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MEASURING THE EMBODIED ENERGY OF CONSTRUCTION MATERIALS THROUGH BUILDING INFORMATION MODELLING

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Abstract: Currently, researchers are more concerned about the calculations of energy at the operational stage, mainly due to its larger environmental impact, but the fact remains, embodied energies represent a substantial contributor unaccounted for in the overall energy computation method. The calculation of materials' embodied energy during the construction stage is complicated. This is due to the various factors involved. The equipment used, fuel needed, and electricity required for each type of materials varies with location and thus the embodied energy will differ for each project. Moreover, the method used in manufacturing, transporting and putting in place will have significant influence on the materials' embodied energy. This anomaly has made it difficult to calculate or even bench mark the usage of such energies. This paper presents a model aimed at calculating embodied energies based on such variabilities. It presents a systematic approach that uses an efficient method of calculation to provide a new insight for the selection of construction materials. The model is developed in a BIM environment. The quantification of materials' energy is determined over the three main stages of their lifecycle: manufacturing, transporting and placing. The model uses three major databases each of which contains set of the construction materials that are most commonly used in building projects. The first dataset holds information about the energy required to manufacture any type of materials, the second includes information about the energy required for transporting the materials while the third stores information about the energy required by machinery to place the materials in their intended locations. Through geospatial data analysis, the model automatically calculates the distances between the suppliers and construction sites and then uses dataset information for energy computations. The computational sum of all the energies is automatically calculated and then the model provides designers with a list of usable equipment along with the associated embodied energies.

1 Introduction

Buildings consume about 40% of the overall global energy demand (Dixit et al.2012). This represents a significant portion of the whole global usage and thus improving the efficiency either during construction or operations can greatly reduce the environmental impact of these structures. Today, the production of energy yields carbon dioxide, which is a substantial contributor in climate change. With the growing number of people, the energy demand is only expected to increase and thus more carbonic emissions will be generated. Many governmental bodies have realized the importance of tackling this issue and henceforward many have begun implementing standards to dictate the energy usage.

The shift towards green buildings has led many to study ways to tackle energy norms. Buildings can consume energy in either embodied or operational forms. From a holistic lifecycle approach, energy is required for producing construction materials, transporting them and then placing them in their intended locations. In the post construction stage, energy is required for operational processes such as lighting and heating. Through the closing stages, energy is required for renovation and finally for disposal. The study of all energy used throughout all phases of building is known as the life cycle energy assessment. Energy may be calculated through the determination of electricity used or through the amount of fossil fuels burned at each phase. Currently, emphasis is given to energy used in the operational stages, also known as operational energy. This is due to its larger energy demand but with the advances in machinery and insulation techniques, the shift is beginning to move towards the energy consumed at other stages. Such energy can be identified as embodied energy. (Balouktsi et al. 2016) state that embodied energy represents 10- 15% of the whole lifecycle but with low environmental initiatives, theoretically embodied energy will present 100% of total energy consumptions.

There are many challenges involved in calculating or benchmarking embodied energy. First of most, many researchers have different interpretation of the term. According to Dixit et al.(2012) embodied energy is the amount of energy required by building materials during all processes of production, construction, and final disposal. On the hand, Gardezi et al.(2014) identify embodied energy as the energy consumed in extraction, manufacturing, assembly and transportation. To add the ambiguity, Ariyaratne et al. (2014) define embodied energy as the sum of fuel-related and process related carbon emissions associated with a building during extraction, manufacturing, transportation, construction, maintenance, refurbishment, and demolition. All such explanations are similar in concept but yet the boundaries involved within each approach vary causing the embodied energy (EE) calculation methodologies to fluctuate.

Another challenge involved with embodied energy quantification is the determination of whether the type of energy used is significant in the computational process (Dixit et al. 2010). Energy is either produced in renewable form or as primary energy made from burning fossil fuels. Since renewable productions have no carbonic emissions, it is beneficial to ignore such energy. The idea of a life cycle assessment is used to assess and eventually reduce environmental effects. Since renewable energy has no effect in climate change, adding such figure to the overall computed energy is misleading especially if comparisons are required (Balouktsi et al. 2016). Nevertheless, feedstock energy is another parameter that could cause inconsistencies between the embodied energy calculation methods. Feedstock energy is the amount of energy possessed in fuels used in material production. For example plastics contain some petrochemicals in which energy isn’t released. Some researchers have opted to add these and thus further variations exist within the different EE computational techniques (Hammond et al.2008).

Calculating embodied energy is rather difficult. According to Dixit et al.(2010), embodied energy varies from one geographic region to another. Travel distances can add to such energy through the added amount of fuel required. Furthermore, Praseeda et al.(2015) state that embodied energy also depends on the regional climate and the technology used for extraction, manufacturing, transportation and construction. This paper lists and evaluates the difficulties and errors existent in the current EE quantification methods. Furthermore, it suggests a systematic approach as to address such complications.

2 Embodied Energy Life Cycle Framework

According to (Dixit et al. 2012) the prevalent standard used for EE life cycle assessments is the ISO 14040. ISO identifies LCA as a 4 stage process involving goal and scope definition, inventory analysis, impact assessments, and finally the improvement or interpretation stage. As within the confinements of ISO, researchers have decided to assess embodied energy through the creation of material energy inventories. Data is collected based on selected system boundaries, quality requirements and most importantly study goals. According to Ariyaratne et al. (2014) there are four main boundaries used to quantify embodied energies. These include cradle to gate, cradle to site, cradle to end of construction and cradle to grave. Energy inventories may include data as to assess each.

Cradle to gate is a system boundary in which energy is calculated for materials through extraction and production (i.e. manufacturing processes). Cradle to site is a system boundary in which material energy is calculated for manufacturing along with the transportation required (Balouktsi et al. 2016). Cradle to end of construction is a system boundary for which the energy used is calculated based on manufacturing, transportation and placement or construction. Overall it is the energy required by materials until the handing of the project (Balouktsi et al. 2016). Cradle to grave is a boundary in which the energy required by materials is calculated from extraction all the way to disposal. This energy involves all energies from previous boundary systems in addition to maintenance, repair, replacement, refurbishment, demolition, transportations, waste processing and disposal (Balouktsi et al.2016).

Within each boundary, the energy collection method used to identify the embodied energy of materials could vary. (Dixit et al. 2010) identify three methods in which material EE may be quantified. These include the process modelling method, input/output modelling method and hybrid energy modelling process.

Process modelling is an energy evaluation method where each material is identified as a final product and then through its set Life cycle boundaries, backward and/or forward analysis compute process energies (Crawford et al. 2005; Dixit et al. 2010) . Unfortunately, the process modelling method can have imperfections due to the confinements of the established boundary system as some lower stage energies may be overlooked (Dixit et al. 2010). This process is the most common due to its directive approach and ease of implementation.

Input output modelling method (I/O) is an energy evaluation method that uses the interdependence of materials to identify energy usage. The Input /output method relies on the idea that materials outputs in certain process can still be inputs required for production and in such perspective one material production affects another. Moreover the input output method analyzes the system from a holistic approach and thus it can allows for high accuracy in primary and renewable energy analysis (Crawford et al. 2005; Dixit et al. 2010). Overall, the process is rather complex as it requires national economics and power production factors to identify each material energy usage.

Hybrid modelling is an energy evaluation method that combines both process and I/O evaluation methods. In cases where it is difficult to compute material embodied energies using I/O models the process modelling methodology may be used for some materials (Sangwon et al. 2007).

Generally, ISO 14040 is widely criticized. According to Jeswani et al. (2010), the use of ISO 14040 presents a number of issues due to the various interpretation users can deduce for calculation methodologies. For example, Zamagni et al. (2008) claim, that ISO 14040 recommends including all processes involved with manufacturing during lifecycle assessment. However, the standard later endorses the removal of processes with no effect to the end results. Such inconsistency causes misinterpretation. On the other hand, many criticize concepts used within the model. ISO standards imply using the process quantification method but due to its accuracy, using the input / output methodology can yield enhanced results (Suh et al. 2004). Furthermore, Dixit et al. (2010) classify ISO lifecycle methodologies as vague and hence many researchers have added subjective improvements to the EE quantification method. Such alterations have caused variability in the used quantification methods. Perhaps, ISO 14040 could be considered flawed but due the lack of other globally recognized standards and due to its popular use in quantification studies. Hammond et al. (2008) imply these guidelines can be used as a preliminary baseline for lifecycle assessments.

3 Embodied Energy Calculation Methods

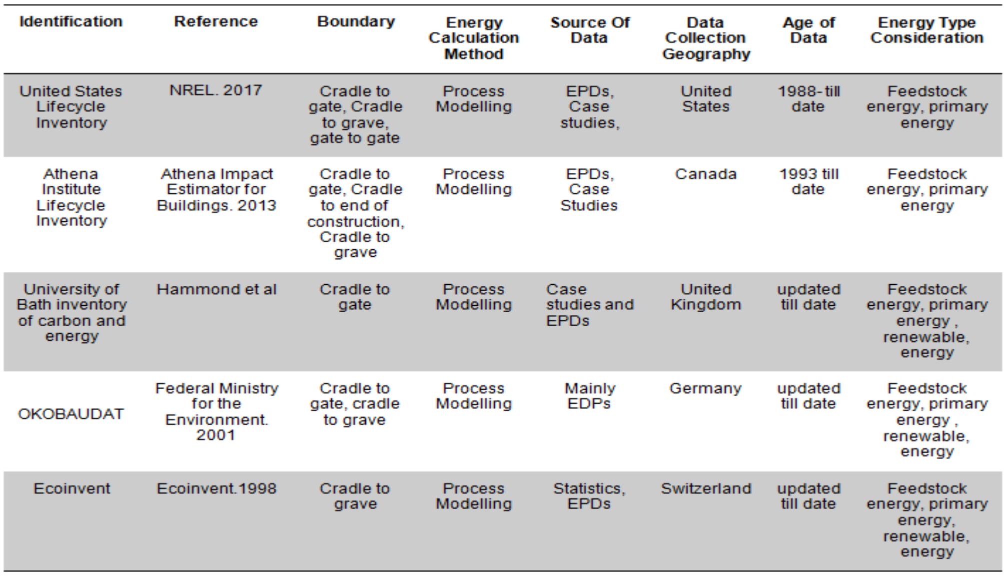
According to Praseeda et al. (2015) embodied energy assessments are mainly attentive to the energy within the cradle to gate boundary. With the aid of various energy declaration requierments, manufacturers are beginning to release EE information for production, and henceforth many researchers are able to collect such figures as to create extraction and manufacturing EE inventories. Through such databases, embodied energy can be quantified for specific materials per unit mass .Unfortunately; this isn’t the case for other sectors involved within a building lifecycle (Praseeda et al.2015). Detailed energy usage information isn’t commonly available for transportation, construction, and end of life stages. Calculating EE based on a cradle to gate boundary represents only a portioned amount of the total EE materials possess and thus, a full analysis is required through a cradle to grave boundary. There have been some efforts intended to produce inventories for such parameter but these results remain estimates as material EEs in cradle to grave boundary greatly vary from one building to another (Praseeda et al.2015). These inventories tend to assume a singular energy value per material regardless of the different factors involved.

To assess a cradle to grave EE, the current practice involves the use of computerized software (Ariyaratne et al. 2014). These allow for a case by case scenario analysis. Unfortunately, some software lack accuracy especially since they depend on approximations in the quantification method. Furthermore these software are programmed in a way as to build on values presented in current EE inventories. This creates imperfections especially since inventories are produced only for specific geographical regions and therefore not all inventories can be used globally. Additionally, EE inventories present inconsistencies in reported values and thus the selection of a reliable inventory can affect the accuracy of the whole lifecycle embodied energy quantification process (Dixit et. al.2012). This is due to the various interpretations deduced from the ISO 14040 standard (Jeswani et al. 2010).

3.1 Available Inventories Used To Quantify Embodied Energy

Table 1 summarizes the list of major comprehensive inventories available worldwide. The table below tends to include the boundaries used for each inventory together with the energy calculation method. Also the source of data, regional preferences and the approximate age of collected data are identified. One additional parameter is the determination of energy type consideration.

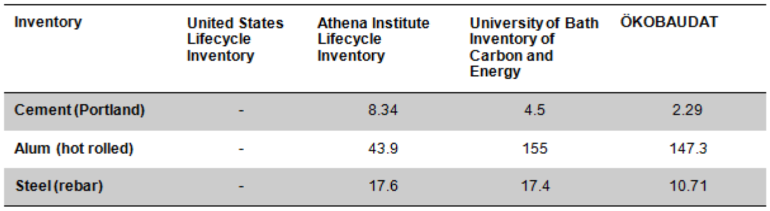
Table 1: Embodied Energy Inventory Summary table



Identification	Reference	Boundary	Energy Calculation Method	Source Of Data	Data Collection Geography	Age of Data	Energy Type Consideration
United States Lifecycle Inventory	NREL. 2017	Cradle to gate, Cradle to grave, gate to gate	Process Modelling	EPDs, Case studies,	United States	1988- till date	Feedstock energy, primary energy
Athena Institute Lifecycle Inventory	Athena Impact Estimator for Buildings. 2013	Cradle to gate, Cradle to end of construction, Cradle to grave	Process Modelling	EPDs, Case Studies	Canada	1993 till date	Feedstock energy, primary energy
University of Bath inventory of carbon and energy	Hammond et al	Cradle to gate	Process Modelling	Case studies and EPDs	United Kingdom	updated till date	Feedstock energy, primary energy , renewable, energy
OKOBAUDAT	Federal Ministry for the Environment. 2001	Cradle to gate, cradle to grave	Process Modelling	Mainly EDPs	Germany	updated till date	Feedstock energy, primary energy , renewable, energy
Ecoinvent	Ecoinvent.1998	Cradle to grave	Process Modelling	Statistics, EPDs	Switzerland	updated till date	Feedstock energy, primary energy, renewable, energy

To analyze EE inventory differences, three materials commonly used in the construction industry are selected. These are cement, aluminum, and steel. Table 2 presents the EE for each material derived from different inventories. The results are presented in MJ/kg.

Table 2: Inventory Result Comparison



Inventory	United States Lifecycle Inventory	Athena Institute Lifecycle Inventory	University of Bath Inventory of Carbon and Energy	ÖKOBAUDAT
Cement (Portland)	-	8.34	4.5	2.29
Alum (hot rolled)	-	43.9	155	147.3
Steel (rebar)	-	17.6	17.4	10.71

- : Limited Data Available

As shown, EE for each material presents irregularities. This is due to the material identification method each inventory follows. For example, in the Athena Institute lifecycle inventory, Portland cement is identified as a generic material while in ÖKOBAUDAT, cement is specified by type i.e. (type 1 -5) . No generic EE values are present. Similarly, in ÖKOBAUDAT aluminum sheets are identified as a singular item with one production process but in the University of Bath inventory multi processes are identified. Consequently, aluminum will possess different embodied energies per processing method in such inventories. The effect of regional data and the use of sources that quantify energy based on various boundaries tend to create additional inconsistencies. For example the United States Lifecycle Inventory tends to use the cradle to grave quantifications while University of Bath Inventory only uses a cradle to gate. Furthermore in the Athena Institute Lifecycle Inventory, EE values are based on Canadian industries and thus electricity usages are different as compared to other inventories. Overall, most inventories seem to use a consistent energy calculation approach but the factor such as the ones identified above cause variances. (NREL. 2017; Athena Impact Estimator for Buildings. 2013; Hammond et al (2008) ; Federal Ministry for the Environment 2001; Ecoinvent.1998)

3.2 Software Used To Quantify Embodied Energy

In an effort to identify cradle to grave embodied energies, computerized softwares may be used. These include Athena Impact Estimator, SimaPro, and openLCA.

Athena impact estimator is an extension of the Athena Institute lifecycle inventory. Initially, users are prompted to manually enter all materials used along with the project location. The estimator will then use the Athena institute inventory to quantify a cumulative EE for materials in a cradle to gate boundary. Simultaneously, the software will determine the average regional energy values for transportation, construction, maintenance and disposal to quantify the total lifecycle EE. Unfortunately, the Athena Impact estimator does not use exact distances or the actual equipment used by each material in a specific project. Such approximation causes inaccuracy in the quantification.

Unlike the Athena impactor estimator, SimaPro and OpenLCA are rather complete and accurate. In such software, different EE inventories can be imported to select the one that suit the project location. These can include Ecoinvent and ÖKOBAUDAT. Users are prompted to enter each material used in a building along with the transportation method, locations, equipment or process types used in construction, maintenance and disposal. These tools will then equate the total EE energy for the lifecycle in cradle to grave boundary. Unfortunately such methodology is tedious especially if a project contains a large number of materials. Moreover, this process is also prone to human errors as some materials may be omitted. Nevertheless, these software tend to create issues in quantifying EE at design stages. During conceptual design, little information is available about the equipment that will be used throughout a project. For example, designers do not know whether haulers or pickup trucks will be used in the transportation. Also, designers have little information about the type of crane and pump that will be used for construction. In such situation these software are difficult to use.

4 BIM Platform

BIM softwares are CAD based platforms in which engineers can create 3D models with detailed metadata. These include properties such as price, volume and material makeup. Consequently, such platform allows for detailed cost and material quantity takeoffs. BIM concepts give engineers from different disciplines the ability to create multiple models and then the ability to superimpose them as to identify clashes. All such properties have driven the industry to adopt BIM tools as their major design tool. Overall, BIM model is considered as a space in which a building can be conceptualized. If external design tools are required, bi-directional transfers can be performed to import and export information. Today, design software such as Etabs, Staad, and Tekla all have the capability to exchange data with BIM tools.

The BIM platform is ideal for EE assessments especially if it is used at early design stages. Currently, EE analyses are performed after the completion of initial designs. According to Ariyaratne et.al.(2014), this is due to the lack of knowledge that designers have with regards to EE quantifications. In practice, completed models are sent to sustainability consultants whom in return adjust the building structure to match criteria specified in green rating programs. Unfortunately, these programs possess ambiguities in terms of EE assessments. For example, LEED, a sustainability green building rating system, gives additional credits to buildings in which materials of low EEs are used, but no specific number is identified (Dixit et al.2012). Furthermore LEED doesn't identify how to quantify EE energy and in such perspective, consultants are able to adjust the design without completely accounting for all the lifecycle EE. For example, limited number of aluminum window frames may be altered to include wood as means to acquire the points specified for the use of low EE materials. This is a flaw, which consultants may take advantage of. Designs are based on certain budgets and resources, and thus any small change performed after the design completion may cause a drastic change in the cost and structural requirements. It is beneficial to address EE at the early design stage. Through BIM plugins, EE for singular and grouped materials may be identified at the conceptual design stage. This also allows for the modification of materials within the assigned budget.

Presently, there is a number of plugins intended to quantify lifecycle EE energy. As discussed above, one issue involved with the use of computerized software is the need to manually enter materials for the assessment. This issue can be solved all within the BIM Environment. One example is the Tally Environmental Impact Tool. This plugin is one of the most comprehensive tools produced for LCA. As this plugin begins to operate, the lists of materials used in the model are identified. Users are then prompted to select the details required for each item identified in the project. To clarify, a wall in BIM tool might be constructed with concrete but in reality concrete has certain strength which needs to become clear for the plugin. Users are required to select such parameter to calculate EE. Tally uses a cradle to grave boundary to assess EE. Through the selection of alternative materials, comparison tables can be used to select low EE options. Overall, this plugin addresses the issue of early EE quantification, but again the results are approximated. Unfortunately, the plugin does not use exact distances nor the actual equipment used by each material in a specific project. Tally quantifies EE based on the average energy required by a material for transportation, construction, maintenance, rehabilitation and disposal.

5 Proposed Solution

Each inventory presented in section 4.1 seems to use a rather consistent approach but still possess errors if used in cradle to grave boundaries. If such inventories are used within the correct geographical region, there are lower chances of inaccuracies especially if used only for cradle to gate EE calculations. In such cases, the EE for extraction and manufacturing can be used as a baseline for the full lifecycle assessment. This idea is derived from the fact that factories tend to use repetitive processes. Unlike buildings where locations, construction methods, maintenance cycles, and disposal approaches vary, plants are rather stationary and rarely change their techniques. They are not dependent on the factors identified and thus EE for manufacturing and extraction are rather constant for different buildings. Furthermore, the concentrated research for cradle to gate boundaries and the continuous improvements in data collections all suggest these values are reliable within their study location (Dixit et al.2010). In an aim to determine a method to calculate EE for materials used in the Canadian industry, a plugin is developed and associated in a BIM tool (Autodesk Revit). This plugin will use the manufacturing and extraction EEs for materials from the Athena lifecycle Inventory and subsequently further analysis will be determined based on a set of created inventories for transportation and construction. These inventories contain a large number of collected information about the energies required by machines per unit distance used for these two processes.

The proposed plugin quantifies the amount of energy building materials require through the cradle to end of construction boundary. The quantification of broader boundaries are currently being analysed and will be published in due course. At the moment, the developed tool identifies the materials used within a BIM model and consequently it determines the minimum amount of EE each material requires. This is done through testing various equipment and vehicles that can be used by materials through manufacturing, transportation and construction. The least energy consuming method for each material is selected to identify the least EE materials will require within the identified boundary. The plugin will store such information in generated xml files and then it will allow users to change building materials as to identify the items with the lower EE at the conceptual design stage. Through the overall proposed practice, the plugin addresses the issues of inaccuracy present within other calculation means. The dictation of equipment used in each process helps in exact EE energy quantification. Unlike other software, the proposed plugin doses not identify a singular method for production, transportation and construction. Through a series of computational comparisons, the least consuming energy equipment is selected for each lifecycle phase and in return it is used to quantify energy at each stage. Overall, the proposed plugin helps designers to identify the least consuming EE material early in the design stage. This allows for reduced sustainability assessment changes especially since designers become able to identify the actual equipment needed for precise quantification.

5.1 Plugin Development

The proposed plugin is developed through the use of Revit API. With the aid of functions presented within the software development kit (SDK), a C# code was written to perform functional analysis required to quantify EEs. The proposed plugin calculates the total EE by quantifying the energy required to extract and manufacture materials, the energy required to transport materials from factories to sites and finally the energy required to place materials through construction activities. To aid in this quantification six inventories were created. These include the cradle to gate inventory, Truck vehicle inventory, Hauler inventory, Concrete mixer inventory, Crane inventory and finally the concrete pump inventory. In the cradle to grave inventory, the amount of energy required to extract and manufacture 185 materials are identified. These are based on values presented in the Athena lifecycle inventory and they represent the most common materials used in buildings. Furthermore, each material is assigned a category, which will be used to link the equipment required for each material in the LCA. A total of 17 categories are used. Furthermore, this inventory contains the density for each material. In the truck inventory a total of 178 vehicles were analyzed. These include pickups, flatbed trucks and Tipper trucks. For each vehicle, the maximum load weight and volume are identified and also the fuel consumption per distance of each is recognized and noted in the inventory. In the hauler database a total of 135 hauler trucks are identified along with their maximum payload weight and fuel consumption per unit distance. In the concrete mixer database, 9 concrete ready mix trucks are identified along with their maximum payload volume and fuel usage per unit distance. Furthermore, in the crane inventory, information is collected for 30 cranes. For each the maximum payload, boom length and the electricity required for operations are determined. In the final database, information is collected for 2 concrete pumps commonly used in the construction industry. For each, the boom length is determined and the amount of fuel required per pumped volume of concrete is noted. Such inventories provide the basis for EE quantification.

Through the collection process it was noticed that energy may be used in different quantifiable units. For example electrical usage is quantified in KWH while fuel is quantified in Gallon per miles. To quantify EE, a single unit of energy is required. With the aid of the developed plugin, all energy values are converted to Mega joules (MJ).

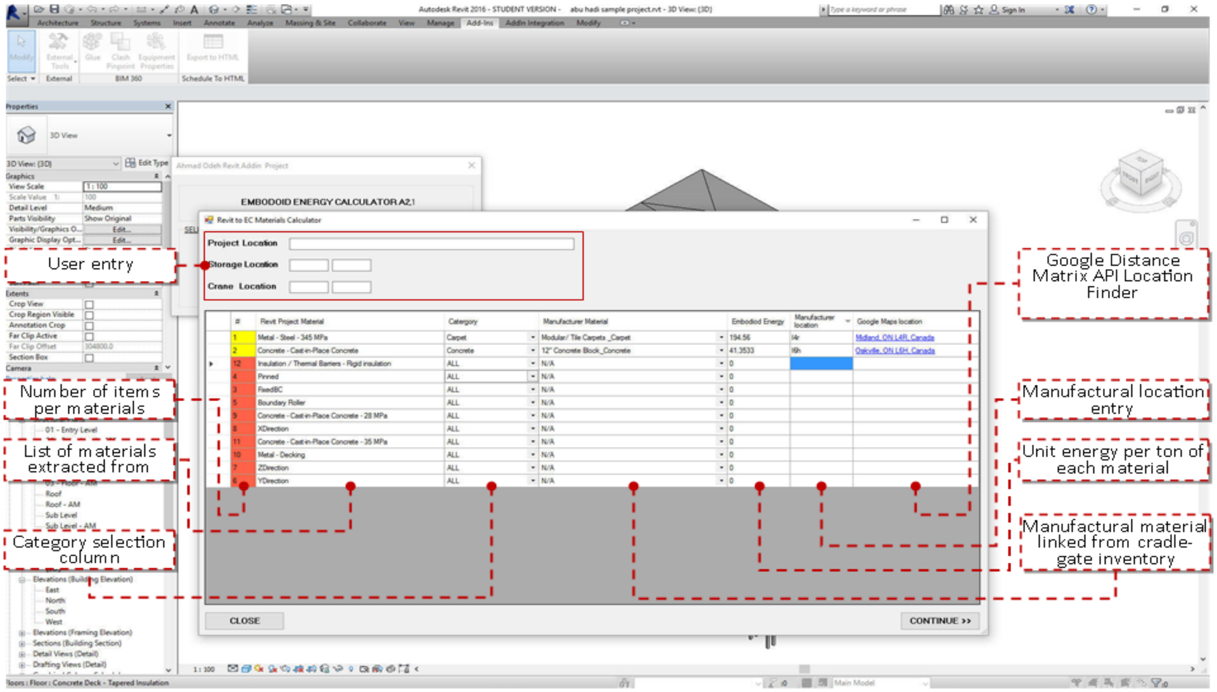
5.1.1 Data Collection Stage

When the plugin begins to operate, all materials existent with the model are identified. Through the element.material, element.getmaterialvolume, and element.getmaterialarea functions, the plugin is able to get and collect material's identities, volumes and areas. Additionally the plugin will ask the user to input the project location, site crane location, storage location, and pumping station location that will be used during the construction stage. These are required as coordinates. Project location coordinates are identified with reference to longitudinal and latitude lines while crane, storage, and pump station locations are identified with reference to the origin point of the BIM model. Such entries will prompt the plugin to move to the quantification of extraction and manufacturing energy stage.

5.1.2 Extraction and Manufacturing Embodied Energy

To quantify cradle to gate EEs, each material within the BIM model needs to be linked to an entity within the cradle to gate inventory. This inventory contains EE information for various materials and therefore the proposed link, will allow the plugin to identify the energy per weight of each material used in the BIM model. Furthermore, material weights can't be extracted from BIM model and therefore they need to be computed through the plugin. Through the proposed link, the plugin will identify the density of each material used in the model and then through the extracted volumes, mass is determined. A multiplication of the unit energy and mass allows for the cradle to gate EE quantification for all extracted materials.

The linking of materials, represent a crucial part of the quantification process. Through the collection of materials in the BIM model, some irregularities were present. Elements that are not materials were also identified in the process such as the “x- direction, y-direction”. Through the linking stage users can identify irrelevant items and remove these from processing. As shown in figure 1, linking is done manually be the user. A list of materials, which is present in the model, appears and then the user identifies the corresponding material from the cradle to gate inventory. It is worth mentioning that, not every individual material needs to be linked but rather similar items can be linked once. For example if four glass panels are identified, the plugin will group such materials as to allow a singular glass material link. Additionally, in an effort to ease the linking process, material categories can be selected as to limit the material search. Material categories are pre-set within inventories and thus the plugin is able to identify the category relevant to each material.



Project Location
Storage Location
Crane Location

#	Revit Project Material	Category	Manufacturer Material	Embodiod Energy	Manufacturer location	Google Maps location
1	Metal - Steel - 345 MPa	Carpet	Modular/ Tile Carpets _Carpet	194.56	l4r	Midland, ON L4R, Canada
2	Concrete - Cast-in-Place Concrete	Concrete	12" Concrete Block_Concrete	41.3533	l6h	Oakville, ON L6H, Canada
12	Insulation / Thermal Barriers - Rigid insulation	ALL	N/A	0		
4	Pinned	ALL	N/A	0		
3	FixedBC	ALL	N/A	0		
5	Boundary Roller	ALL	N/A	0		
9	Concrete - Cast-in-Place Concrete - 28 MPa	ALL	N/A	0		
8	XDirection	ALL	N/A	0		
11	Concrete - Cast-in-Place Concrete - 35 MPa	ALL	N/A	0		
10	Metal - Decking	ALL	N/A	0		
7	ZDirection	ALL	N/A	0		
6	YDirection	ALL	N/A	0		

Figure 1: Plugin interface after material collection in Revit Software

5.1.3 Transportation Embodied Energy

After materials are selected, further information is required during the linking stage. Users need to identify the location of the suppliers for each grouped item. It is assumed that a single supplier is responsible for each material item. Users may enter the location based on any form they typically use in Google Maps. Such information will allow the plugin to identify distances between the material producer and the building location. Through the use of the Google distance matrix API, the plugin can determine the travel distance for a matrix of origins and destinations using a specialized URL path. Such process generates an xml file readable through the .NET application. At this stage, the distance each material requires is identified.

To quantify the energy required for transportation, the plugin assigns each grouped material a transportation method. Based on the assigned categories, materials may be transported either through trucks, haulers, or concrete mixers. If the material category is ready mix concrete, the materials are transported through a concrete mixer. All other materials are assigned to either trucks or haulers. For concrete, the plugin will determine the total volume based on extracted concrete items. The plugin will then select all concrete mixers from the concrete mixer database and it will calculate the fuel required in transportation for each. Fuel for each truck is calculated based on the distance between the factory and the site and furthermore the number of trips required. After full analysis, the plugin will select the truck that requires the least fuel and assign it as the mixer that can be used in the quantification. As a final stage, the fuel used is converted to mega joule units based on conversion factors identified in the United States lifecycle inventory (NREL.2017).

For other materials, the remaining groups are selected. Within each group, the materials with the largest volume and weight are identified. The plugin will then import all trucks and haulers from the truck and hauler databases. Next, the plugin will identify the vehicles that cannot carry such bulky materials and thus the plugin considers these unsuitable for the specified group. Within each group the remaining vehicles are identified and a computational analysis will be performed as to identify the number of items a vehicle may carry in a single trip. This will allow the plugin to identify the number of trips required by each vehicle to carry all materials identified within each group. Based on the number of trips and the required transportation distances, the plugin will identify the fuel required for each vehicle used. The plugin will then identify the least fuel consuming truck or hauler for each grouped material and will assign it as the transportation mean that can be used for the identified group. Next, the fuel used for each material group is converted to energy values in mega joule units. Finally, the plugin will then move to the placement energy quantification.

5.1.4 Material Placement Embodied Energy (Construction Embodied Energy)

To quantify the energy required to place a material in its intended location, two processes are identified. These include either using a crane or a concrete pump. In this stage, the plugin identifies the coordinates of each material within the BIM model. Through the getboundarybox function, the minimum coordinates for each element is determined. This identifies the location of each material within the model. For materials under the ready mix concrete category, the plugin identifies concrete pumps as the required placement tool. For such materials, the plugin begins by determining the maximum distance where elements are located with reference to the pumping stations. Next, the plugin will extract all the pumps presented in the concrete pump database. The plugin will then determine which pumps have booms that can satisfy the maximum distance computed. Only acceptable pumps are selected. Subsequently the plugin will identify the amount of fuel each pump requires for full concrete placement and finally the least fuel consuming pump is selected. Again the fuel consumed by pumps is converted to Mega joules. The plugin will save the pump and the EE required.

For other materials, cranes are selected. First the plugin will determine the maximum weight that needs to be carried along with the maximum horizontal distance between the model materials and the identified crane location. The plugin will then extract all cranes placed within the crane database and will then compare them to the identified criteria. Acceptable cranes are selected. Furthermore the plugin will remove materials that have weights less than 23 kilograms as these can be carried manually. For the remaining materials, the plugin will calculate the electricity each acceptable crane requires to transport all material from the identified storage location to its indented place within the model. The least energy consuming crane is selected. The total electrical usage the crane requires to transport all materials from the storage location is converted to an energy unit represented as Mega joules. To calculate crane electrical usage three crane functions are identified. These are vertical, horizontal, and angular movements. Each movement has a motor function that uses energy based on distances and thus the plugin identifies such distances as to calculate EE.

After all processing is complete; a report is presented to the user identifying the EE for each material based on the equipment used. If changes are required, all links are saved and thus the user may adjust only the item changed within the model. The User can quickly rerun the analysis as to identify the specific EE energy for the changed item.

6 Conclusion

This paper presented a methodology to effectively calculate materials' embodied energy in a cradle to end of construction boundary. The issue of imprecise EE quantification used in the currently available methods and software is addressed through the created BIM tool plugin. Through the selection of equipment, the proposed plugin can exactly quantify the EE materials required in a building lifecycle and automate the equipment selection process required as to lower EE usage. This is not the case with the other available software. Moreover, the created plugin allows designers to quantify EEs early in design stages and thus this prevents future sustainability assessment changes. Since the created datasets will control the quality of the quantification method, more records can allow for better results and thus governmental agencies collaboration would help researchers develop such inventories. Additionally, the EE of materials during the maintenance, rehabilitation, and disposal stages represent a substantial portion of the total EE used in a building lifecycle and thus further research is underway to exactly quantify energy usage used through each.

7 References

Ariyaratne, Chamindika I. and Alice M. Moncaster. “Stand-Alone Calculation Tools Are Not the Answer to Embodied Carbon Assessment.” *Energy Procedia* 62 (2014): 150–59.

Athena Impact Estimator for Buildings. Vers. 4.2. Merrickville, Ontario, Canada: Athena™ Sustainable Materials Institute, 2013. Computer software.

Balouktsi, Maria and Thomas Lützkendorf. “Energy Efficiency of Buildings: The Aspect of Embodied Energy.” *Energy Technology 4*, no. 1 (January 2016): 31–43.

Crawford, Robert H. “Validation of the use of input-output data for embodied energy analysis of the Australian construction industry.” *Journal of Construction Research 06*, no. 01 (March 2005): 71–90.

Dixit, Manish Kumar, José L. Fernández-Solís, Sarel Lavy, and Charles H. Culp. “Identification of Parameters for Embodied Energy Measurement: A Literature Review.” *Energy and Buildings 42*, no. 8 (August 2010): 1238–47.

Dixit, Manish K., Jose L. Fernández-Solís, Sarel Lavy, and Charles H. Culp. “Need for an Embodied Energy Measurement Protocol for Buildings: A Review Paper.” *Renewable and Sustainable Energy Reviews 16*, no. 6 (August 2012): 3730–43.

Ecoinvent Association, 2017 ecoinvent. 1998. Accessed 2017. https://v33.ecoquery.ecoinvent.org/Search/Index.

Gardezi, Syed Shujaa Safdar, Nasir Shafiq, Noor Amila Wan Abdullah Zawawi, and Syed Ahmad Farhan. 2014. "Embodied Carbon Potential Of Conventional Construction Materials Used In Typical Malaysian Single Storey Low Cost House Using Building Information Modeling (BIM)". *Advanced Materials Research* 1043: 242-246.

German Federal Ministry for the Environment. “ÖKOBAUDAT.” 2001. Accessed February 12, 2017. http://www.oekobaudat.de/.

Hammond, G. P. and C. I. Jones. “Embodied Energy and Carbon in Construction Materials.” *Proceedings of the ICE - Energy 161*, no. 2 (January 5, 2008): 87–98.

Jeswani, Harish Kumar, Adisa Azapagic, Philipp Schepelmann, and Michael Ritthoff. “Options for Broadening and Deepening the LCA Approaches.” *Journal of Cleaner Production 18*, no. 2 (January 2010): 120–27.

National Renewable Energy Laboratory (NREL). “U.S. Life Cycle Inventory Database.” Accessed 2017. https://uslci.lcacommons.gov/uslci/search

Praseeda, K. I., B. V. Venkatarama Reddy, and Monto Mani. “Embodied Energy Assessment of Building Materials in India Using Process and Input–output Analysis.” *Energy and Buildings 86 (January 2015*): 677–86.

Suh, Sangwon and Shinichiro Nakamura. “Five Years in the Area of Input-Output and Hybrid LCA.” *The International Journal of Life Cycle Assessment 12*, no. 6 (September 2007): 351–52.

Suh, Sangwon, Manfred Lenzen, Graham J. Treloar, Hiroki Hondo, Arpad Horvath, Gjalt Huppes, Olivier Jolliet, et al. “System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches.” *Environmental Science & Technology 38*, no. 3 (February 2004): 657–64.

Zamagni, Buttol, Porta, Buonamici, Masoni, Guinée, Heijungs, et al. *Critical Review of the Current Research Needs and Limitations Related to ISOLCA Practice*. Italy: ENEA, The Italian National Agency on new Technologies, Energy and the Environment, 2008.