stage . Further, these stages also have categorized into few sub sections as well. There, raw material supply, transport and manufacturing include in product stage. Construction stage consists transport and construction- installation process. Then use stage includes repair, refurbishment and replacement. Ultimately, end of life stage encompasses demolition, transportation, waste processing and disposal of those materials.

Further explanations from the interviewee

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5. In considering the Embodied Energy of building materials there is a term called energy intensity. Energy intensity of a brick is 4.25 MJ (Reddy & Jagadish, 2003). Energy intensity of cement is 4.9 MJ (Dissanayake & Jayasinghe, 2015). Energy intensity of sand 0.08 MJ (Dissanayake & Jayasinghe, 2015). Energy intensity of aggregate is 0.11 MJ (Dissanayake & Jayasinghe, 2015). Could you please explain these values (Energy consuming processes in defining these Energy intensities for the materials)

   Explanations from the interviewee

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6. Does Sri Lankan construction industry actually consider about the energy accounts in construction activities? What is the current state and progress of it?

   Explanations from the interviewee

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7. What are the strategies in reducing Embodied Energy within the building life cycle?

- Adopting for alternative building materials with low Embodied Energy content (Dixit, Fernandez-Solis, Lavy, & Culp, 2010).
- Reducing the material quantity which is used in the construction process (McAlinden, 2015). According to the author it reasons for the minimization of Embodied Energy usage.
- Designing the buildings by allowing them to reuse and deconstruction. (McAlinden, 2015).
- Waste minimization- it has found that nearly around 120 million tons of waste are generated within a year from construction industry (Langdon, 2009). These waste are responsible for 22% of Embodied Energy in whole construction (Hammond & Jones, 2008).
- Constructing buildings which are having an excellent energy efficiency (Pacheco-Torgal et al., 2013).

  Further explanations from the interviewee

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3.0 Embodied Carbon

1. What do you mean by Embodied Carbon of a building?

Embodied Carbon (EC) refers to the sum of fuel related Carbon emissions and non-fuel related (due to the processes) Carbon emissions within the life cycle of a building (Moneaster & Symons, 2013).

Further explanations from the interviewee

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2. Can we calculate Embodied Carbon? If yes, how can we calculate it?
   Further explanations from the interviewee

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3. What are the strategies in reducing Embodied Carbon within the building life cycle?

- Going for the alternative building materials.
  It has been found that nearly around 47% of GHG emissions (within the manufacturing phase) can be removed with the replacement of fly ash, recycled aluminum and recycled steel (Biswas, 2014). In supporting this Damgaard, Larsen, and Christensen, (2009) also utter that the substitution of new aluminum with recycled aluminum, reasons for the reduction of GHG emissions in a large amount.
- Reusing and recycling are motivated through the designing procedure of the construction to reduce the wastages (Lupisek et al., 2015). With the minimization of waste and adopting for both reusing and recycling, energy

usage for these processes can be reduced and it results for the minimization of carbon emissions as well (Lockie & Berebecki, 2012).

- Due to the higher usage of nonrenewable energy, GHG emission also has become high. Therefore, no other option other than using renewable energy (De Wolf et al., 2017).
- Designing the building by allowing it to use for any of the purposes with minimum changes (Su & Zhang, 2016). It really helps to reduce the energy usage for the processes (future refurbishments) and in other words it reasons to minimize the Embodied Carbon in refurbishment processes (Lockie & Berebecki, 2012).

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4. What is the view, current state and progress over Embodied Carbon in Sri Lankan construction industry?

   Explanations from the interviewee

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5. What is the best way of ranking these parameters, Embodied Energy, Embodied Carbon and Cost (initial and maintenance)

   Explanations from the interviewee.

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6. Do we have a separate EE or EC database available for the Sri Lankan context?

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7. What is the most suited analysis method to develop a database of EE and EC values for the Sri Lankan context?

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I really appreciate your contribution in fulfilling my thesis well. Furthermore, if you are interested, I am really happy to share the outcome of this research with you.

Thank you,

……………………………

Namal Anuradha.

APPENDIX B

Calculating the EE and EC intensity values (MJ and kgCO2e values) of a conventional clay tile by using the process analysis.

Here, the EE intensity value of a conventional clay tile (MJ per tile) was calculated first and EC intensity value was calculated next. For the calculation of these values, the collected data through work studies were used. Furthermore, some EE and EC intensity values (ex:- EE value of cement is 4.9 MJ/kg and EC value of cement is 0.83 kgCO2e/kg) which were not capable of calculating easily from process analysis were gained from published data bases. By using all these including the data, following calculations were done in a step by step manner for the easy reference.

Step-1 Mining Clay

Number of clay cubes can be mined and loaded within 1hr = 15 Cubes

Number of diesel liters are consumed by dozer (for 1hr) = 8 L

EE related with one hour of diesel consumption of dozer = ***8 L x 35.90 MJ/L = 287.20 MJ***. (EE intensity value of diesel is 35.90 MJ/L)

Step-1 Bringing mined clay to the tile manufacturing factory.

Conventional Clay tiles are prepared with the use of two types of clays and they are Bangadeniya clay and land clay**.** Bangadeniya clay is brought from Chilaw and land clay is brought from Dankotuwa.

Distance from Chilaw clay mining place to factory = 44 kms

Distance from Dankotuwa clay mining place to factory = 6 kms

Diesel consumption by a 1 cube sized tripper = 8 km/ L

Diesel consumption by a tripper to bring 1.5 cubes of bangadeniya clay = 22 L

Diesel consumption by a tripper to bring 1.5 cubes of land clay = 3 L

EE associated with diesel consumption = ***(22+3) L* 35.9 MJ/L = 897.5 MJ***

Step 3 - Manufacturing clay tiles

Mixing clay

First, the clay (which was brought to the factory) is hipped within the factory land. Then these clay is brought to a bin with the use of a dozer.

Dozer takes around 15 mins to bring 1.5 cubes of Bangadeniya clay and 1.5 cubes land clay to the bin (where clay is stored inside the factory for the usage).

Diesel consumption of the dozer for the work of around 15 mins = 1.5 L

EE related with the dozer for the 15 mins of work = ***1.5 L x 35.9 MJ/L = 53.85 MJ***

Here, Bangadeniya clay and land clay is mixed in 1:1 to prepare the necessary mixture. Average usage for 8 hours of work (per day) is 3 cubes of mixed clay for the manufacturing of clay tiles. Water is necessary to mix the clay and it will take around 1 h for watering.

Electricity usage of the mortar per second (mortar is used to get well water to the tank) = 1.5 kW

EE associated with electricity usage of the water mortor (within 1hr) = ***1.5kW x 1hr x 3.6 MJ/kWh = 5.4 MJ***

How long does mini dozer take to mix the 3 cubes of clay = 2.50 h

Diesel consumption of the (mini) dozer per hour (for this work) = 1.5 L

EE related with the work of the mini dozer to mix 3 cubes = ***2.5 h x 1.5 L/h x 35.9 MJ/L = 134.63 MJ***

Pug mill process

How long will it take to work with 3 cubes of mixed clay = 8.5 h

Electricity usage of the mortar of pug mill per second = 18.4 kW

Electricity usage of the pug mill to work with above clay quantity = (18.4 kW x 8.5 h) = 156.4 kWh.

EE associated with above electricity usage = ***156.4 kWh x 3.6 MJ/kWh = 563.04 MJ***

Output of the pug mill within 8.5 hrs of work (6 sets of clay) = 425

Sorting is done for the output of the pug mill and average damage (6 sets of clay) = 4

<u>Forming process</u>

Kerosene is used to make clay (each 6 set of clay) workable = 25 L

EE associated with kerosene necessity for the forming process (for 421 -6 sets of clay) is = ***25 L x 36.70 MJ/L = 917.5 MJ***

Forming machine is work with the use of electricity and its usage per second (mortar kW value) = 7 kW

One 6 set of clay can be used to form 6 clay tiles.

Time takes to form 421 - clay sets into clay tiles = 8.5 hrs

Total electricity usage for forming of 421 clay sets = 7 kW x 8.5 h = 59.50 kWh

EE associated with above electricity usage = ***59.50 kWh x 3.6 MJ/kWh = 214.20 MJ***

No of clay tiles formed from forming unit = 421 x 6 = 2526

<u>Drying manually</u>

Tiles are allowed to dry manually and when drying some tiles are damaged.

Number of clay tiles have to remove for 1000 clay tiles are 150-200 = 175

Number of clay tiles have to remove for 2526 tiles = (2526/1000) x 175 = 242

Remaining amount of clay tiles as suitable for burning = (2526 – 242) = 2084

<u>Burning</u>

It takes around 5 loads of wood to burn 15000 clay tiles (amount of tiles burn once within the kiln)

One lorry can bring one load and it consumes diesel = 8 L/ km

Wood for burning is brought from Giriulla, Narammala & Kuliyapitiya.

Average diesel consumption by one lorry for travelling (one lorry can bring only one load of wood) = 6.25 L

Total diesel consumption by 5 lorries = (6.25 L x 5) = 31.25 L

Total EE consumption for the diesel to bring wood for burning (15000 clay tiles) = ***31.25 L x 35.9 MJ/L = 1121.88 MJ***

Wood is sawed with the use of a machine and its electricity consumption per second = 7.5 kW

It takes around 8 hrs to saw 5 loads of wood & electricity usage within 8 hrs = 7.5 kW x 8 h = 60 kWh

EE associated with electricity units = ***60 kWh x 3.6 MJ/kWh = 216 MJ***

Blower machine is used to cool the kiln after removing the burned tiles from the kiln. Blower machine takes around 4hrs to cool the whole kiln and its having a mortar with 3kw.

Electricity consumption by blower = 3kW x 4h = 12 kWh

EE associated with electricity usage of blower = ***12 kWh*** x ***3.6 MJ/kWh = 43.2 MJ***

From a 15000 batch around 200 tiles are removed as damaged and others are suit for roofing of houses, etc.

How many tiles will remove as damaged tiles out of 2084 = (200/15000)*2084 = 27.79 = 28

Therefore, in order to get 2056 (2084-28) good burned clay tiles, we have to burn 2084 clay tiles.

EE associated with 2056 burned clay tiles = ((***43.2 MJ + 216 MJ + 1121.88 MJ)/14800)*2056 = 191.86 MJ***

Total EE associated with 2056 burned clay tiles = (***191.86 MJ + 214.20 MJ + 917.5 MJ + 563.04 MJ + 134.63 MJ + 5.40 MJ + 53.85 MJ + 287.20 MJ + 897.50 MJ) = 3265.17 MJ***

EE of burned one conventional clay tile = 1.59 MJ

Average weight of burned clay tile = 2.80 kg

EE of a burned conventional clay tile per kg = 1.59 MJ / 2.80 kg

= ***0.57 MJ/kg***

In analyzing the final value of this process analysis, Embodied Energy of a burned conventional clay tile from extraction of raw materials to it's manufacturing was 1.59 MJ. It is quite obvious that this value depends on varies things such as type of method use for the work (man power energy or machines), transportation method (type of vehicle use) and transportation distance. Therefore, the researcher has developed a work sheet relevant to this case study and someone else who does this analysis for a different site (situated somewhere else other than Katubedda) can use the same work sheet and change the relevant traveling distances and get the desired output.

Next, the researcher has calculated the Embodied Carbon value of block by using a similar kind of process. It has been shown in detail below. Embodied Carbon values of diesel, electricity and cement are 2.688 kgCO2e/L, 0.6 kgCO2e/kWh (Hammond & Jones, 2008).Therefore, in applying these values to the same steps used for Embodied Energy analysis, following EC values were gained.

Step-1 Mining Clay

Number of clay cubes can be mined and loaded within 1hr = 15 Cubes

Number of diesel liters are consumed by dozer (for 1hr) = 8 L

EC related with one hour of diesel consumption of dozer = ***8 L x 2.688 kgCO2e/L*** = ***21.50 kgCO2e***.

Step-1 Bringing mined clay to the tile manufacturing factory.

Conventional Clay tiles are prepared with the use of two types of clays and they are Bangadeniya clay and land clay**.** Bangadeniya clay is brought from Chilaw and land clay is brought from Dankotuwa.

Distance from Chilaw clay mining place to factory = 44 kms

Distance from Dankotuwa clay mining place to factory = 6 kms

Diesel consumption by a 1 cube sized tripper = 8 km/ L

Diesel consumption by a tripper to bring 1.5 cubes of bangadeniya clay = 22 L

Diesel consumption by a tripper to bring 1.5 cubes of land clay = 3 L

EC associated with diesel consumption = ***(22+3) L x 2.688 kgCO2e/L*** = ***67.20 kgCO2e.***

Step 3 - Manufacturing clay tiles

<u>Mixing clay</u>

First, the clay (which was brought to the factory) is hipped within the factory land. Then these clay is brought to a bin with the use of a dozer.

Dozer takes around 15 mins to bring 1.5 cubes of Bangadeniya clay and 1.5 cubes land clay to the bin (where clay is stored inside the factory for the usage).

Diesel consumption of the dozer for the work of around 15 mins = 1.5 L

EE related with the dozer for the 15 mins of work = ***1.5 L x 2.688 kgCO2e/L = 4.03 kgCO2e***

Here, Bangadeniya clay and land clay is mixed in 1:1 to prepare the necessary mixture. Average usage for 8 hours of work (per day) is 3 cubes of mixed clay for the manufacturing of clay tiles. Water is necessary to mix the clay and it will take around 1 h for watering.

Electricity usage of the mortar per second (mortar is used to get well water to the tank) = 1.5 kW

EE associated with electricity usage of the water mortor (within 1hr) = ***1.5kW x 1hr x 0.6 kgCO2e/kWh = 0.9 kgCO2e***

How long does mini dozer take to mix the 3 cubes of clay = 2.50 h

Diesel consumption of the (mini) dozer per hour (for this work) = 1.5 L

EC related with the work of the mini dozer to mix 3 cubes = ***2.5 h x 1.5 L/h x 2.688 kgCO2e/L = 10.08 kgCO2e***

<u>Pug mill process</u>

How long will it take to work with 3 cubes of mixed clay = 8.5 h

Electricity usage of the mortar of pug mill per second = 18.4 kW

Electricity usage of the pug mill to work with above clay quantity = (18.4 kW x 8.5 h) = 156.4 kWh.

EC associated with above electricity usage = ***156.4 kWh x 0.6 kgCO2e/kWh = 93.84 kgCO2e***

Output of the pug mill within 8.5 hrs of work (6 sets of clay) = 425

Sorting is done for the output of the pug mill and average damage (6 sets of clay) = 4

Forming process

Kerosene is used to make clay (each 6 set of clay) workable = 25 L

EC associated with kerosene necessity for the forming process (for 421 -6 sets of clay) is = ***25 L x 2.5404 kgCO2e/L = 63.51 kgCO2e***

Forming machine is work with the use of electricity and its usage per second (mortar kW value) = 7 kW

One 6 set of clay can be used to form 6 clay tiles.

Time takes to form 421 - clay sets into clay tiles = 8.5 hrs

Total electricity usage for forming of 421 clay sets = 7 kW x 8.5 h = 59.50 kWh

EE associated with above electricity usage = ***59.50 kWh x 0.6 kgCO2e/kWh = 35.70 kgCO2e***

No of clay tiles formed from forming unit = 421 x 6 = 2526

Drying manually

Tiles are allowed to dry manually and when drying some tiles are damaged.

Number of clay tiles have to remove for 1000 clay tiles are 150-200 = 175

Number of clay tiles have to remove for 2526 tiles = (2526/1000) x 175 = 242

Remaining amount of clay tiles as suitable for burning = (2526 – 242) = 2084

Burning

It takes around 5 loads of wood to burn 15000 clay tiles (amount of tiles burn once within the kiln)

One lorry can bring one load and it consumes diesel = 8 L/ km

Wood for burning is brought from Giriulla, Narammala & Kuliyapitiya.

Average diesel consumption by one lorry for travelling (one lorry can bring only one load of wood) = 6.25 L

Total diesel consumption by 5 lorries = (6.25 L x 5) = 31.25 L

Total EC consumption for the diesel to bring wood for burning (15000 clay tiles) = ***31.25 L x 2.688 kgCO2e/L = 84.00 kgCO2e***

Wood is sawed with the use of a machine and its electricity consumption per second = 7.5 kW

It takes around 8 hrs to saw 5 loads of wood & electricity usage within 8 hrs = 7.5 kW x 8 h = 60 kWh

EC associated with electricity units = ***60 kWh x 0.6 kgCO2e/kWh = 36 kgCO2e***

Blower machine is used to cool the kiln after removing the burned tiles from the kiln. Blower machine takes around 4hrs to cool the whole kiln and its having a mortar with 3kw.

Electricity consumption by blower = 3kW x 4h = 12 kWh

EC associated with electricity usage of blower = ***12 kWh*** x ***0.6 kgCO2e/kWh = 7.20 kgCO2e***

From a 15000 batch around 200 tiles are removed as damaged and others are suit for roofing of houses, etc.

How many tiles will remove as damaged tiles out of 2084 = (200/15000)*2084 = 27.79 = 28

Therefore, in order to get 2056 (2084-28) good burned clay tiles, we have to burn 2084 clay tiles.

EC associated with 2056 burned clay tiles = ((***43.2 MJ + 216 MJ + 1121.88 MJ)/14800)*2056 = 191.86 MJ***

Total EE associated with 2056 burned clay tiles = (***191.86 MJ + 214.20 MJ + 917.5 MJ + 563.04 MJ + 134.63 MJ + 5.40 MJ + 53.85 MJ + 287.20 MJ + 897.50 MJ) = 3265.17 MJ***

EE of burned one conventional clay tile = 1.59 MJ

Average weight of burned clay tile = 2.80 kg

EE of a burned conventional clay tile per kg = 1.59 MJ / 2.80 kg

= ***0.57 MJ/kg***

Since the manufacturing stage of conventional clay tile has already been studied, Embodied Energy and Embodied Carbon of conventional clay roof tile within the construction phase was considered next.

7.1.1.1 Embodied Energy and Embodied Carbon calculations of the conventional clay roof within construction phase.

Materials necessary to construct the roof are Clay tiles, rafters, reapers, nails, cement and sand (to lay the tiles on ridge plate).

House model: Sri Lankan basic home built over the entire island Source- National housing authority. It was considered that the site is situated at Katubedda, Moratuwa for the easiness of calculations. (all these were explained within the Methodology chapter).

Roof covering area = (Area A + Area B) * cosec angle = (248.548 + 241.158) ft2 x Cosec Q = 500 ft2.

Step -1 Bringing clay tiles to the construction site.

Travelling distance from Dankotuwa to katubedda = 64.80 kms

Number of clay tiles necessary to lay on the roof (assuming wastage is zero) = (91/100) x 500 = 455 Nr

Diesel consumption of a mini truck (8-10 km/L) = 9.00 km / L

EE associated with transportation of clay tiles to the site = ***((64.8 x 2)/ 9) L x 35.9 MJ/L = 516 .96 MJ***

EE associated with 455 conventional clay tiles = ***455 x 1.59 MJ = 722.59 MJ***

Step -2 Bringing rafters, reapers and nails to the construction site.

It was assumed that both cutting down trees and sawing them are done manually. EE value of steel is = 24.40 MJ/kg.

The weight of nails approximately necessary for the fixing of reapers and rafters = 2 kg

EE associated with nails necessary for fixing = ***(24.4 MJ/kg) x (2 kg) = 48.8 MJ***

Distance from nail manufacturing factory (Ceylon steel corporation) to Katubedda = 27.1 km

Diesel consumption of a lorry (7km/L) to bring nails (1000 kg) from Ceylon Steel Corporation to Katubedda = ((27.1 x 2) / 7) = 7.74 L

EE associated with diesel consumption of a lorry to bring 2 kg of nails from factory to Katubedda = ***((7.74 L/1000) x 2)*** x ***35.9 MJ/L = 0.56 MJ***

Step - 3 Bringing cement and sand necessary for ridge plate.

Cement is brought to the site (katubedda) from Puttlam cement factory and distance = 171 kms

Basically cement is distributed to hardware from factory through lorries that can load around 400 bags of cement.

Diesel consumption by a lorry = 5 km / L

Diesel consumption to bring 400 bags of cement to hardware = (171 x 2) / 5 = 68.4 L

Diesel consumption to bring only 2 bags of cement from Puttlam factory to the hardware at Katubedda = 0.34 L

EE associated with diesel consumption to bring two cement bags to the site = ***0.34 L*** x ***35.9 MJ/L = 12.28 MJ***

EE associated with cement necessary for tile laying = ***2 x 50 kg x 4.9 MJ/kg = 490 MJ***

Sand is brought to hardware situated in Katubedda from Manampitiya and they are mined from river manually.

Distance from Manampitiya to Katubedda = 254.00 kms

Diesel consumption by 3 cube size trippers = 8 km / L

Diesel consumption to bring 3 cubes = ((254 x 2)/ 8) = 63.50 L

Sand necessity for preparation of mortar (1:3) for laying work of tiles at ridge plate = 0.21 m3 (Page 266 – ICTAD)

Diesel consumption to bring 0.21 m3 of sand to site from Manampitiya = 1.57 L

EE associated with diesel consumption to bring sand = ***1.57 L x 35.9 MJ/L = 56.37 MJ***

EE associated with sand necessary for tile laying = ***0 MJ***

Total cradle to gate EE (EE related to the manufacturing works of all relevant materials) = (***722.59 MJ + 48.80 MJ + 490 MJ + 0 MJ) = 1261.39 MJ***

Total EE within Construction Phase = ***586.16 MJ***

Therefore, EE of conventional clay tile within the manufacturing stage and construction stage are 1261.39 MJ and 586.16 MJ accordingly. Since, the life span of clay tiles are more than 50 years (as per the warranty period), EE related with operational stage becomes 0 MJ. After identifying the EE related activities within the selected boundary (Cradle to end of Operational phase) of Conventional Clay tile, EC related activities have been studied.

Step -1 Bringing clay tiles to the construction site.

Travelling distance from Dankotuwa to katubedda = 64.80 kms

Number of clay tiles necessary to lay on the roof (assuming wastage is zero) = (91/100) x 500 = 455 Nr

Diesel consumption of a mini truck (8-10 km/L) = 9.00 km / L

EC associated with transportation of clay tiles to the site = ***((64.8 x 2)/ 9) L x 2.688 kgCO2e/L = 38.71 kgCO2e***

EC associated with 455 conventional clay tiles = ***455 x 0.15 kgCO2e = 69.58 kgCO2e***

Step -2 Bringing rafters, reapers and nails to the construction site.

It was assumed that both cutting down trees and sawing them are done manually. EC value of steel is = 1.77 kgCO2e

The weight of nails approximately necessary for the fixing of reapers and rafters = 2 kg

EC associated with nails necessary for fixing = ***(1.77 kgCO2e) x (2 kg) = 3.54 kgCO2e***

Distance from nail manufacturing factory (Ceylon steel corporation) to Katubedda = 27.1 km

Diesel consumption of a lorry (7km/L) to bring nails (1000 kg) from Ceylon Steel Corporation to Katubedda = ((27.1 x 2) / 7) = 7.74 L

EC associated with diesel consumption of a lorry to bring 2 kg of nails from factory to Katubedda = ***((7.74 L/1000) x 2)*** x ***2.688 kgCO2e/L = 0.04 kgCO2e***

Step - 3 Bringing cement and sand necessary for ridge plate.

Cement is brought to the site (katubedda) from Puttlam cement factory and distance = 171 kms

Basically cement is distributed to hardware from factory through lorries that can load around 400 bags of cement.

Diesel consumption by a lorry = 5 km / L

Diesel consumption to bring 400 bags of cement to hardware = (171 x 2) / 5 = 68.4 L

Diesel consumption to bring only 2 bags of cement from Puttlam factory to the hardware at Katubedda = 0.34 L

EC associated with diesel consumption to bring two cement bags to the site = ***0.34 L*** x ***2.688 kgCO2e/L = 0.92 kgCO2e***

EC associated with cement necessary for tile laying = ***2 x 50 kg x 0.83 kgCO2e/kg = 83 kgCO2e***

Sand is brought to hardware situated in Katubedda from Manampitiya and they are mined from river manually.

Distance from Manampitiya to Katubedda = 254.00 kms

Diesel consumption by 3 cube size trippers = 8 km / L

Diesel consumption to bring 3 cubes = ((254 x 2)/ 8) = 63.50 L

Sand necessity for preparation of mortar (1:3) for laying work of tiles at ridge plate = 0.21 m3 (Page 266 – ICTAD)

Diesel consumption to bring 0.21 m3 of sand to site from Manampitiya = 1.57 L

EC associated with diesel consumption to bring sand = ***1.57 L x 2.688 kgCO2e/L = 4.22 kgCO2e***

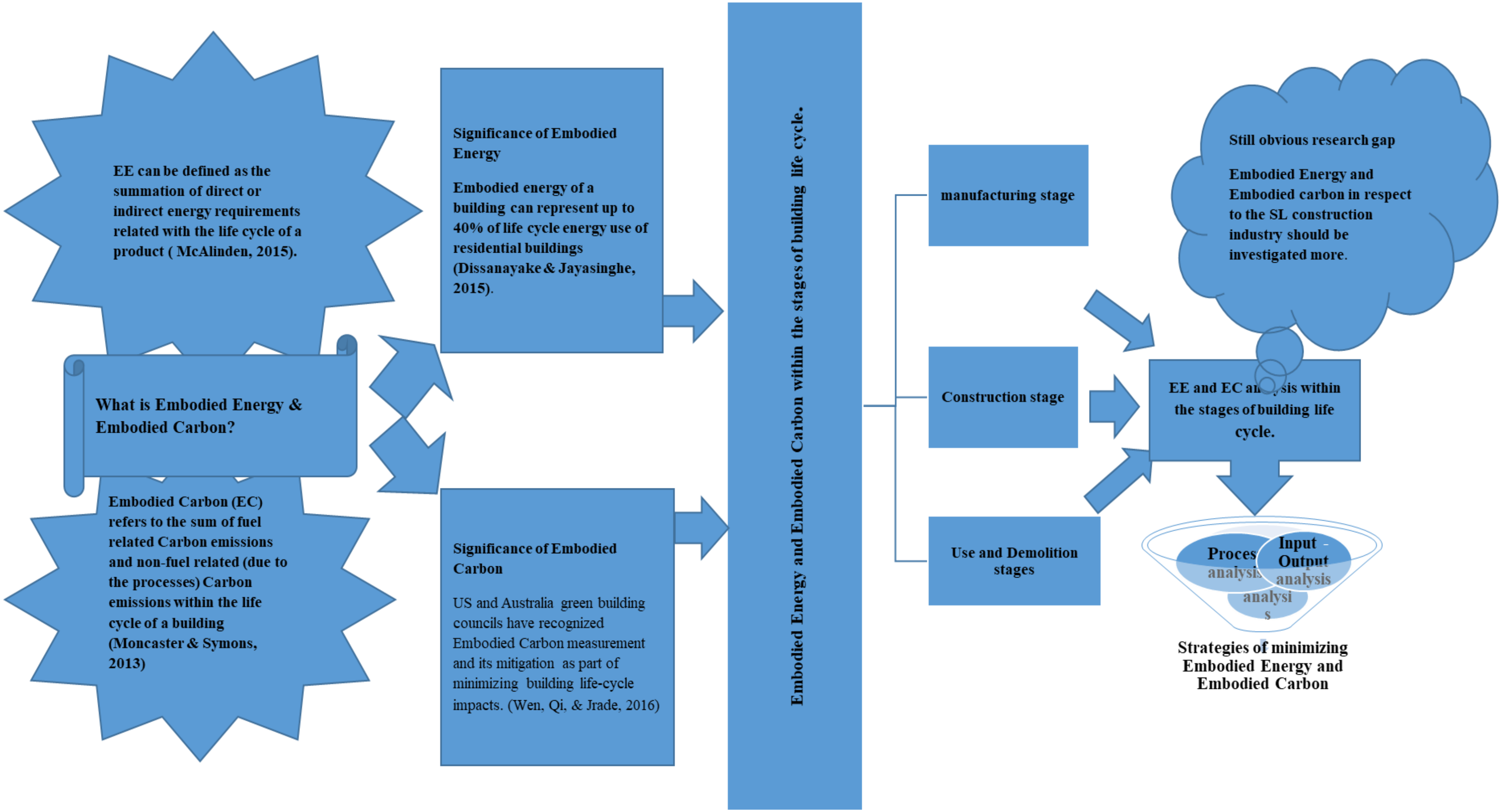
EC associated with sand necessary for tile laying = ***0 kgCO2e***

Total cradle to gate EC (EC related to the manufacturing works of all relevant materials) = ***156.12 kgCO2e***

Total EC within Construction Phase = ***43.89 kgCO2e***

Therefore, EC of conventional clay tile within the manufacturing stage and construction stage are 156.12 kgCO23 and 43.89 kgCO2e accordingly. Since, the life span of clay tiles are more than 50 years (as per the warranty period), EC related with operational stage becomes 0 kgCO2e. Therefore, similar procedure was adopted to calculate EE and EC of asbestos sheet, automated clay tile and concrete roofing.

APPENDIX C


EE can be defined as the summation of direct or indirect energy requirements related with the life cycle of a product (McAlinden, 2015).
What is Embodied Energy & Embodied Carbon?
Embodied Carbon (EC) refers to the sum of fuel related Carbon emissions and non-fuel related (due to the processes) Carbon emissions within the life cycle of a building (Moncaster & Symons, 2013)
Significance of Embodied Energy
Embodied energy of a building can represent up to 40% of life cycle energy use of residential buildings (Dissanayake & Jayasinghe, 2015).
Significance of Embodied Carbon
US and Australia green building councils have recognized Embodied Carbon measurement and its mitigation as part of minimizing building life-cycle impacts. (Wen, Qi, & Jrade, 2016)
Embodied Energy and Embodied Carbon within the stages of building life cycle.
manufacturing stage
Construction stage
Use and Demolition stages
Still obvious research gap
Embodied Energy and Embodied carbon in respect to the SL construction industry should be investigated more.
EE and EC an ysis within the stages of building life cycle.
Proces analysis
Input - Output analysis
analysi s
Strategies of minimizing Embodied Energy and Embodied Carbon