A Framework for an Improved Input-output-based Hybrid Method for Embodied Energy Calculation

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The global construction industry and its support industries deplete approximately 16% of water, 40% of energy, and 20% of raw stone, sand, and gravel each year. This extensive use of resources generates huge amounts of waste and releases harmful gases such as carbon dioxide to the atmosphere. The total energy consumed by a facility over its life cycle consists of embodied and operating energy. The embodied energy represents the sum of all energy sequestered in materials, products, and processes used in a facility's construction, use, and final demolition. The operating energy is expended during the use phase in operating the facility. While quantifying operating energy is standardized and straightforward, the calculation of embodied energy is not. This is due to a wide range of methodological and data quality issues. Until these issues are addressed, the application of embodied energy analysis to construction research and practice would remain limited. One major issue identified in the literature is the lack of a complete and standard embodied energy calculation method. This paper investigates relevant literature to identify major problems with the available calculation methods and the improvements to address them. A model to completely and reliably calculate embodied energy of construction materials is proposed.

Keywords: Embodied Energy, Construction materials, Life cycle assessment, Embodied carbon

Introduction

The construction industry consumes 40% of total global energy and 16% of water annually causing significant emission and pollution (Horvath, 2004; Langston and Langston, 2008). One of the primary sources of anthropogenic carbon dioxide emission is energy consumption by built facilities. The total energy consumed by a facility over its life cycle is made of embodied and operating energy (Treloar, 1998). The embodied energy, also known as capital energy, is consumed through the construction materials, products, and processes used in construction, maintenance, and final demolition of the facility (Treloar, 1998). The operating energy is consumed in building air conditioning, heating, lighting, and powering building appliances when the facility is occupied (Plank, 2008). For evaluating a sustainable built environment, accounting for both the embodied and operating energy is important. Quantifying operating energy is more standardized and straightforward than embodied energy. In fact, there is no globally accepted definition of embodied energy to date (Dixit et al., 2010). In addition, the lack of a complete, consistent, and construction material-specific embodied energy database hampers an industry-wide application of embodied energy analyses. According to studies (e.g. Plank 2008; Khasreen et al. 2009), the quality and reliability of available embodied energy databases is questionable due to some methodological and data quality parameters. Dixit et al. (2010 & 2012) discussed these issues in detail and recommended developing a protocol for embodied energy calculation. One major need identified in Dixit et al. (2012) was of a consistent and complete calculation method.

Among the commonly used embodied energy calculation methods are process-based analysis, input-output (IO)-based analysis and hybrid analysis each of which has advantages and disadvantages. For instance, a process-based method is considered more specific but incomplete than IO-based methods (Ting, 2006; Treloar, 1998). The major difference among these methods is attributed to a parameter called system boundary. A system boundary defines all major or minor energy or non-energy inputs covered by a study (Dixit et al., 2013). An IO-based method covers a wider system boundary than a process-based method (Dixit, 2013). When studies select calculation methods subjectively, it causes their results to have different levels of completeness (Dixit et al., 2013). The results of such studies cannot be compared due to a difference in their input coverages (Khasreen et al., 2009; Dixit et al., 2010). This paper focuses on investigating existing literature to determine major issues with the three calculation methods and propose a method for calculating complete and material-specific embodied energy of construction materials.

Literature Review

Embodied Energy of a Built Facility

Built facilities are constructed using a wide range of construction materials and assemblies which consumes energy during their life cycle stages of manufacture, use, and final disposal. The total energy consumed in these stages is termed the material or assembly's embodied energy (Vukotic et al., 2010; Dixit et al., 2010). Like a construction material or assembly, each facility also depletes energy during its life cycle stages of construction, maintenance, repair and replacement, and demolition and disposal. When the facility is constructed, each preconstruction and construction stage involves the use of construction materials, assemblies, and equipment. These stages also incorporate processes of construction, installation, fabrication, transportation, administration, and management (Treloar, 1998; Crawford, 2004; Dixit et al., 2013). The total energy embedded in construction materials and processes used in constructing the facility is termed its initial embodied energy (IEE). After the building is occupied, it is maintained and some of its components or systems are replaced over its service life. The total energy embodied in materials and processes used in maintenance and replacement processes is called recurrent embodied energy (REE) (Vukotic et al., 2010; Dixit et al., 2014b). At the end-of-life stage, when the building is demolished, the sum of energy used in demolition, waste sorting, hauling, and disposal is known as demolition energy (DE). The total life cycle embodied energy (LCEE) is made of IEE, REE, and DE (Cole and Kernan, 1996; Vukotic et al., 2010). The operating energy (OE) and LCEE of a building constitute its total life cycle energy (LCE) (Crowther, 1999; Ding, 2004; Dixit et al., 2010). For a complete and systemic reduction in building energy use and resulting carbon emission, reducing total LCE is critical. Since, OE and LCEE are interdependent, focusing only on OE or LCEE may not be as effective as optimizing the total LCE. Figure 1 demonstrates the LCE model for a building.

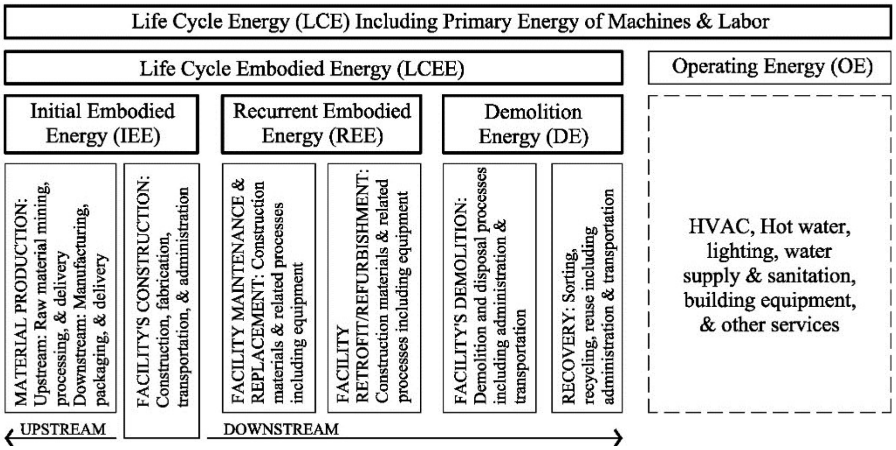

Figure 1: LCE model for a building

Embodied energy Components

The total embodied energy of a building or a construction material is composed of two primary components: (1) direct energy and (2) indirect energy (Ding, 2004; Dixit et al., 2010). The energy consumed directly by a construction material's main manufacturing process is called direct energy (Fay & Treloar, 1998). For instance, if a steel plant consumes electricity, natural gas, and coke in steel production, the sum of the energy contents of the three energy sources is termed direct energy consumption. In the case of a building, it is the sum of all types of energy consumed in manufacturing the building, which involves all onsite and offsite construction, fabrication, installation, transportation, and administration activities. Energy sources such as electricity, natural gas, and diesel used by construction equipment, vehicles, and labor are counted as direct energy (Treloar, 1998; Ding, 2004; Dixit, 2013). Energy is also consumed directly in maintenance, replacement, and demolition activities. Therefore, each embodied energy component (IEE, REE, and DE) consists of a direct energy use (Chen et al., 2001; Dixit et al., 2014b). When a construction material is produced, both the energy and raw materials are consumed directly. Since the energy use is already counted as direct consumption, any energy embodied in raw materials should be included in the calculation. The total energy embodied in all materials, products, machines, vehicles, etc. used in manufacturing the material is termed indirect energy (Treloar, 1998; Dixit et al., 2014b). The total indirect energy can be calculated using regressions at multiple levels. For instance, the process of cement production requires limestone, coal, and gypsum. When the energy embodied in in these ingredients is accounted for, it is called stage one regression. Each of the three ingredients also has its own ingredients when it was produced. Incorporating the energy embodied in the ingredients of the ingredient is a stage two regression. We can continue this regression until stage infinity to include all indirect energy usage (Treloar, 1998; Miller & Blair, 2009; Dixit, 2013). The same regression would be required for all machines and vehicles used in the manufacturing plant operations. It is important to note that, for a complete calculation, both the human and mechanical energy should be counted. The calculation of direct energy is fairly straightforward than indirect energy (Treloar, 1998; Dixit, 2013).

Embodied Energy Calculation Methods

Among the commonly used embodied energy calculation methods are process-based analysis, IO-based analysis, and hybrid analysis (Treloar, 1998; Ding, 2004; Langston, 2006). There is another method called statistical analysis, which utilizes national statistics to calculate the embodied energy using the total energy supplied to a particular industry sector and its total output (Treloar, 1998; Langston, 2006). Since this type of analysis is similar to the process-based analysis with the same limitations (Treloar, 1998; Langston, 2006), it is not discussed in detail in this paper. The following sections discuss the three commonly used methods:

Process-based Analysis. Process-based analysis provides more accurate (Ding, 2004) and reliable embodied energy results (Alcorn and Baird, 1996; Pullen, 2000b). In the case of a construction material, all direct energy inputs are collected from the main manufacturing plant. To account for indirect energy, indirect inputs are traced in the upstream of the main manufacturing process. In the case of a building, all direct inputs are quantified using the bill of quantities and materials' embodied energy coefficients. All indirect inputs are counted by going into the upstream of building construction (Treloar, 1998; Alcorn and Baird, 1996). After a certain stage in the upstream, tracing energy inputs becomes increasingly difficult. This happens due to the extensive efforts required to identify and count each input of the complex upstream processes (Alcorn and Baird, 1996; Ding, 2004). In such a case, the system boundary is truncated to complete the calculation. This truncation of system boundary causes a truncation error due to the exclusion of certain inputs (Lenzen, 2000). The process analysis is considered specific to a study but incomplete due to the boundary truncation (Ting, 2006; Khasreen et al., 2009; Dixit et al., 2010).

Input/output-based Analysis. An IO-based calculation utilizes the national input output accounts, which show the monetary transactions among various industry sectors of an economy (Miller & Blair, 2009). If inputs purchased by an industry sector from an energy providing sector are known, the energy intensity of the industry sector can be quantified using energy prices (Treloar, 1998; Dixit et al., 2014). The national IO accounts include a direct requirement matrix, which lists the inputs directly required to produce one unit of an industry sector's output (Miller and Blair, 2009). For instance, to manufacture one automobile tire, the rubber industry sector directly requires some amount of inputs from industry sectors "C" and "D." When the rubber industry sector increases its output by $1, it causes sectors "C" and "D" to increase their outputs. The increased output of sectors "C" and "D" requires their input providing sectors to increase their outputs. Therefore, the impact of increasing $1 output of an industry sector can be felt throughout the economy. All of these requirements excluding the direct requirements are called the indirect requirements of the rubber industry sector. The indirect requirements can be quantified by subtracting direct from the total requirements (Treloar, 1998; Miller & Blair, 2009; Dixit, 2013). There are two approaches to calculate total requirements: (1) Leontief's Inverse Matrix (LIM) and (2) power series approximation (PSA) method. The LIM can be calculated by subtracting the direct requirement matrix from an identity matrix and finding the inverse of the resulting square matrix. Since this method provides the total requirements from stage one through infinity in the upstream, the indirect requirement of each stage are not known. If PSA method is used, indirect requirements associated with each upstream stage can be calculated. The calculation can go on up to stage infinity but is not required, since calculation up to stage 12 covers nearly 99% indirect requirements (Treloar, 1998; Miller & Blair, 2009; Dixit, 2013).

Hybrid Analyses. A hybrid analysis unifies the benefits of process-based and IO-based methods to provide more complete, accurate, and material specific results (Treloar, 1998; Crawford, 2006; Acquaye, 2010; Dixit, 2013). The goal is completeness and specificity, which come from an IO-based and a process-based framework, respectively. There are two types of hybrid analyses: (1) process-based and (2) IO-based hybrid analysis.

Process-Based Hybrid Analysis: For improving the completeness of the system boundary of a process-based method, IO data are integrated into a process-based framework (Treloar, 1998; Crawford, 2004; Dixit, 2013). For instance, whenever it becomes impractical to trace upstream energy inputs, the process-based framework can be truncated and remaining inputs can be counted using IO analysis. In the case of a building, material quantities used in building construction can be sourced and multiplied by materials' IO-based energy intensities (Dixit, 2013).

IO-based Hybrid Analysis: To improve the reliability of embodied energy results, process data of energy use are inserted into an IO framework (Treloar, 1998; Langston, 2006). The process-based direct energy use data is derived for all industry sectors of an economy, data of which may be readily available. These process-based direct energy data are then incorporated in the direct requirement matrix if process data are available for all industry sectors. It is assumed that the more the inclusion of actual energy use data, the more reliable the hybrid model (Dixit, 2013; Dixit et al., 2014). If process data are not available for all industry sectors, integrating them in the IO model may generate some unwanted indirect impacts as warned by Treloar (1998).

Research Methods

There is a lack of a standard method to comprehensively calculate embodied energy specific to a material under study. The main purpose of this study is to research the available embodied energy calculation methods, identify key issues with them, and propose a method to calculate embodied energy of a built facility and its constituent materials in a complete and study-specific manner. Since no perfect calculation method exists currently, we surveyed relevant literature to identify key issues related to commonly-used embodied energy calculation methods. Using inferences from the literature review, we proposed a method that can provide a complete and specific embodied energy calculation. Deriving conclusions from an extensive literature survey is also known as literature-based discovery (LBD), a method proposed in 1986 by Dr. Don R. Swanson (University of Chicago). This method was originally proposed in the field of biomedical sciences but its use in other fields have also been successfully demonstrated (Weeber, 2007). We created a matrix of commonly-used calculation methods and key embodied energy issues identified in the literature to compare the relative capabilities of the methods. The matrix helped identify the most promising quantification method. Using a rigorous literature survey, we gathered a set of improvements to address the unresolved issues with the identified method in order to improve it further. Finally, we proposed a method to completely quantify the embodied energy of construction materials.

Results

Main Issues with Current Embodied Energy Calculation Methods

Table 1 provides a comparison matrix of various embodied energy computation methods and major methodological issues. These issues were selected based on published case studies such as Treloar (1998), Joshi (1998), Crawford (2004), Langston (2006), Miller & Blair (2009), Acquaye (2010), and Dixit (2013). Currently, there exists no perfect method that can provide complete, reliable, and material-specific embodied energy results (Ting, 2006; Menzies et al., 2007; Khasreen et al., 2009; Dixit, 2013). We found the following main issues with the available calculation methods:

Completeness: The completeness relates to how well a method covers all major and minor inputs in the calculation. A process-based method provides incomplete results due boundary truncation and data unavailability. Even detailed and most extensive process-based calculations fail to attain reasonable completeness (Treloar, 1998; Acquaye, 2010). Since an IO-based analysis is done at a macro level, it covers a wider system boundary providing more complete calculation (Treloar, 1998; Crawford, 2004; Dixit, 2013). Even though the completeness of a process-based hybrid method is improved, it still carries some of the limitations of its process-based framework (Crawford, 2004; Dixit, 2013). For instance, the energy embodied in services such as banking, finance, architectural and engineering consultancy, and other related services remain excluded (Treloar, 1998; Crawford, 2004). An IO-based hybrid methods still remains the most complete method of embodied energy calculation (Alcorn and Baird, 1996; Langston and Langston, 2008). In addition, by adding human and capital energy inclusion, the current form of IO-based hybrid method can be greatly improved, (Dixit, 2013).

Specificity: The results of a process-based analysis is considered more specific to a material under study than IO-based results (Treloar, 1998; Crawford, 2004; Dixit, 2013). In an IO-based analysis, the energy intensity is calculated for an entire industry sector with an aggregated output of a wide range of products. This means that each of the products would have the same energy intensity, which may not be accurate (Treloar, 1998; Langston, 2006; Acquaye, 2010; Dixit, 2013). Therefore, the results of IO-based analyses lack specificity. Since IO-based energy intensities are used in a process-based hybrid analysis, its results are less material-specific than a process-based analysis (Dixit, 2013). The IO-based hybrid method also lacks specificity due to its IO-based framework (Joshi, 1998; Acquaye, 2010).

Table 1

Major issues with current embodied energy calculation methods

Issues	Process-based Analyses	IO-based Analyses	Process-based Hybrid Analyses	IO-based Hybrid Analyses
Completeness	Questionable completeness	Most complete calculation	Improved completeness	Most complete calculation
Specificity	Material-specific results	Aggregated results for an entire industry sector	Material-specific results	Less-aggregated results for an entire industry sector
Reliability	Reliable results	Poor reliability	Reliable results	Poor reliability
Representativeness	Relatively robust	Lacks temporal representation	Relatively robust	Lacks temporal representation
Common errors	Truncation	Energy double counting	Truncation & energy double counting	Energy double counting

Reliability: Since most process data are collected from manufacturers' sources, process-based results are considered more reliable than IO-based results (Crawford, 2004; Dixit, 2013). The results of an IO-based method are regarded as less reliable due to some methodological issues. Since the energy intensities are computed in \$energy use per unit of \$output, energy prices are required to convert them to energy units (e.g. MBtu/\$output) (Crawford, 2004; Acquaye, 2010). In addition, in order to calculate embodied energy per unit of volume or mass, product prices are used (Treloar, 1998; Dixit, 2013). Because energy and product prices fluctuate significantly, the use of prices multiple times makes the results less reliable. In addition, the IO-accounts are conventionally developed based on proportionality and homogeneity assumptions (Crawford, 2004; Acquaye, 2010). According to the proportionality assumption, the inputs are proportional to output which may not be accurate. For instance, if 20 kg of steel is required to produce one washing machine then 40 kg of steel would be required for two washing machines of the same cost. Under the homogeneity assumption, the mix of inputs to an industry sector is considered homogenous across all products produced by the sector (Acquaye, 2010; Dixit, 2013). For instance, all products produced by an aluminum industry sector would consume the same amount of aluminum, other alloy metals, electricity, etc. per unit of their output that may be inaccurate.

Representativeness: The process-based method, due to its robust data, produces results that are geographically, temporally, and technologically representative (Treloar, 1998; Dixit, 2013). However, most economic data are not reported in a timely manner, which may affect the temporal representativeness of IO-based analyses (Crawford, 2004; Langston, 2006; Miller & Blair, 2009). Due to the presence of IO data, a process-based hybrid method may lack temporal representation. Similarly, the temporal representation of an IO-based hybrid method is questionable if old data are used (Dixit, 2013).

Common errors: One major error with a process-based method is of truncation error which could cause up to 50% incompleteness in the calculation (Lenzen, 2000; Ting, 2006; Khasreen et al., 2009). Other exclusions such as the embodied energy of services may also cause serious incompleteness. In the case of IO-based analyses, the most common error is of counting energy inputs multiple times (Treloar, 1998; Langston, 2006; Dixit, 2013; Dixit et al., 2014). Double counting of energy inputs occurs when the energy contents of both the output as well as inputs of an energy providing sector are counted. This is particularly true for energy providing sectors that purchase large quantities of primary fuel from energy extraction sectors (Dixit et al., 2014). Since a process-based hybrid analysis utilizes IO data in a process framework, it may contain both the truncation and energy double counting error.

Improving the IO-based Hybrid Method

Improving the completeness of a process-based method is difficult than enhancing the reliability and specificity of an IO-based framework. Although a process-based hybrid method provides improved completeness, it still excludes many energy inputs. Studies (Treloar, 1998; Crawford, 2004; Dixit et al., 2014) suggested that the IO-based hybrid method is the only method that has the potential of providing a complete, reliable, and study-specific results. Table 1 shows four major issues with the IO-based hybrid method, which if addressed, can drastically improve the quality of its results. Figure 2 illustrates a model to improve the current state of IO-based hybrid embodied energy. A rigorous survey of literature revealed the following improvements:

Completeness: Although an IO-based hybrid method provides relatively complete energy calculation, its completeness can be further enhanced by calculating and integrating the energy embodied in labor (human energy) and capital investment (capital energy) as demonstrated by FAO (2001) and Dixit (2013). Two energy sectors can be inserted into the IO model representing human and capital energy.

Specificity: An aggregated industry can be broken down into two sectors, one representing the construction material under study and other denoting all other products. Disaggregation can be done on the basis of total inputs required to produce the construction material. The method is described in detail in Joshi (1998) and Dixit (2013).

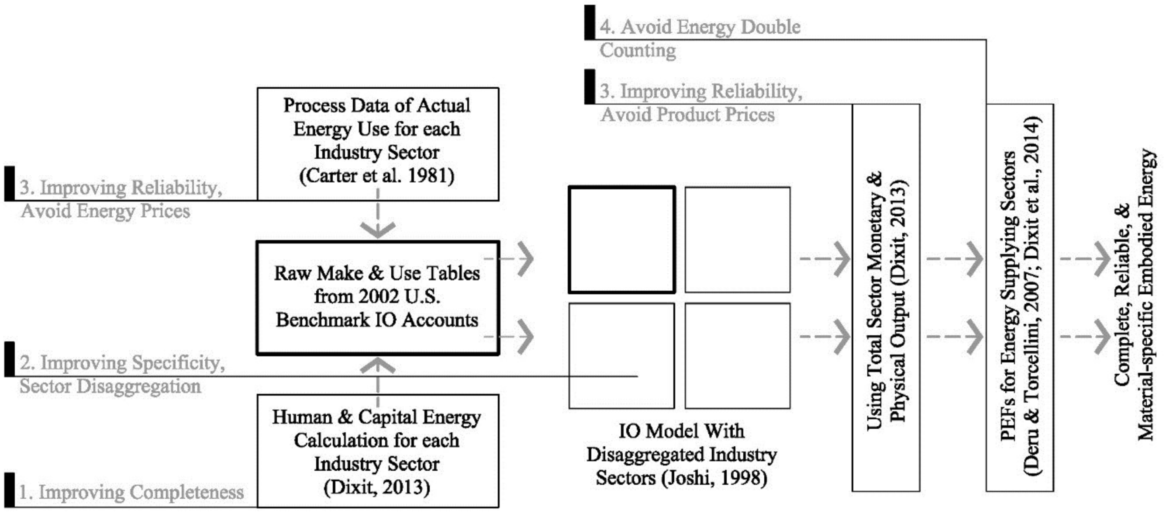

Figure 2: Improved IO-based Hybrid Embodied Energy Model

Reliability: The results of IO-based hybrid method are considered unreliable due to the use of energy and product prices, which may be inaccurate. Carter et al. (1981) proposed a method to collect the data of energy used by each industry sector and insert them into an IO framework. In this method, energy intensities are calculated in the unit of MBtu/$ without using the unreliable energy prices. To translate the IO-based hybrid energy values to embodied energy per unit mass or volume of a construction material, the price of material is required. Dixit (2013), recommended calculating the total embodied energy of the industry sector by multiplying its total monetary output ($) and its embodied energy intensity (MBtu/$). Dividing the total embodied energy of the industry sector by the total physical output of construction material (in lbs. or cubic feet) can provide embodied energy per unit mass or volume without using the material prices. If industry sectors are disaggregated using the material input mix as suggested by Joshi (1998), the impact of proportionality and homogeneity assumptions can also be reduced.

Energy Double Counting: To avoid accounting for energy inputs more once, all inputs to main energy providing sectors are kept at zero. This curtails all direct and indirect energy paths to energy providing sector obviating any double counting of energy usage. To account for the curtailed direct and indirect energy inputs, a set of PEFs can be used as described by Deru and Torcellini (2007) and Dixit et al. (2014). However, the set of PEFs must be calculated in a complete and accurate manner.

Conclusions

In this paper, relevant literature was reviewed to identify key issues with current embodied energy calculation methods. In addition, improvements to these method suggested by various studies were also identified. The literature review indicated that the process-based methods suffered from the issues of incompleteness and truncation errors. At a construction material level, these methods may exclude a significant portion of indirect embodied energy. This incompleteness can increase greatly at a facility level due to the use of large quantities of construction materials and a wide range of construction-related processes. The conventional IO-based calculation methods produce complete but unreliable and aggregated results, which may contain serious errors. Based on the literature review, it was found that the IO-based hybrid method contained the potential of providing complete, reliable, and material-specific embodied energy calculation. Using literature recommendations, the current form of IO-based hybrid method was improved. A model was proposed to calculate the embodied energy of construction materials.

This model can help establish a complete, reliable, and material-specific embodied energy database that can be integrated into a building information modeling (BIM) authoring tool (e.g. Revit Architecture) for its industry-wide application. With a slight modification, this IO-based hybrid embodied energy model can be applied to any national economy across the world. The future research may include developing the improved IO-based hybrid model, experimentation using case studies, and validating its results.

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