RELATIONSHIP BETWEEN EMBODIED ENERGY AND COST OF BUILDING MATERIALS: A CASE STUDY

A Thesis

by

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ABSTRACT

The annual energy consumed in building construction and operation is approximately 48% of the total energy in the United States. The total life cycle energy of buildings comprises of operational energy and embodied energy. Recent research has emphasized the significance of embodied energy and has acknowledged its relative proportion of total energy, which is growing with the emergence of more energy efficient buildings. Embodied energy is the energy utilized by building materials during production, on-site processes, and demolition and disposal. Buildings use following two types of energy consumption: Direct Energy and Indirect Energy. Lack of globally accepted embodied energy calculation method is a hindrance to establish complete and consistent embodied energy database.

The methodologies typically used for EE calculations can be classified into three types: process-based, input-output based and hybrid of these two methods. For process-based, The process starts with taking building material as a final product and works backward in upstream process, taking into account all possible direct energy inputs. Input-output based analysis is top-down approach which contains direct requirement coefficients from an economic input-output model. Hybrid analysis consists combining advantages of two methods to eliminate fundamental errors and limitations of process and input-output analysis. The current input-output hybrid methods lack specificity and reliability. Therefore, input-output hybrid model suggested by Dixit (2017) was used

which focuses on sectoral disaggregation of industry sectors to increase the specificity of results.

As economic activity is used to calculate embodied energy, there exists a relationship between embodied energy and cost. Various studies suggest a strong positive correlation between embodied energy and cost of building. Meanwhile, the strength of correlation decrease at material level. This study focused on finding the relationship between embodied energy and cost of building materials using the input-output model suggest by Dixit (2017).

After regression analysis, the strength of correlation between embodied energy (MBTU) and cost of building materials ($) was found to be strong and positive. For embodied energy per unit mass (MBTU/Kg) and cost per unit mass ($/Kg), the correlation was found to be very strong and positive.

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NOMENCLATURE

MBTU	Million British Thermal Units
EE	Embodied Energy
$	U.S. Dollar
NAICS	North American Industry Classification System

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CHAPTER I

INTRODUCTION

1.1 Embodied Energy

The energy embodied in a building includes the energy consumed directly during its construction and related processes and indirectly through the use of construction materials. (Dixit, 2017)

1.2 Introduction And Background

The increasing awareness of Greenhouse Gas emissions and natural resource shortages, public and commercial building developers are tending to move towards energy efficient buildings (Jiao et al., 2012). The total life cycle energy of buildings comprises of Operational energy and Embodied energy. The embodied energy in modern, well-insulated, energy efficient buildings can even exceed the operational energy (Balouktsi & Lützkendorf, 2016; Chang et al., 2012).

Calculating embodied energy is complicated and inconsistent (Dixit, 2017). Embodied energy is time consuming and contains complexity as standard protocol or methodology is unavailable (Dixit et al., 2012). The most important requirement for embodied energy assessment of a building is availability of relevant data and information of building materials and products which constitute the building (Balouktsi & Lützkendorf, 2016). Inaccurate, incomplete and inconsistent data cannot be used for decision making while selecting low-energy building materials (Dixit et al., 2013).

As there is growing trend towards energy-efficient or net-zero buildings, more emphasis would be on embodied energy of a building as it would contribute to a higher proportion of total life cycle energy of a building (Marszal et. al., 2011).

1.3 Problem Statement

Embodied energy calculations can be done on a project level by taking into consideration total cost of construction as well as at the cost component level by disaggregation into building materials and costs associated with labor and equipment. As calculation by disaggregation is complex, the necessity for disaggregation needs to be investigated.

Finding the relationship between energy and cost of materials in terms of correlation would help understand the dependency of embodied energy on cost

1.4 Research Questions

Is there a need to calculate embodied energy by disaggregating into building materials?

What is the correlation between embodied energy and cost?

1.5 Research Goals

To investigate the need to calculate embodied energy by disaggregation into building materials by comparing embodied energy values at project level and material level.

To investigate the correlation between embodied energy and cost.

To examine whether the variation in cost data could explain the variation in embodied energy values by simple regression analysis.

CHAPTER II

LITERATURE REVIEW

2.1 Background And Importance Of Embodied Energy

The annual energy consumed in building construction and operation is approximately 48% of the total energy consumed in the United States (Dixit, 2017). The embodied energy in modern, well-insulated, energy efficient buildings can even exceed the operational energy (Balouktsi & Lützkendorf, 2016). Construction activities, in addition to energy consumption, cause environmental pollution and emission of greenhouse gases affecting climate change. Recent research has emphasized the significance of embodied energy and has acknowledged its relative proportion of total energy, which is growing with the emergence of more energy efficient buildings (Dixit et. al., 2012; Moncaster & Song, 2012). Various countries in Europe and North America are following regional energy-reduction framework standards. In the effort to reduce the operational energy or moving towards self-sustaining buildings, embodied energy becomes that much more important in life-cycle energy analysis of buildings. The goal of nearly zero-energy buildings by 2020 means that embodied energy will be 100% of the energy footprint of buildings in Europe (Balouktsi & Lützkendorf, 2016).

The total life cycle energy of a building comprises of Embodied Energy (EE) and Operational energy (OE) (Copiello, 2016; Dixit, 2017; Dixit et. al., 2012; Jiao et. al., 2012; Srinivasan et. al., 2014). Embodied energy is the energy utilized by building materials during production, on-site processes, and, demolition and disposal. Operational

Energy is energy used to maintain the inside environment through cooling, heating, lighting and operating appliances (Dixit et. al., 2010). Measuring operating energy is easy and less complicated, but, embodied energy calculations are complex (Dixit et al., 2010).

The relative importance of production phase is likely to increase as energy phase in operating stage can be reduced by well-proven technologies (Nässén et al., 2007).

2.1.1 Direct and Indirect Energy

Buildings use following two types of energy consumption: Direct Energy and Indirect Energy (Crawford, 2004; Treloar et al., 2001) (See Figure 1). Direct Energy is consumed in various on-site and off-site processes such as construction prefabrication, transportation and administration. Indirect energy is consumed during manufacturing of building materials, upstream and downstream processes, also, during renovation, refurbishment, and demolition (Crawford, 2004; Nässén et al., 2007). Indirect energy is used to create the inputs of goods and services to the main process (Crawford, 2004).

Indirect energy is further classified into Initial embodied energy (IEE), Recurrent embodied energy (REE) and Demolition energy (DE) (Dixit et al., 2010). Initial embodied energy is the energy used during production of materials and components of a building, including raw material procurement, building material manufacturing and final product delivery to construction site (Dixit, 2017). Recurrent embodied energy is the energy used in various processes for maintenance and refurbishment of buildings during their useful life. Demolition energy is the energy necessary for deconstruction of building and disposing of building materials (Costanza, 1980; Dixit et al., 2010; Treloar, 1997). Embodied energy can only be reduced if low energy intensive materials and products are selected in its initial stages of building design (Dixit et al., 2012).

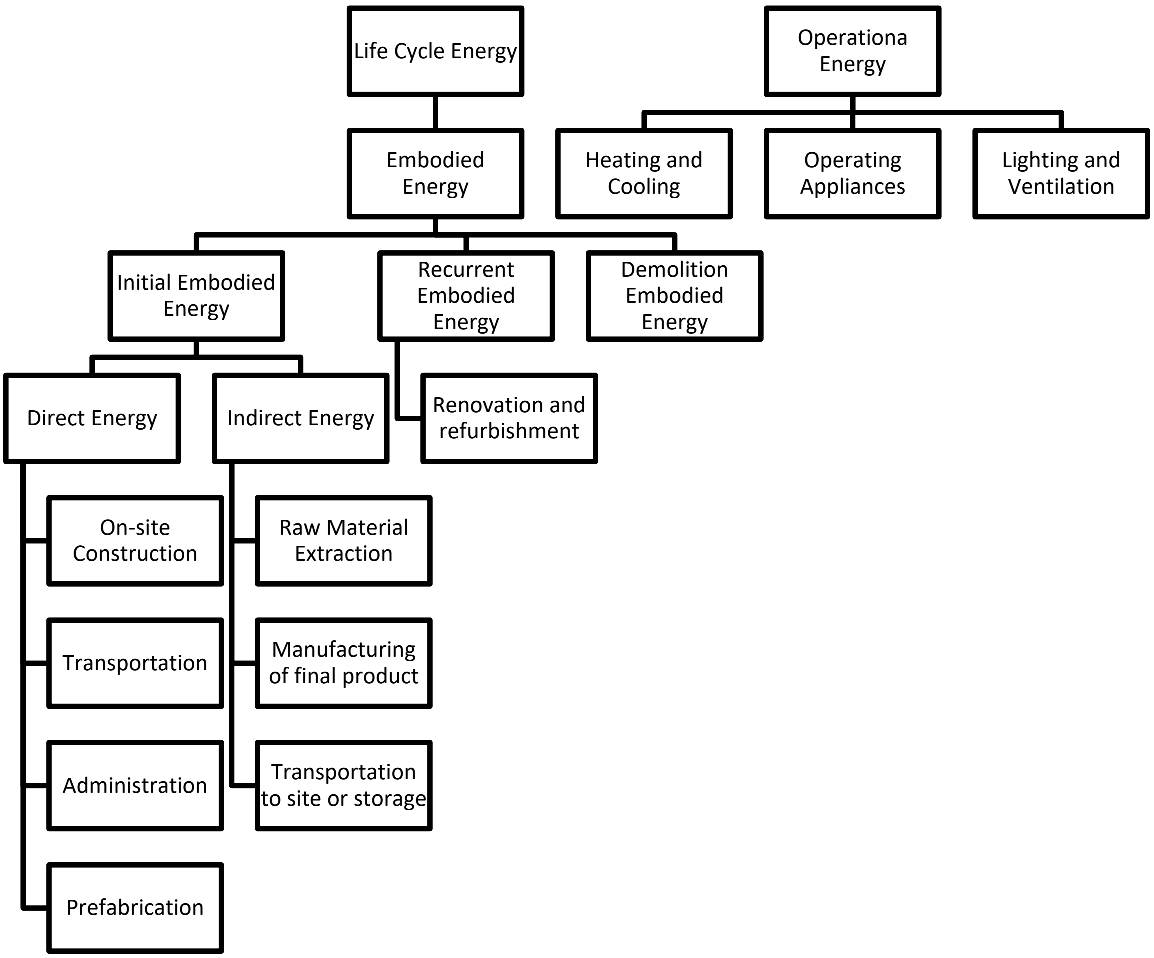

Figure 1: Embodied Energy Classification

2.1.2 Lack Of Standardized Protocol

There is no generally accepted method for calculation to compare embodied energy accurately and consistently resulting in variation in measurement figures (Dixit et al., 2010). Lack of globally accepted embodied energy calculation method is a hindrance to establish complete and consistent embodied energy database (Dixit et al., 2015).

2.1.3 Variation And Inconsistency In Embodied Energy Measurement

The mean of residential units' embodied energy is 5.506 GJ/m^2 and standard deviation is found to be 1.56 GJ/m^2 while commercial buildings' embodied energy mean is 9.19 GJ/m^2 with standard deviation of 5.4 GJ/m^2 showing commercial buildings have greater variability than residential units in terms of embodied energy (Dixit et al., 2010).

In Dixit et al., (2010), the factors responsible for inconsistency and variation are given as mentioned below.

1. System boundaries
2. Method of embodied energy analysis
    a. Process-based analysis
    b. Input-output-based analysis
    c. Hybrid analysis
        i. Process-based hybrid
        ii. Input-output-based hybrid
3. Geographic location of study area
4. Primary and delivered energy
5. Age of data sources
6. Source of data
7. Completeness of data
8. Technology of manufacturing processes

9. Feedstock Energy consideration
10. Temporal representatives

Parameters such as system boundaries, primary or delivered energy and feedstock energy, define the input variables that are included in embodied energy calculations. Global comparability and reliability are crucial data qualities for embodied energy research. Incompleteness and variation are two key issues associated with current calculation methods, which may cause variation in embodied energy values. (Dixit et al., 2012).

Different component materials with different exploitation methods and production processes, various transportation energy costs and different recycle rates of component material are the main reasons leading to different embodied energy values for different building materials (Jiao et al., 2012).

2.1.4 System Boundaries And Their Significance

System boundaries range from extraction of raw material in upstream direction to demolition and disposal in downstream direction.

Types of system boundaries (Balouktsi & Lutzkendorf, 2016):

1. Cradle to gate – Extraction to finished product leaves factory gate.
2. Cradle to site – Extraction to transportation of finished product to construction site; on-site construction and assembly included in some cases.
3. Cradle to end of construction – Represents initial embodied energy (IEE) of building; extraction to on-site assembly.

4. Cradle to end of use – Extraction to construction/handover plus all the maintenance, replacement and refurbishment which constitute recurrent embodied energy (REE).
5. Cradle to grave – Extraction to demolition, disposal and waste treatment.
6. Cradle to cradle – Represents entire life cycle of a product, and then, at the end, converting it into a new component.

The choice of system boundaries is critical as it defines the difference between net inputs and internal transactions (Costanza, 1980).

System boundaries differ in three ways: Firstly, all life cycle stages are not included, especially, transportation and transformation between two life cycle stages is seldom considered. Second, range of upstream and downstream processes is unclear. Finally, EE calculations cover only few components of buildings instead of considering whole building. Therefore, problem of variation and incompleteness can be seen due to exclusion of life cycle stages or building materials. Selection of system boundary is subjective leading to variation in EE values (Dixit et al., 2013).

According to Dixit et al., (2013), system boundary can be viewed as a three dimension model; X-axis consisting of building's life cycle phases, Y-axis measuring the range of system boundary in upstream and downstream process, Z-axis indicates the differing levels of studies changing according to scope of study.

Selection of system boundary is subjective leading to variation in EE values (Dixit et al., 2013). As acquiring necessary data and understanding it is difficult, a boundary has been drawn around the quantification of inputs to the product being assessed. Therefore, many inputs are neglected in quantification of inputs to a product making the system boundary incomplete (Crawford, 2004).

2.2 Calculation Methodologies

The methodologies typically used for EE calculations can be classified into three types: calculation based on quantity of building material, calculation based on geometry of the building and calculation based on hybrid of these two methods (Jiao et al., 2012). These methodologies are categorized as process-based, input-output based and hybrid of these two methods (Treloar et al., 2001).

An embodied energy analysis in its current form is expensive and time-consuming, and is based on a number of assumptions (Langston, 2006). Every method utilizes different types of data sources and covers varying scopes of system boundaries.

The accuracy and level of completeness of embodied energy analysis is dependent on the method chosen: process, input-output or hybrid analysis (Treloar, 1997). A method’s completeness is dependent on the energy flows incorporated in the analysis (Dixit, 2017). Quantification of inputs to the product is the most important stage in embodied energy analysis (Fay et al., 2000).

2.2.1 Process-Based Analysis

Process-based analysis provides material-specific energy values, its calculations are significantly incomplete (Dixit, 2017). The process starts with taking building material as a final product and works backward in upstream process, taking into account all possible direct energy inputs. This system is incomplete and has errors due to truncation in system boundary i.e. exclusion of many upstream processes. According to

Moncaster and Song (2012), for process-based calculation, only product stage is recommended as mandatory out of the four stages.

Although process based provides values specific to the building, embodied energy during construction and other services remain excluded from the calculation. Results from Bullard et al., (1978), Peet and Baines (1986) and Lenzen and Dey (2000) show that process-based inventories do not achieve system completeness due to complexity of upstream requirements of goods and services. Lenzen (2010) quantified the incompleteness and truncation error due to boundary truncation as 50% and 10%, respectively.

2.2.2 Input-Output Based Analysis

The input-output method is considered more comprehensive than process based. This method uses national average data for each sector of the economy (Lanzen, 2000, 2001, Lave, 1995; Treloar, 1997). Input-output based analysis is relatively complete as it accounts most direct and indirect energy in the process of production of building materials and also embraces nearly entire system boundary (Dixit, et al., 2014). Input-output based analysis is top-down approach which contains direct requirement coefficients from an economic input-output model (Horowitz, & Planting, 2009). This process makes use of economic data of monetary flow in various sectors of industry in the form of input-output tables made available by national government. These inputs are in monetary units and require energy prices to convert them to energy units (Dixit, et al., 2014). The quality of input-output-based results depends upon the quality of energy price data (Dixit, 2015).

A direct requirement coefficient represents inputs (in $) required by an industry sector from other sectors to produce a unit dollar output (Dixit, 2017; Miller, & Blair, 2009). Direct energy inputs from energy providing sectors can be quantified using direct requirements coefficients. Every industry sector has a chain of suppliers which are responsible for indirect requirements from direct requirements. For example, cement industry sector increases its production of cement by $1, all other industry sectors supplying inputs, such as limestone, gypsum etc., also increase their production in order to meet the increased demand. Such increased requirements are termed stage one indirect requirements. The total indirect requirement is the sum of all indirect requirements spread over stage 1 to stage ∞ (Dixit, 2017; Dixit et al., 2015; Miller & Blaire, 2009). These stages of indirect requirements are known as indirect stages (See Figure 2). Direct requirements are subtracted from total requirements to calculate indirect requirements. The direct and indirect requirements can be converted from monetary to energy units by using appropriate energy tariffs (Acquaye, 2010; Crawford, 2004; Treloar, 1998).

The primary limitations of input-output analysis include homogeneity assumption, proportionality assumption, sector classification and aggregation (Crawford & Treloar, 2004, Lanzen, 2001). Results of input-output method maybe aggregated and not product specific. The energy intensity of a manufacturing sector is calculated in energy units per unit of monetary output. To convert energy intensity into energy units per mass or volume, product prices are used. Any fluctuation in product prices grossly affects the embodied energy calculation (Dixit, 2017).

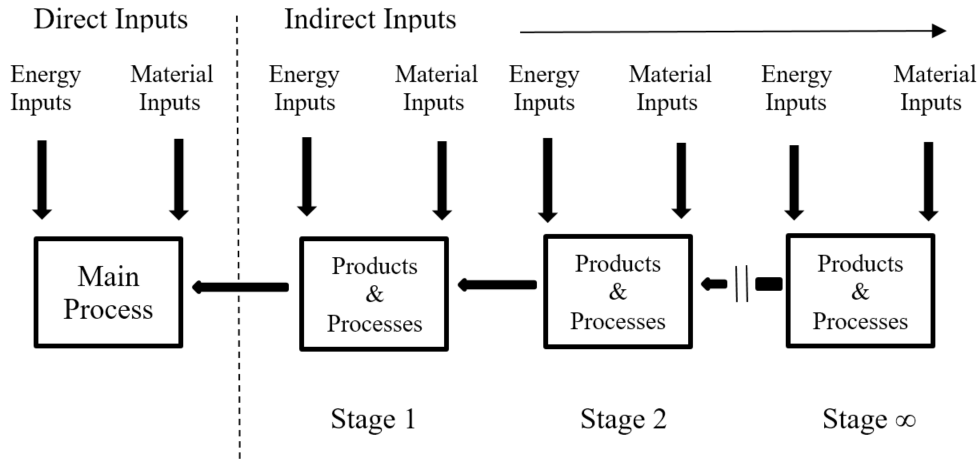

Figure 2: Direct and indirect embodied energy inputs

Input-output tables are also prepared based on the assumptions of homogeneity and proportionality. According to the homogeneity assumption, each product produced by a sector has a homogeneous mix of inputs that may not be correct. In the proportionality assumption, the cost of a product is directly proportional to its input requirements, which may be inaccurate (Crawford, 2004). According to Treloar (1998), an input-output based embodied energy calculation entails counting energy inputs multiple times. For example, if the electricity sector purchases coal, natural gas, and petroleum, the total energy embodied in electricity, according to the input-output model, would include all energy purchased, as well as the energy content of generated electricity.

In input-output method, all products would have the same energy intensity which may not be the case. Completeness is governed by the energy inputs which are taken into account by system boundary. If energy prices are inflated, a serious error in calculation may occur (can be used for assumption). Also, the inability of input-output based hybrid model to incur human labor and capital investment is a problem (Dixit et al., 2015).

According to Moncaster and Song (2012), for input-output LCA, countries calculate gross domestic product (GDP) and carbon emissions by economic sector; by considering the inputs and outputs from and to other sectors, the input-output model can calculate the total impact of construction. The input-output approach is too broad and general to be helpful. Therefore, an input-output hybrid method can be used by using advantages of process and input-output based methods to improve accuracy.

2.2.3 Hybrid Analysis

Hybrid analysis consists combining advantages of two methods to eliminate fundamental errors and limitations of process and input-output analysis (Dixit et al., 2010). The term hybrid represents the use of physical and monetary units or a combination of process and input-output data. The input-output hybrid analysis is most complete for embodied energy calculations (Chang et al., 2012; Copiello, 2016; Dixit, 2017; Islam, Jollands, & Setunge, 2015; Jiao et al., 2012; Moncaster & Song, 2012). Studies such as Bullard et al., (1978), Carter et al., (1981), Crawford, (2004), Dixit et al., (2015), Treloar, (1998) have proposed various versions of input-output hybrid method with gradual improvements. Carter et al., (1981) proposed inserting actual energy use data of industry sectors in the input output model in energy units, while other flows of goods and services remain in monetary units.

Treloar (1998) proposed an approach to extract direct energy paths from an input-output model and replace them with process-based energy data to improve the calculation reliability. Treloar (1998) has suggested keeping all energy and non-energy inputs of energy providing sectors at zero in the input-output model and using a set of primary energy factors (PEFs) instead to avoid counting energy inputs multiple times. The PEFs that are used to convert delivered energy to primary energy represent all energy used and lost in producing and distributing one unit of delivered energy such as electricity. Crawford (2004) suggested a correction to Treloar's method and proposed extracting and replacing total energy paths instead.

Suh et al. (2004) discussed an integrated input-output hybrid analysis, in which a technology matrix integrates detailed process data at the level of unit processes into an input-output model. This method avoids double counting of inputs and offers a consistent approach to allocation. Suh and Huppes (2005) discussed that no method is better than the other methods and the suitability and choice of a method depends on the data availability, quality, goal and scope of a study, and the time and resources available.

The process-based hybrid method may yield energy values that are nearly two times those obtained by process and input-output based methods. Similarly, the input-output based hybrid values may be over two times the process and conventional input-output based values. In fact, input-output based hybrid values are significantly higher than the process-based hybrid values (Dixit, 2017).

2.2.4 Input-Output Hybrid Analysis By Sectoral Disaggregation.

The input-output based hybrid method has the prospective to offer a more complete calculation compared to other methods. The current input-output hybrid method lacks specificity and reliability. Techniques such as sectoral disaggregation have been proposed to improve the specificity and reliability of the input-output hybrid method which would make it more complete (Dixit, 2017) Completeness of the method refers to how well all the energy flows are incorporated in the calculations. The results of input-output based framework are highly aggregated lacking specificity (Acquaye, 2010; Treloar, 1998). The inability of input-output based hybrid model to provide material-specific results is a major issue. This problem can be addressed by disaggregating an industry sector in input-output framework (Dixit, 2017).

Although there is a need to disaggregate input-output industry sectors to quantify product-specific embodied energy, the disaggregation process is data intensive. Therefore, application of sectoral disaggregation to input-output hybrid methods should be tested to improve their specificity so that complete and product-specific embodied energy can be calculated in a reliable manner (Dixit, 2017).

The material quantities must be calculated in a building to estimate the energy required to manufacture them. The outline of distribution with respect to energy requirement is very different from the percentages by weight. (Adalberth, 1997).

2.3 Standards, Softwares And Databases In Life Cycle Assessment (LCA)

Previous studies have either not mentioned using any standard or used standards provided by ISO and SETAC (Society for Environmental Toxicology and Chemistry).

Most current databases of embodied energy include data that are derived using guideline by International Standardization Organization (ISO) for Life Cycle Assessment (LCA). In 2006, ISO reviewed and updated standards for guiding LCA. Current literature suggests in spite of existence of ISO LCA standards, there is a need for robust standards for building products to calculate embodied energy.

ISO 14040 (second edition updated in 2006) and ISO 14044 (2006) are the currently used ISO standards which help to make a framework for LCA, guideline related to allocation and system boundaries. Explanation for missing data or data gaps in the LCA database is given (Dixit et al., 2012). LCA studies are undertaken using ISO 14044 standards, which define the functional unit as a unit of comparison.

A variety of tools exist in the form of software, along with datasets of environmental impacts of building materials (See Table 1). The tools, such as ATHENA, Ecoinvent, Eco-Quantum, Envest2, OPTIMIZE, LICHEE, SimaPro, etc. provide a user-friendly approach to determine life cycle impacts of a building. Refer Table 1 for construction specific LCA softwares. Most of these do not cover all stages of a building's cycle and none of the tools are capable to perform full LCA of a building (Dixit et al., 2012). Srinivasan et al. (2014) illustrates use of two existing LCA tools, an economic input-output based model, Economic Input-Output LCA (EIO-LCA), and a process based model, ATHENA Impact Estimator, to estimate life cycle energy use in a building. ATHENA Impact Estimator is a decision support tool that provides a cradle-to-grave process based LCA incorporating regional data such as appropriate electricity grid, transportation modes and distances to estimate life cycle energy use in TJ.

Although ATHENA Impact Estimator and EcoCalculator are used to act in accordance with building rating systems for whole life cycle of the building, they do not account for all components of buildings such as HVAC, electrical and plumbing components.

Software	Developer	Default data used
Athena EcoCalculator	Athena institute, Canada	Athena's In-house datasets, US Life Cycle Inventory
BEES	NIST, US	In-house Database
Carbon Calculator	Environment Agency, UK	Bath ICE v. 1.6a, Jakobs UK in-house calculation
Life Cycle	Franklin & Andrews, UK	In-house Database
Knowledgebase	Faithful & Gould, UK	In-house Database
DEMScot model	Cambridge Architectural Research (CAR), UK	Bath ICE v. 1.6a

Table 1: Construction Specific LCA Softwares

LCA is an effective tool for measuring embodied energy in buildings, although, it is data intensive and requires robust data. LCA was designed to evaluate environmental impacts over a life cycle of a product. Using LCA for buildings is complex they are large, unique and use of various number of products, Also, buildings have much more lifespan making tracking and data collection that more difficult. Lack of reliable and accurate information hinder LCA process for buildings (Dixit et al., 2012). Life cycle assessment and life cycle costing approaches assess the life cycle environmental impacts and life cycle cost (LCC), respectively (Islam et al., 2015).

LCA consists of four major steps: Definition of goal and scope, life cycle inventory (LCI), Life cycle Impact assessment, and interpretation of results (Srinivasan et al., 2014).

2.4 Embodied Energy And Cost Relationship

Some level of relationship can be observed while using economic activities to calculate embodied energy. The economic activities in monetary units can be converted to energy units using energy prices. As economic activity is used to calculate embodied energy, there exists a relationship between embodied energy and cost (Dixit, 2017). Studies have discovered a strong positive correlation at project level while computing the relationship between embodied energy and cost of a building (Costanza, 1980; Ding 2004; Jiao et al., 2012; Langston, 2006). But the correlation was found out to be weak when computed at material level (Jiao et al., 2012; Langston, 2006).

Input-output analysis has been used to calculate total energy required to produce goods and services in U.S. economy termed as embodied energy. The results of such an analysis demonstrate a strong relation between embodied energy and dollar value. Input-output analysis is effective when calculating indirect effects in a systematic and all-inclusive accounting. With appropriate perspective and boundaries, market-determined dollar values are proportional for all but the primary energy sectors (Costanza, 1980). Costanza established a strong relationship between the energy embedded in a product and the monetary output of its production sector.

Ding (2004) investigated the relationships of environmental benefits, environmental impacts, life cycle cost and energy consumption by analyzing 20 public high schools in Australia as case studies. The results suggested a strong positive correlation between total building cost and energy consumption. Also, Ding suggested that taking measures to save operating energy may result in high embodied energy usage while using energy efficient materials with high embodied energy content. Results from analysis of case studies suggest that about 70% of variations in building energy usage can be explained by cost variation at project level ($r^2 = 0.7$).

Langston (2006) hypothesized a strong positive correlation between capital and recurring cost of a building with its operating and embodied energy. The estimate of embodied energy from cost could be possible if the strong positive correlation exists. For calculating the embodied energy of the buildings under study, Langston used an approach proposed by Treloar (1998) which includes collecting bill of quantities for cost data. Langston found a strong positive correlation at project level but positive yet weak correlation at cost component level.

Jiao et al. (2012) suggests finding a general relationship between embodied energy and the cost of buildings can give a shortcut to such embodied energy estimates, which may also be of assistance to help reduce energy consumption. Three case studies (commercial buildings) from New Zealand and China were used to obtain embodied energy and cost data. The inclusion of labor energy was an important step towards improving the accuracy of embodied energy results. The results suggest a strong and positive correlation between embodied energy and cost of buildings ($r^2 = 0.99$ and 0.93).

Also, a positive correlation exists between embodied energy and cost components for two Chinese buildings whereas the correlation is weak for the building in New Zealand. As the study comprises of only three buildings from two different countries, results on correlation should be interpreted with attention.

The relationship between energy and cost has been defined in terms of energy intensity factors having same units. Energy intensity of materials produced can change every few years depending upon the trend towards making low energy-intensive materials and products (Jiao et al., 2012).

Copiello (2016) attempted to investigate the relation between the embodied energy of a broad amount of construction materials and their production cost. This study hypothesized that embodied energy correlates with the cost incurred during construction process. The author suggested the occurrence of a non-linear relation between EE and construction cost. Also, the production cost can be an indicator of embodied energy of buildings. The relation is found out to be positive except for notable raw-materials.

CHAPTER III

RESEARCH METHODS

3.1 Data Collection

For the purpose of this study, five educational buildings on-campus at Texas A&M University were selected (see Table 2). Also, all the buildings in this study are constructed in the past ten years to minimize the impact caused by construction techniques and materials used.

#	Building	Year Built
A	Physical Education Activities Program Building	2013
B	Mitchell Physics Building	2009
C	Liberal Arts and Arts & Humanities Building.	2012
D	Agriculture and Life Sciences Building	2011
E	Emerging Technologies Building	2011

Table 2: List of buildings

The data regarding cost for these five buildings was acquired from the University Architect Office at Texas A&M University. The data provided was scheduled cost values of building materials, labor, etc. in a master format. All values were in terms of U.S. Dollar ($). The materials considered for this study are shown in Table 3. Materials such as terrazzo flooring, ceramic tiles and face brick were clustered as the manufacturing industry sector was assumed common for these materials. Similarly, membrane, damproofing and waterproofing materials were clustered for similar reasons.

As all materials were available in terms of monetary units ($), they needed to be converted into mass units (Kg). RSMeans Building Construction Cost data was used to convert all materials in terms of total mass in Kg. RSMeans data is often used in the United States to estimate the cost or mass of material. Buildings considered for the purpose of this study were constructed in different years (2009, 2011, 2012, and 2013). As RSMeans Building Construction Cost data is updated every year, different versions of RSMeans data was used according to the year in which the building was constructed. After converting materials in terms of mass (Kg), material coefficients in terms of $ per Kg were computed for correlational analysis.

For the purpose of this study, input-output hybrid model suggested by Dixit (2017) was used. The most significant aspect of this model is the sectoral disaggregation of industry sectors in the Use and Make table. Input-output accounts from United States Bureau of Economic Analysis (USBEA) were used while constructing the model. The model involves use of square matric calculations to calculate direct, indirect and total requirements. The model proposed by Dixit (2017) is in the form of a spreadsheet containing Industry by Commodity matrix. The coefficients in the model are in terms of energy units (MBTU) per monetary units ($). The inclusion of energy units instead of energy tariffs makes the model more sophisticated as fluctuation in energy tariffs, a major issue, has been resolved. Further, industries were disaggregated for materials in used to reduce the effect of aggregated values (see Table 3).

There are five main energy providing sectors in the US economy: coal mining; oil and gas extraction; natural gas distribution; electric power generation, transmission, and distribution; and petroleum refineries. As these industries have indirect requirements, a set of primary energy factors (PEF's) by Dixit et al., (2014) were used to convert secondary energy into primary energy (see Table 4). Human and capital energy were also encompassed in the embodied energy calculations.

#	**Material**	**NAICS Code**
1	Concrete	327320
2	CMU	327330
3	Cut Stone	327991
4	Structural Steel	331110
5	Wood	321100
6	Membrane, Damproofing, Waterproofing	324122
7	Flashing	331420
8	Plaster	327400
9	Aluminum	33131A
10	Glass	327215
11	Paint	325510
12	Terrazzo Flooring, Ceramic Tile and Face Brick	327100
13	Carpet	314110
14	Ceiling	327993
15	Gypsum	327400

Table 3: Building materials and disaggregated industry sectors with NAICS codes

After calculating all the coefficients in terms of MBTU per $, embodied energy values for each building material was calculated by multiplying the cost of each building material across all five buildings by respective MBTU per $ coefficients. For the purpose of correlational analysis, coefficients of building materials in terms of energy units (MBTU) per unit mass (Kg) were calculated.

#	**Industry**	**PEF**
1	Coal Mining	1.03
2	Oil and Gas Extraction	1.21
3	Natural Gas Distribution	1.53
4	Petroleum Refineries	1.27
5	Electric power generation, transmission, and distribution	4.22

Table 4: Primary Energy Factors (PEFs)

3.2 Data Analysis

Data analysis included calculating the correlation between embodied energy and cost of building using Excel spreadsheets. The strength of the correlation was measured using r^2-value (coefficient of determination) and were categorized in specific ranges as; 0 – 0.09 (weak), 0.09 – 0.64 (strong moderate), 0.64 – 0.81 (strong) and 0.81 – 1.0 (very strong) (Chan, 2003; Dixit et al., 2014, Taylor 1990). These ranges were used as reference to determine the strength of correlation between embodied energy and cost of building materials.

Regression analysis was performed if the correlation between energy and cost of building materials was strong. R^2 (coefficient of determination) was used to examine the strength of correlation, coefficient or slope gradient (m) (used to predict embodied energy from cost), t-statistic to test the estimating confidence and p-value to test the existence of any relationship.

Correlational analysis was performed in this study by two ways: first, correlation between embodied energy (MBTU) and cost ($) was calculated; second, correlation between embodied energy unit per unit mass (MBTU/Kg) and cost per unit mass ($/Kg) was calculated.

3.3 Case Study As A Research Method

The case study method is a good way to define cases and to explore a setting in order to understand it (Cousin, 2005). Stake (1995) tells that a case study can have a tricky type of approach and therefore it can be a tough job for the researcher to report the study. But when the findings are presented in a specific way the case study is easy to understand by the reader. He also writes that the researcher has a vision about the understanding of the case study for the readers. It includes that the readers can understand the findings so well that they can implement the study in their own situation.

The detailed examination of a single example of a class of phenomena, a case study cannot provide reliable information about the broader class, but it may be useful in the preliminary stages of an investigation since it provides hypotheses, which may be tested systematically with a larger number of cases. (Abercrombie et al., 1984). The purpose with case studies are to produce background material to a discussion about a concrete problem.

A case study can contain either a single study or multiple studies. The researcher therefore have to consider if it is wise to make a single case study or multiple case studies for the understanding of the concept (Gustaffson, 2017).

Interpretation is a key part in research. On the basis of observation and other data, researchers draw their own conclusions, which are also called as assertions, a form of generalization (Stake, 1995).

Flyvbjerg (2006) examines five common misunderstandings about case-study research are theoretical knowledge is more valuable than practical knowledge; one cannot generalize from a single case, therefore, the single-case study cannot contribute to scientific development; the case study is most useful for generating hypotheses, whereas other methods are more suitable for hypotheses testing and theory building; the case study contains a bias toward verification; and it is often difficult to summarize specific case studies. These five misunderstandings indicate that it is theory, reliability, and validity that are at issue; in other words, the very status of the case study as a scientific method. Despite the difficulty or undesirability in summarizing case studies, the case-study method in general can certainly contribute to the cumulative development of knowledge, for example, in using the principles to test propositions described above with regard to the second and third misunderstandings.

The conclusion that is aimed by a case study can be either illustrative or confirmable. These issues confuse the design of a case study and will further do so because they are inherent in the company (Gustaffson, 2017).

CHAPTER IV

FINDINGS

For the purpose of this study, embodied energy was calculated for all the buildings at material level and project level. At material level, the entire building was disaggregated into building materials and cost of these materials were used to calculate embodied energy. For embodied energy calculation at project level, the total construction cost of the building was used.

Building	EE without disaggregation into building materials (MBTU) (a)	EE after disaggregation into building materials (MBTU) (b)	% increase [From (a) to (b)]
A	125130.8	272308.5	217.6
B	408326.7	812675.8	199.0
C	211760.8	526407.1	248.6
D	382566	992814.2	260.0
E	449041.6	739950.7	165.0

Table 5: Difference in embodied energy values

After comparing embodied energy values at material level and project level, a significant increase in embodied energy values can be seen after disaggregation into building materials. The values after disaggregation increase in a range of (164% to 260%) when compared to values without disaggregation (see Table 5).

As the correlation of all the building materials under study across all five buildings was strong, regression analysis was performed.

Building	R	R^2	Adjusted R^2	Coefficient	t-stat	p-value
A	0.90541	0.81977	0.80591	0.01679	7.68963	3.43E-05
B	0.78151	0.61076	0.58082	0.01948	4.51648	0.00058
C	0.86694	0.75159	0.73248	0.01379	6.27164	0.00003
D	0.90724	0.82309	0.80948	0.01385	7.77719	3.04E-06
E	0.75079	0.56369	0.53013	0.01280	4.09823	0.00126
A+B+C+D+E	0.88089	0.77597	0.77290	0.01460	15.90106	2.03E-25

Table 6: Regression analysis for embodied energy (MBTU) and cost of building materials($).

In regression analysis, the adjusted R^2 takes into account the number of data points on the regression line. As 75 data points (15 materials each of all 5 buildings) is a reliable indicator of correlation (the difference between R and R^2 is small), fewer data points increases the gap between both variables. P-values were calculated to confirm the existence of relationship at 95% confidence. Therefore, where p-value was smaller than 0.05, as was the case for all buildings, we can say that relationship exists between embodied energy and cost, Also, the value of t-critical for one-tailed relationship was significantly greater than zero, it increased the estimating confidence in the slope coefficient of the regression line (see Table 5).

Building	R	R^2	Adjusted R^2	Coefficient	t-stat	p-value
A	0.9986	0.99727	0.99706	0.0235	68.8848	4.72E-18
B	0.9985	0.99714	0.99692	0.0235	67.2887	6.44E-18
C	0.9985	0.99711	0.99689	0.0235	67.0274	6.73E-18
D	0.9988	0.99760	0.99742	0.0235	73.5789	2.00E-18
E	0.9981	0.99628	0.99599	0.0234	59.0117	3.51E-17
A+B+C+D+E	0.9985	0.99707	0.99703	0.0235	157.5660	3.30E-94

Table 7: Regression analysis for embodied energy per unit mass (MBTU/Kg) and cost of building materials per unit mass ($/Kg).

Similarly, after analyzing the correlation between embodied energy per unit mass (MBTU/Kg) and cost of building materials per unit mass ($/Kg), correlation across all five buildings was very strong. Therefore, regression analysis was performed (See Table 7).

In regression analysis, the difference between R and R^2 values is small (see Table 6).As p-values were less than 0.05, we can say that relationship exists between embodied energy and cost. Similarly, the value of t-critical for one-tailed relationship was significantly greater than zero, increasing the estimating confidence in the slope coefficient of the regression line (see Table 6).

In Building A, the coefficient of correlation was very strong ($R^2 = 0.8198$) and the equation of regressed line was Y = 0.0168 X + 2489.4 (See Figure 3). When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9973$) and the equation of regressed line was Y = 0.0236 X + 0.0459 (See Figure 4).

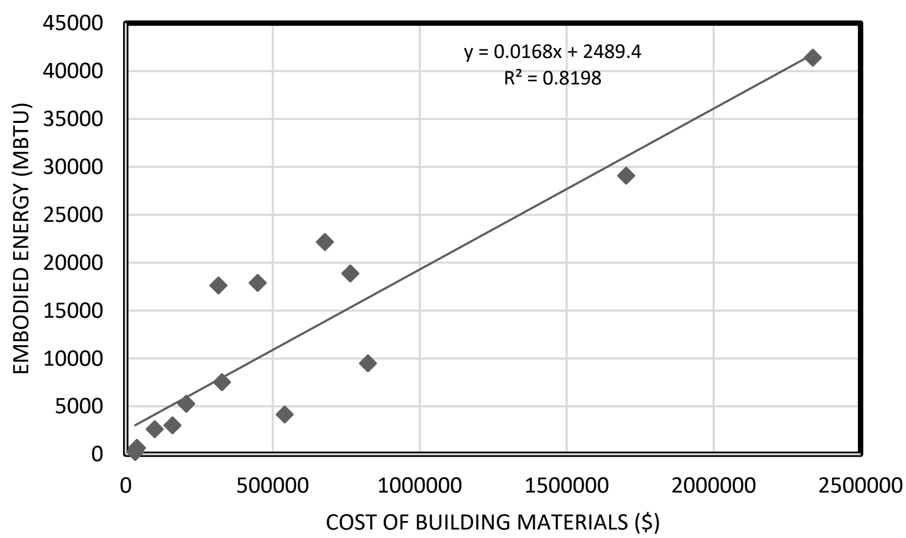

Figure 3: Embodied energy vs cost of building materials correlation for building A.

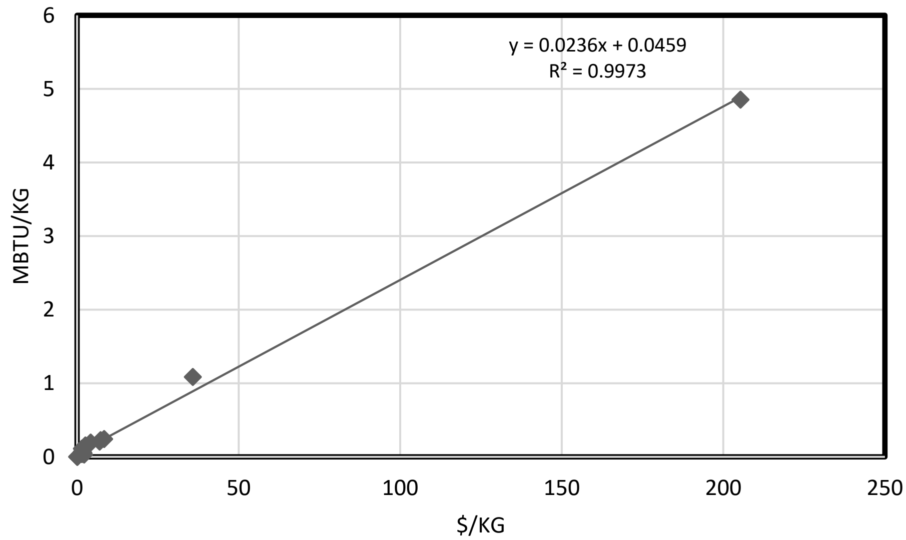

Figure 4: Embodied energy per unit mass vs cost of building materials per unit mass correlation for building A.

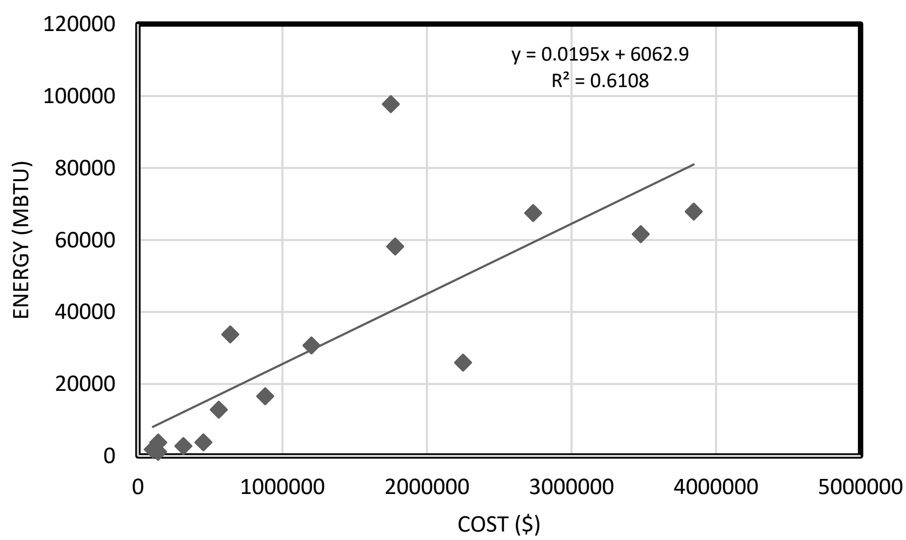

Figure 5: Embodied energy vs cost of building materials correlation for building B.

In Building B, the coefficient of correlation was strong moderate ($R^2 = 0.6108$) and the equation of regressed line was Y = 0.0195 X + 6062.9 (See Figure 5).

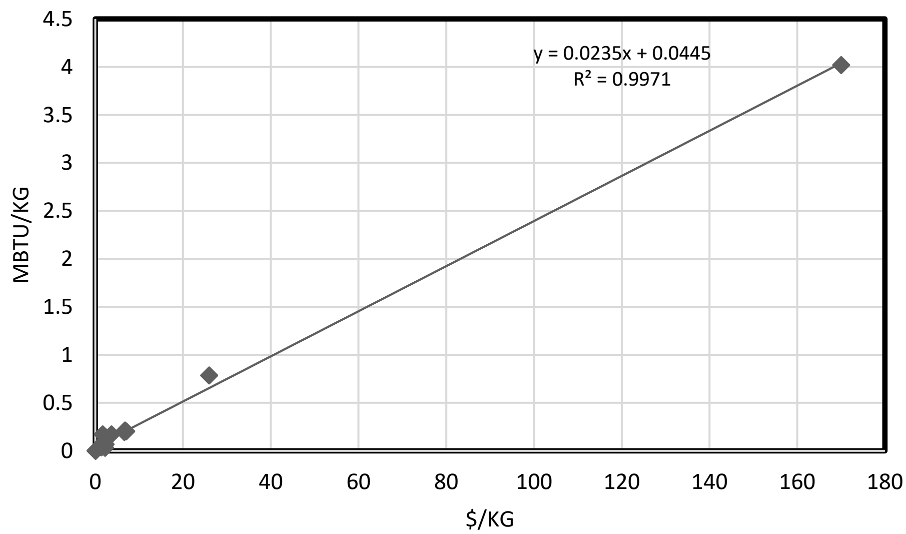

Figure 6: Embodied energy per unit mass vs cost of building materials per unit mass correlation for building B.

When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9971$) and the equation of regressed line was Y = 0.0235 X + 0.0445 (See Figure 6).

In Building C, the coefficient of correlation was strong ($R^2 = 0.7516$) and the equation of regressed line was Y = 0.0138 X + 7596.5 (See Figure 7). When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9971$) and the equation of regressed line was Y = 0.0235 X + 0.0509 (See Figure 8).

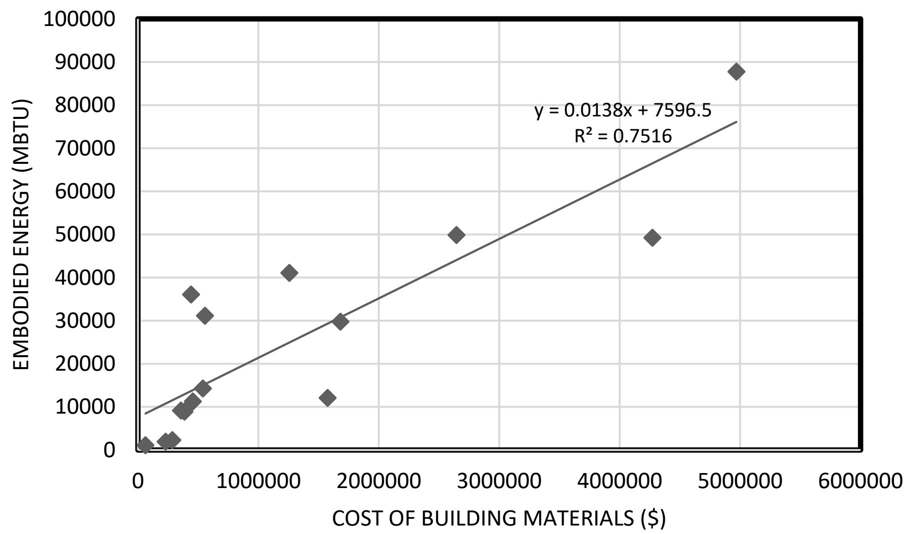

Figure 7: Embodied energy vs cost of building materials correlation for building C.

In Building D, the coefficient of correlation was very strong ($R^2 = 0.8231$) and the equation of regressed line was Y = 0.0138 X + 12763 (See Figure 9). When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9976$) and the equation of regressed line was Y = 0.0235 X + 0.0473 (See Figure 10).

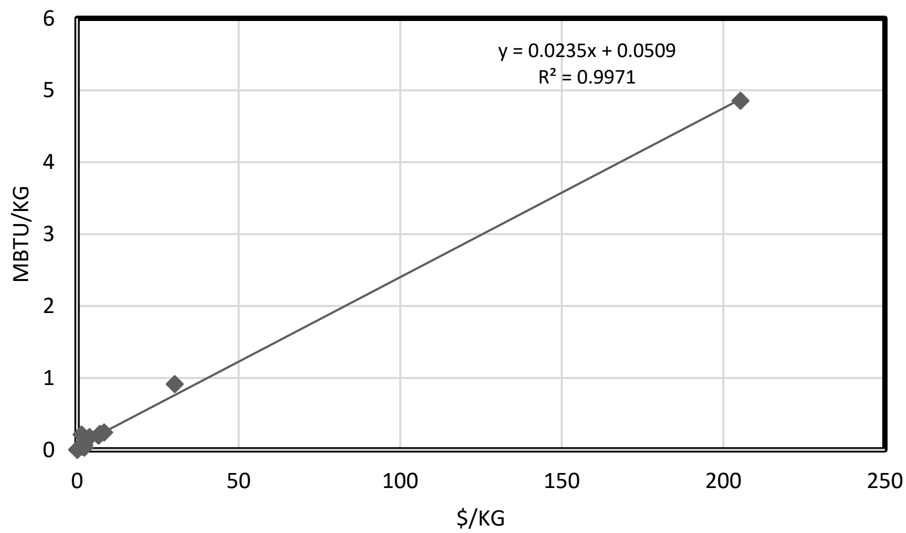

Figure 8: Embodied energy per unit mass vs cost of building materials per unit mass correlation for building C.

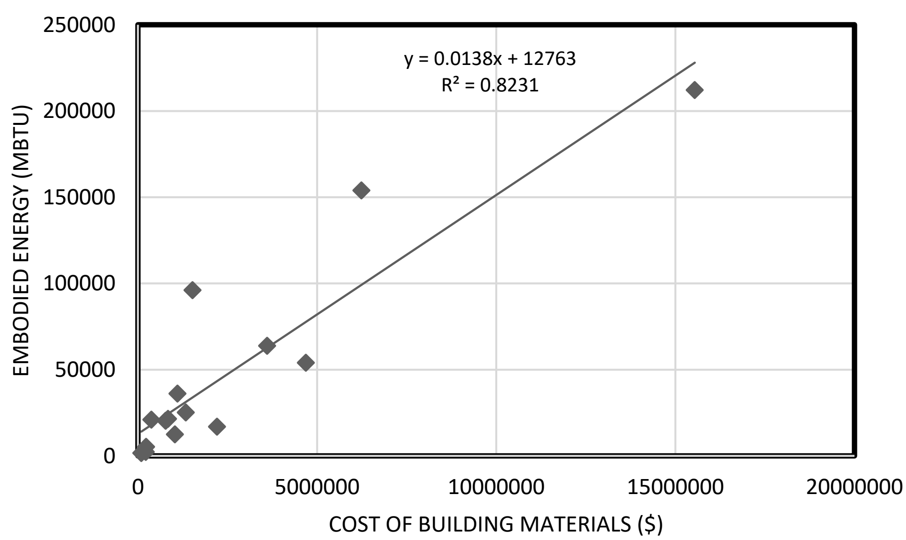

Figure 9: Embodied energy vs cost of building materials correlation for building D.

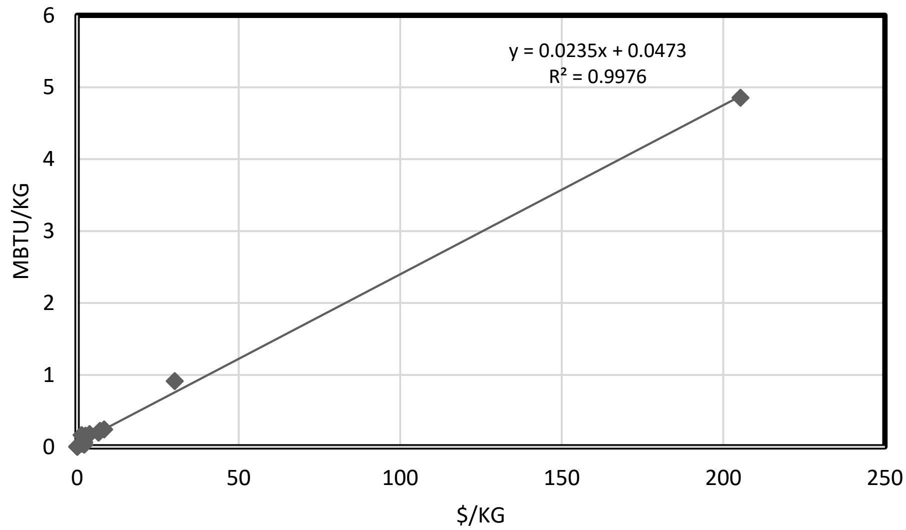

Figure 10: Embodied energy per unit mass vs cost of building materials per unit mass correlation for building D.

In Building E, the coefficient of correlation was strong moderate ($R^2 = 0.5637$) and the equation of regressed line was Y = 0.0128 X + 8463.4 (See Figure 11). When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9963$) and the equation of regressed line was Y = 0.0235 X + 0.0551 (See Figure 12).

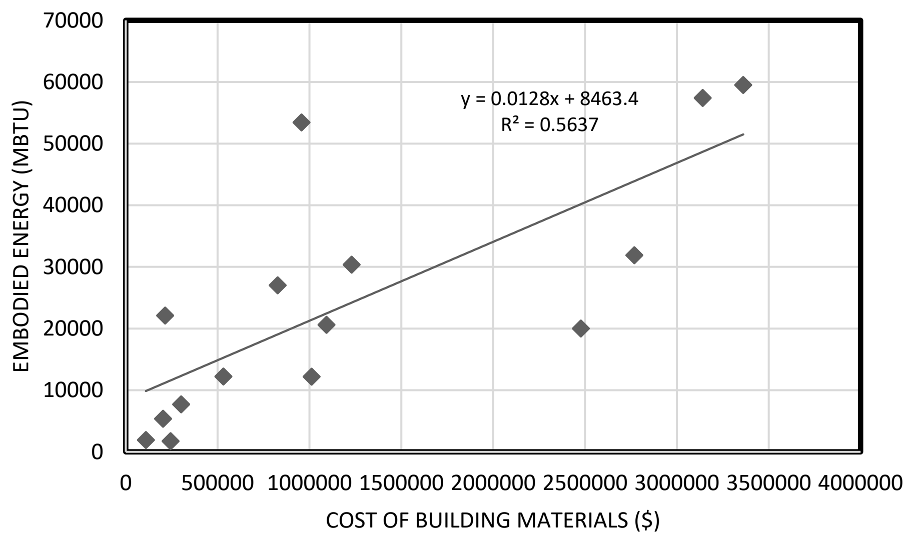

Figure 11: Embodied energy vs cost of building materials correlation for building E

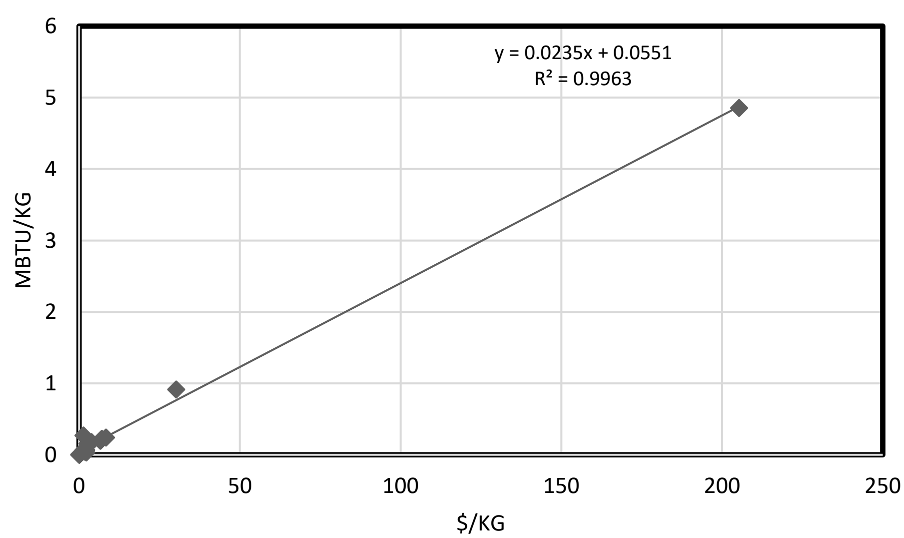

Figure 12: Embodied energy per unit mass vs cost of building materials per unit mass correlation for building E.

For all five buildings, the coefficient of correlation was strong ($R^2 = 0.776$) and the equation of regressed line was Y = 0.0146 X + 7984.2 (See Figure 13). When correlation was computed using coefficients per unit mass, the coefficient of correlation was very strong ($R^2 = 0.9971$) and the equation of regressed line was Y = 0.0235 X + 0.0487 (See Figure 14).

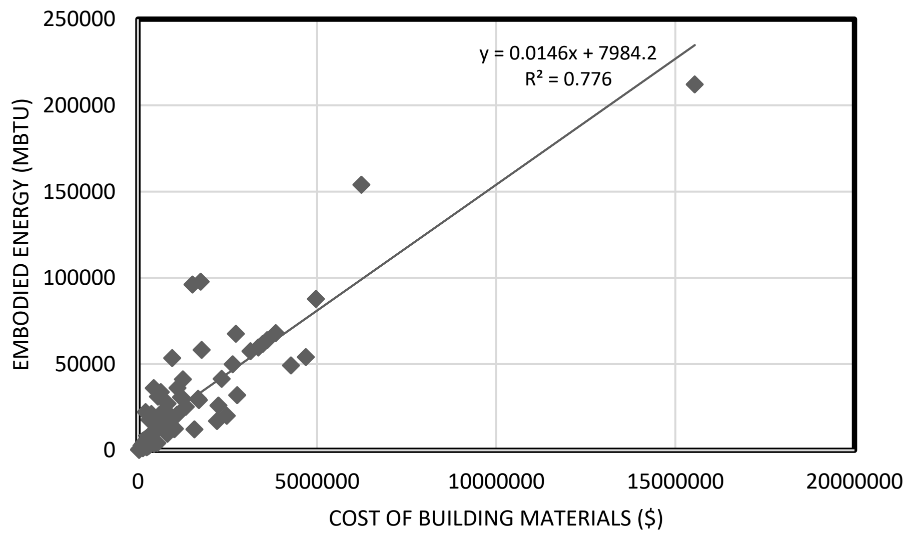

Figure 13: Embodied energy vs cost of building materials correlation of all buildings

For the purpose of estimation of embodied energy from cost of building materials at the initial stage of the project, the correlation between embodied energy (MBTU) and cost ($) should be used.

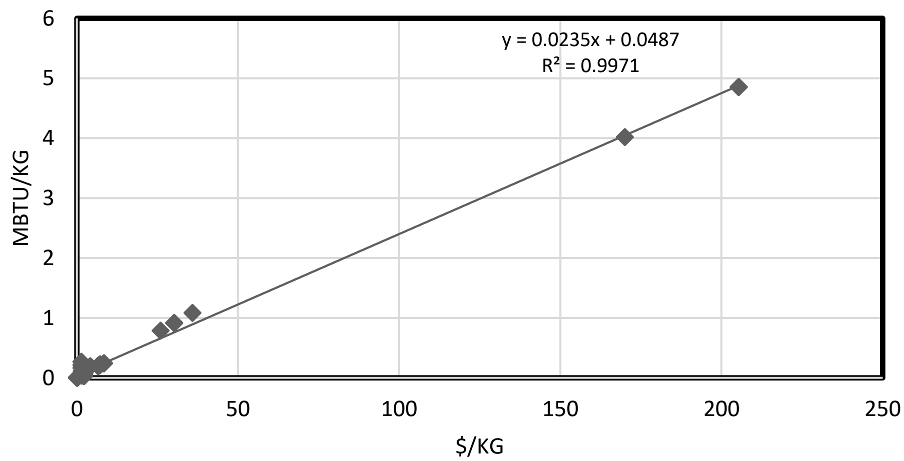

Figure 14: Embodied energy per unit mass vs cost of building materials per unit mass correlation of all buildings.

The equation for regressed line was Y = 0.0146X + 7984.2 (Y is the dependent variable i.e. embodied energy and X is the independent variable i.e. cost) for all the building materials in all five buildings which can be used to estimate the embodied energy from cost of building materials under this study.

CHAPTER V

DISCUSSION

Embodied energy calculations are complex and data intensive. Primary data is difficult to obtain and secondary data has issues such as reliability. Previous studies have tried to calculate embodied energy using various methods. As a standard method is not available, different studies use different methods incorporating varying energy inputs and hence their results are not comparable. For the purpose of this study, the input-output hybrid model suggested by Dixit (2017) has been used to calculate embodied energy.

Embodied energy calculation was performed on two levels: material level and project level. As embodied energy calculation at material level is complex and time consuming, the need to disaggregate needed to be investigated. For material level calculations, buildings were disaggregated into building materials. From results in table #, we can observe a substantial increase in embodied energy values while comparing embodied energy values with and without disaggregation. Embodied energy values indicate an increase of 165% to 260% when calculated at material level which is significant. The primary reason for the difference in values between project level and material level is the process of calculating embodied energy. After disaggregating building materials, embodied energy is calculated for materials using material specific industry sector. For instance, while calculating embodied energy of structural steel, the industry sector used is iron, steel and ferroalloy manufacturing. For calculating embodied energy for concrete, ready-mix concrete manufacturing industry is used. But while calculating embodied energy at project level, only educational and vocational structures industry is used. As calculation by disaggregation provides material specific results, the substantial difference is embodied energy values justifies the need of disaggregation during embodied energy calculation.

The dependency of embodied energy on cost was investigated by calculating the coefficient of correlation between embodied energy and cost and further performing regression analysis. The correlation was very strong for buildings A and D, strong for building C and strong moderate for buildings B and E. The difference between R^2 values across five buildings under study could be explained by the type of structure and the varying material proportions in the buildings. For instance, Building C is a green building with light-reflecting roof and a large water cistern churning in the basement. Building B has an auditorium and a basement level in the building. Presence of such additional systems in educational buildings could have an impact on the correlation between embodied energy and cost. Another reason for explaining the difference in R^2 values could be the widely varying cost to energy ratios for different materials.

Regression analysis was performed as correlation across all five buildings was strong ($R^2 = 0.776$). The equation of the regressed line was $Y = 0.00146 X + 7984.2$. The above equation can be used to estimate embodied energy from cost of building materials under this study in which X is cost (independent variable) and Y is embodied energy (dependent variable).

Correlation between embodied energy per unit mass (MBTU/Kg) and cost per unit mass ($/Kg) was investigated. The correlation was very strong between the coefficients for all buildings individually and across all buildings. The difference between R^2 values for these coefficients was negligible. As the coefficients are in terms of energy and cost per unit mass, the impact of cost to energy ratios is minimum. Further, R^2 also determines how variation in one variable can be explained by variation in the second variable. As embodied energy and cost were converted into embodied energy per unit mass and dollar per unit mass coefficients using same database (RSMeans Construction Cost Data), variation in MBTU/Kg can be easily explained by Cost/Kg (hence high R^2 values). To further enhance the understanding between differing R^2 values, more studies need to be performed.

While using RSMeans Construction Cost Data, this study used the costs in which the buildings were constructed. Future research can be focused on converting these costs for a specific year to increase uniformity and comparability.

CHAPTER VI

CONCLUSIONS

This study aimed to calculate the correlation between embodied energy and cost of building materials under study using input-output hybrid analysis. The embodied energy of 15 commonly used materials was calculated by using input-output hybrid model suggested by Dixit (2017) for 5 educational buildings on-campus at Texas A&M University. The correlation was tested to examine whether embodied energy could be estimated by cost of building materials under study. The results support a strong and positive correlation between embodied energy and cost of building materials for all five buildings under study where $R^2 = 0.776$. As correlation was strong, simple linear regression analysis was performed. Low p-value and t-statistic value significantly above zero confirm existence of relationship which increased the estimating confidence in the slope coefficient or gradient (m) of the regression line. The slope coefficient was 0.0146 which would help estimate embodied energy (dependent variable) from cost of building materials (independent variable). The equation of regressed line was $Y = 0.0146 X + 7984.2$

As embodied energy calculation by disaggregating into building materials is extensive and time consuming, the need of disaggregation was investigated by comparing results at material level and project level. As results demonstrate a significant increase in embodied energy values, the need for disaggregation can be justified to enhance completeness, accuracy and specificity of embodied energy calculation.

In order to better predict embodied energy from cost, more commonly used materials should be included. Also, including systems such as mechanical, electrical and plumbing should be considered for energy-cost relationship. As more and more focus turns towards energy efficient buildings, the relationship between embodied energy and cost could be more significant. Although there is a misunderstanding that reducing energy is expensive, a positive strong correlation between embodied energy and cost could indicate cost savings while reducing energy. The important thing to be considered is that such an analysis should be carried out over its life cycle as cheaper materials could result low initial embodied energy but significant recurrent embodied energy. A positive correlation between energy and cost could also provide incentive for owners and designers to choose energy efficient alternatives due to cost savings.

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