ENABLING A BIM-BASED EMBODIED ENERGY CALCULATION TOOL

A Thesis

by

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ABSTRACT

Nearly 48% of annual energy supply is depleted through building construction and operation processes. The entire life cycle energy consumption of a building is constituted of operating energy and embodied energy. To optimize the whole building energy use, both embodied energy and operating energy should be targeted. While significant efforts have been made to optimize and quantify the operating energy, inconsistency which exists in embodied energy calculation makes embodied energy quantification very complicated. Although there are tools, such as Tally, that integrate life cycle assessment data with Building Information Modeling (BIM) systems and calculate the embodied energy, their databases are not certain according to the literature. While Tally could address issues such as BIM integration, early design phase implementation, and user-friendliness, its capability in suggesting material alternatives for optimum embodied energy is limited. Tally also does not expose its embodied energy database to the user, and therefore, user preference in selecting a database is limited.

This study presents a data exchange model between a BIM tool and a customizable database. The data exchange model enables a BIM-based embodied energy calculation tool for architects and designers. The tool tackles current issues existing in Tally and other embodied energy calculation methods. Finally, the results of the application of the proposed tool and that of Tally on a BIM model are compared.

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NOMENCLATURE

EE	Embodied Energy
LCA	Life Cycle Assessment
BIM	Building Information Modeling
IEE	Initial Embodied Energy
REE	Recurrent Embodied Energy
DEE	Demolition Embodied Energy
IOH	Input-Output-based Hybrid
EA	Environmental Assessment
PHM	Process-based Hybrid Method
IOHM	Input-output-based Hybrid Method

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1. INTRODUCTION

Approximately half of all natural resources are annually consumed by the construction industry and its main sectors, including residential, commercial, heavy civil, environmental, and industrial (Langston & Langston, 2008). Horvath (2004) believes the effect of such a huge energy consumption can significantly harm Earth’s environment. With continuously constructing buildings, the amount of fossil fuel burned has been increased radically, and therefore, not only is the limited energy not being saved for the future generation, it also raises the extent of carbon emission (Holdren & Ehrlich, 1974). However, sustainability practices can help to save natural resources by reducing energy consumption and carbon emission and, eventually, provide a more sustainable environment (Motawa & Carter, 2013). To effectively conserve renewable and non-renewable energy resources, many different practices are applied in different phases of the building life cycle. However, decisions made in the conceptual design phase are of greater effectiveness, as there would not many changes required.

The entire amount of energy consumed over the life span of a building is the sum of operating energy and embodied energy (Treloar, 1998). The energy used in processes of material production and building construction, including manufacturing, transportation, construction, maintenance, final demolition, and disposal is called embodied energy. The energy consumed during the operation of a building once it is occupied, such as providing air conditioning, heating, and electricity, is called operating energy (Dixit et al., 2010). Conventionally, the latter has been considered to have a bigger share of the total life-cycle energy. However, recent studies show embodied energy can have more contribution to the total life-cycle energy, due to the arrival of more low-energy buildings (Dixit et al., 2012). Thormark (2007) believed the more energy efficient a building becomes, the more building materials it uses. Although new insulating materials and energy efficiency practices have significantly reduced the total operation energy usage, embodied energy is still difficult to be optimized and quantified, because of its complicated nature (Khasreen et al., 2009). The key factor in life-cycle energy optimization is to have a trustworthy energy database, and lack of that would result in fragmented energy data reported by manufacturers. The absence of such a database would also make it impossible to develop a comprehensive embodied energy calculation method. In order to have an accurate building life-cycle analysis, both the quality energy database and reliable energy calculation methodology should be provided (Khasreen et al. 2009). According to Dixit et al. (2012), an embodied energy computation protocol has the potential to fill this gap.

The most common embodied energy calculation methods are process-based, input-output (IO)-based and hybrid, and each implements a related database to do the computation. The main difference between current methods is their system boundary definitions. Dixit (2017) defined the embodied energy system boundary as a combination of building materials and processes relating to the construction of a building. Although each method could be applied based on the availability of data, and they could have pros and cons, recent studies have emphasized the potentials existing in the IO-based hybrid method as the most accurate and reliable method (Dixit et al., 2015). While the process and hybrid process-based methods are more reliable as they are product-specific, IO and

IO-based hybrid methods cover a much bigger system boundary because of using the economic model. Joshi (1999), Treloar (1998), and Crawford (2004) have improved reliability in the IO-hybrid method. Dixit et al. (2015) has come up with an approach to compute the capital input and human energy, and eventually integrate them with the current IO-hybrid method. The sectoral aggregation issue has also been improved by Dixit (2017). Although the improved IO-hybrid is considered the most reliable embodied energy calculation method, further research is required to address overdependence on price data and other existing issues (Acquaye & Energy, 2010).

As was mentioned in the earlier paragraph, the conceptual design stage has the potential to be fed with building life-cycle analysis. Therefore, fundamental design decisions can be made in a direction that would facilitate the optimization of both operating energy and embodied energy. Conventionally, life-cycle assessment procedures have been done at later phases of projects when it is too late to make any crucial changes (Schlueter & Thesseling, 2009). While there are life-cycle assessment tools such as Tally that can address some of the issues that exist in life-cycle assessment tools, such as early design phase implementation and user-friendliness, their assessment databases are not certain. For instance, Tally, the most common embodied energy calculation tool, has two main issues. First, while the user is not able to choose their EE database of choice, its database also is not the most complete based on the literature, and second, Tally's capability in suggesting design alternatives for optimum embodied energy has not been explored yet (Voshage, 2015). This research proposes an embodied energy calculation tool for architects and designers. The proposed tool addresses issues among current embodied energy calculation methods. Finally, the results of applying the proposed tool and that of Tally on a BIM model are presented and discussed.

1.1. Problem Statement

Quantifying and optimizing the embodied energy is rather complicated, since it's associated with the integration of various construction materials and processes. Although there are tools, such as Tally, developed to calculate the embodied energy, their databases are not representative according to the literature. While Tally as a commercial tool can be implemented in the very early design stage, its capability in suggesting design alternatives for optimal embodied energy is limited.

1.2. Research goal and objectives

Although there are studies which have previously tried to provide architects with embodied energy calculation tools, they have issues such as using unrepresentative data, and deficiency in suggesting optimum design alternatives. The main goal of this research is to enable an embodied energy calculation tool for designers and architects. There are two main objectives defined to achieve the research goal:

1) create a data exchange model between a BIM tool and a customizable database to enable embodied energy computation, and
2) create and demonstrate an embodied energy tool that suggests material alternatives to help optimize embodied energy.

1.3. Research assumptions and limitations

For this Master's thesis, a BIM model was selected to test both the proposed custom tool and Tally. The tool was limited to a BIM model. Hybrid Input-out-based method created using 2007 economic model is assumed to have the most complete and reliable database and thus, it has been used to test the tool. The system boundary of the IO-based hybrid database used for testing the tool was limited to the product stage and does not cover the whole life cycle. Floor, wall, and roof were the only building envelope assemblies used for this custom tool.

1.4. Significance of the study

Enabling an embodied energy calculation tool for architects would provide them information about the embodied energy of their design alternatives without having to pay for commercial products. Each designer might have their limitation in terms of what embodied energy database would be required for their design assessment. Therefore, the proposed embodied energy plugin would allow them to select the database of choice. The computation procedure embedded in the proposed plugin would provide the architects with the opportunity to know the combination of materials with the lowest embodied energy value. However, choosing the materials solely because they have the lowest EE values and not considering other design aspects is not recommended.

2. LITERATURE REVIEW

2.1. Life cycle energy (LCE)

The energy a product consumes in processes of its manufacturing, performing and recycling phase is called the product life cycle energy. In case of a building, this energy consumption is in two types, operating energy or embodied energy (Treloar, 1998; Hegner, 2007). The energy used for providing building materials and processes of building construction such as extraction, manufacturing, transportation, assembly, disassembly, and decomposition is called embodied energy (Vukotic et al., 2010; Dixit et al., 2010). The energy used in providing and controlling the comfort zone for the building occupants such as providing air conditioning, lighting, and electricity is called operating energy (Hegner, 2007).

2.2. Embodied energy

Various types of building materials and components are used to construct a building. Each of which exploits energy when they are extracted as raw materials, produced by manufacturers, used in job sites, and finally disposed. Vukotic et al., (2010) defined a component or material’s embodied energy as the sum of the energy consumed in the above stages to produce that component or material. Similarly, and in the case of constructing a building, energy is consumed when different materials and components are manufactured, transported, used, and demolished. The entire energy used before the building is occupied in fabrication, installation, and transportation is called initial embodied energy (IEE) (Ramesh et al., 2010). Once the residents occupy the building, the total energy consumed in maintenance and material replacement is called recurrent embodied energy (Cole, 1996). The longer the building continues to exist, the higher the amount of total energy consumption would go (Scheuer et al., 2003). And finally, as soon as the building demolition processes begin, the energy also is consumed in disposal and waste management processes. This energy is called demolition embodied energy (DEE) (Cole et al., 1996; Dixit et al., 2014; Vukotic et al., 2010).

As was mentioned in the introduction section, the total life cycle energy (LCE) of a building is composed of embodied energy (EE) and operation energy (OE). To optimize and quantify the entire energy consumed by a building and eventually, reduce the extent of carbon emission, LCE should be targeted. Although successful efforts have been done to reduce the OE, literature has constantly emphasized EE reduction as well. Moreover, because these two types of energy are calculated independently, aiming solely at each may not provide the most optimum result (Dixit et al., 2015).

2.3. Direct and indirect energy

Ding (2004) claimed that the entire energy embedded in a construction material or component is consumed either directly or indirectly. When a building component is fabricated, the energy consumed directly by major fabrication processes is called direct energy (Fay & Trelor, 2003). The same rule can apply for a building. In another word, if the energy used by the major construction processes, including production, transportation, construction, maintenance, final demolition, and disposal are added together, the result would be the total direct energy (Shrivastava & Chini, 2015). In case of construction material, for instance, a precast concrete panel, the casting should be done on the concrete as a raw material. The energy consumed solely on the casting stage is called the direct energy of a precast concrete panel.

On the other hand, energy is also used when concrete is fabricated from mixing a chemically mineral composition (e.g., sand), a binder (e.g., cement), and other additives. The entire energy consumed in all processes involved to produce the concrete from its raw materials is called indirect energy (Ding, 2004; Dixit et al., 2013; Doh & Panuwatwanich, 2014; Buchanan & Honey, 1994). According to Dixit et al. (2015), indirect energy calculation consists of multiple regression levels. Miller & Blair (2009) claimed that indirect embodied energy calculation could be continued up to level infinity, as each ingredient used to produce an end product, consume energy in their production stages. In precast concrete panel example, when mineral composition, cement, and other additives are combined to form a slab of concrete, it is called the first level regression. Accordingly, the second level is when cement, stone or other major ingredients are produced. To effectively cover the total indirect energy consumption, the regression (going backward) should continue up to level infinity (Dixit, 2017).

2.4. Methods of embodied energy calculation

The three methods that are commonly used to calculate the embodied energy are process-based, Input-Output-based, and hybrid analysis. Based on the availability of the data and the system boundary defined for the life-cycle energy analysis, each of the methods could be selected (Marszal et al., 2011). However, the bottom line is that the results of applying different methods would not be comparable as the system boundary and the data used are not the same. (Dixit et al., 2015).

2.4.1. Process-based analysis

Process-based is a bottom-up approach as it should keep going upstream to cover more indirect energy inputs. Although this method produces relatively accurate energy values for the specific product under the study, the outcome of its calculation is not comprehensive (Robertson et al., 2012). This method utilizes the data collected from manufacturers, and that is the reason its accuracy is relatively high. However, once the actual energy data are collected from the manufacturers and in the first level regression, it goes backward to cover and calculate more indirect energy inputs. The deeper it goes upstream until stage infinity, the more difficult it becomes to calculate the entire indirect energy path. The reason behind this is the lack of available and appropriate energy information provided by the manufacturers while the regression continues to final stages (Dixit, 2017). Therefore, as soon as collecting date in backward processes become impossible, the system boundary defined for the calculation has to be shortened (Lenzen, 2000). Thus, while the process-based database would be reliable due to using manufacturing energy data, it does not provide the complete database for the embodied energy calculation.

2.4.2. Input-output-based analysis

The IO-based method is deeply coupled with the economic sector. This method utilizes the national IO reports, which published every once in a while. The IO account shows the exchange of services and goods in terms of price entities between various industry sectors (Carter et al., 1981). In IO-based calculation method and for an end product of an industry sector, a direct requirement matrix is defined to represent all the inputs needed to produce the end product (Miller & Blair, 2009). For instance, the leather industry sector would directly ask for some raw materials (inputs) to produce a leather handbag. Those raw materials are from other industry sectors ("A" and "B") and when leather sector increases its end-product cost, "A" and "B" would do the same to keep up. Moreover, "A" and "B" sectors may require raw materials input from other sectors ("E" and "F") in their manufacturing process. The added cost path should be continued with them ("E" and "F") as well. Therefore, the cost increase of the leather industry would directly affect sector "A" and "B," and indirectly affect sector E" and "F" (Dixit et al., 2015). The big strength of the IO calculation method is its ability to cover all the direct and indirect inputs. Thus, while IO analysis provides a more complete database compared to process-based, there are issues including overdependence to price data and aggregated industry sectors which remain unresolved (Joshi, 1999; Langston, 2006; Dixit, 2017).

2.4.3. Process-based hybrid method (PHM)

While the process-based method lacks completeness, literature emphasized the potential in IO-based to provide a more complete analysis. To cover a bigger system boundary for the calculation, the PHM method integrates the IO database with a process-based model (Acquaye & Energy, 2010; Treloar, 1998). The process-based method will be complete if we do not calculate the indirect inputs. Thus, PHM uses actual data collected from manufacturers for the direct energy inputs, and indirect energy inputs are also collected from the integrated IO database (Carter et al., 1981). While PHM provides a complete result rather than process-based, it lacks some direct energy inputs in processes including transportation, fabrication, and services (Acquaye & Energy, 2010). Crawford (2004) claimed the more complex the end-product would be, the larger the number of missed direct energy inputs would become. Therefore, in the case of a building as a complex product, missing direct inputs could make the PHM very incomplete.

2.4.4. Input-output-based hybrid method (IOHM)

The hybrid method is driven from the combination of process-based and IO method. The biggest issue for an IO-based method is reliability, as the actual input data from manufacturers are not provided. The input-output-hybrid (IOH) method tries to improve reliability by integrating the process-based data with the IO-based framework (Alcorn & Baird, 1996; Lenzen, 2000). This integration could happen in multiple ways. If all industry manufacturers provide the direct energy input, the integration of process data into the IO model would perfectly occur **(**Peuportier, 2001). However, this is not usually the case. Missing direct energy input from some industry sectors would cause involving of some indirect input effect (Carter et al., 1981). Treloar (1998) believed this issue could be resolved by removing the direct energy input from the IO-based model and replacing them with actual data from the manufacturers. Dixit et al. (2015) claimed while there is no perfect embodied energy calculation method, IOHM has the potential to provide the most reliable and accurate analysis.

2.5. Embodied energy calculation issues

As discussed earlier there are issues that make embodied energy quantification and calculation very complicated. Some of those issues are listed and elaborated below.

2.5.1. Completeness

The extent which the system boundary could cover the entire direct and indirect energy inputs define the degree of completeness. As discussed, the process-based method lacks completeness due to the complexity of providing actual energy data from manufacturers (Treloar, 1998; Acquaye & Energy, 2010). While this issue has been improved in process-based hybrid, actual energy data for processes such as administrating, finance, and consulting are still missing (Crawford, 2004; Dixit et al., 2013). As of now, according to Dixit (2017). The input-output-hybrid (IOH) method offers the most complete embodied energy database.

2.5.2. Data quality

Data quality and representativeness are other obstacles in providing a trustworthy embodied energy analysis. Representativeness means the data should be used according to the time and the region that it is coming out (Praseeda et al., 2015; Szalay & Nebel, 2006). Optis & Wild (2010) claimed approximately 20% of research studies lack indication of their data origin and therefore, their research outcomes are not accurate.

2.5.3. Lack of globally accepted embodied energy calculation method

The first thing required to create a reliable embodied energy database is a standardized calculation method which is globally accepted. Such a standard EE method does not usually exist as different regions apply their calculation methods owe to differences in manufacturers' energy inputs (Khasreen et al., 2009; Optis & Wild, 2010). The more energy inputs relate to a specific material under the study is provided, the more accurate the embodied energy calculation would become. In another word, aggregated results and using IO-based method bring inaccuracy to the calculation. While IO-based method results can significantly lack accuracy, it covers a bigger system boundary and therefore, provides a complete analysis (Crawford, 2004; Dixit et al., 2013).

2.5.4. Sector aggregation

As discussed earlier, the national IO account is used when using an IO-based hybrid method. Therefore, the results from the EE calculation method are not specific to the study material. It also includes all the industry sectors that cover that specific material and thus, errors would come to the computation. Dixit (2017) investigated and improved the accuracy of an IOH method using sectoral disaggregation. He concluded that aggregated results, and not using sectoral disaggregation could potentially cause a high level of inaccuracy to an IOH calculation method.

2.5.5. Human and capital inputs

Joseph & Tretsiakova-McNally (2010) claimed Construction of the buildings along with all the processes involved from the very beginning until the demolition phase require human energy, which is often excluded from the calculation in most of the studies. The other major input missing in current embodied energy calculation methods is capital energy (Dixit et al., 2014). While literature has constantly emphasized adding human energy and capital inputs to the calculation, this would not usually occur because of two reasons. First, the lack of tangible human energy calculation, and second, the clear procedure of calculation of energy consumed in providing capital goods (Murphy et al., 2011). Dixit et al. (2015) proposed a framework to compute the human energy and capital input and eventually, incorporate them with current IO-based hybrid method.

2.6. The most reliable embodied energy method

Crawford (2004) claimed that the improved embodied energy method and database could be created if the proposed hybrid model could address the incompleteness in the process-based and the lack of reliability in the IO-based. Dixit (2017) argued that there are other factors including sectoral disaggregation, human and capital energy that should be quantified and addressed to increase the robustness of the hybrid analysis. With sectoral disaggregation, Dixit (2017) has proposed an improved IOHM which not only does eliminate the problem of aggregation in IOHM; it also pointed out the possibility to add more reliability to the model by using more trustworthy energy inputs.

2.7. Embodied energy and carbon emission

Quantifying and optimizing the embodied energy (EE) and carbon has been an issue for years, and still, there is no complete analysis capable of addressing flaws in conventional calculation methods. While the issues about EE computation methods have never been resolved, the applications of using EE analysis to reduce the total life cycle energy consumption in real-world projects failed (Schlueter & Thesseling, 2009). Ariyaratne & Moncaster (2014) believed that this analysis if done, occurs when it is too late to use the results possibly coming from EE analysis and make major design changes. Consequently, the total life cycle energy consumption and carbon emission remain high.

2.8. Tally

Tally is a Revit life cycle assessment tool developed by Autodesk. This commercial product allows architects to run environmental assessment analysis on building components and compare various design options. While Tally was developed to address issues that exist in the current embodied energy calculation methods, there are more needs and gaps that Tally does not covers. First, Tally is driven from a process-based model which is not the most accurate database according to the literature. Second, Tally's database is not exposed to the user and therefore, the capability of adding other databases is missing. Third, Although Tally integrates a building environmental analysis with BIM systems, it does not integrate the cost to the BIM model. Finally, Tally is considered a passive tool due to its limited ability in suggesting design alternatives for optimum embodied energy (Voshage, 2015).

2.9. Issues in current environmental assessment tools

In the past few years, many companies and researchers have tried to come up with a comprehensive environmental assessment (EA) tool. Sima Pro, Athena Eco, and Tally are examples of current EA tools. Literature pointed out the uncertainty of such tools due to some major issues, such as BIM integration, complexity, uncertain embodied energy database, and passive functionality (inability in suggesting design alternative) (Schlueter & Thesseling, 2009). While Tally was able to address issues such as early design phase implementation and complexity in the tool's implementation, it does not allow the user to select their database of choice. Another major issue in current EA tools is their limited capability in providing the user with low EE material suggestions. Using that information would help designers and architect to make a better-informed decision and possibly save energy.

3. RESEARCH METHODOLOGY

This study believes there is an opportunity to simplify the complexity of integrating an embodied energy database with design processes. Building Information Modeling (BIM), as today's most common design database has the potential to exchange data with a customizable embodied energy database. This data exchange functionality does not exist in the most common BIM software (Revit). However, Revit exposes the out of the box feature, which allows developers to add this functionality by designing and developing custom tools.

While this study aims to show that the proposed embodied energy tool is not dependent to the type of embodied energy database, and the user would be able to select their database, it utilizes the IOH database created using the 2007 economic model to test the tool and compare it with Tally.

3.1. Developing the custom tool

For developing this custom tool, Revit software as a BIM environment has been chosen. Revit has the out of the box potential, which allows developers to design and develop custom tools and applications, and define new functionality based on their needs. This out of the box feature is called Revit API (Application Programming Interface).

3.1.1. Data exchange between BIM tools and other software

Among available data exchange formats between BIM tools and other software are IFC, gbXM. The industry foundation classes (IFC) are public and globally accepted as the standard transferring data format in the construction industry (Eastman et al., 2011). While using IFCs to facilitate data transferring in the BIM environment have been tested many times before, literature pointed out that this functionality in developing software applications has not fully explored (Kam et al., 2003). However, there are many cases of utilizing IFCs through IFC-compliant software for different purposes such as energy modeling and environmental impact assessment (Kiviniemi, 2006). Although there are many available compatible software with IFC data format, exchanging data with not IFC compatible software requires parsing IFC data to a meaningful format for the destination software. However, most of the available IFC-compliant software have already included the parsing step in their application development phase. Therefore, if the target software is not compatible with the IFC data format, the user should parse the IFC data using API.

3.1.2. Revit API (Application Programming Interface)

Software programming is a chain of commands to simply ask the software to do a task for you. Once you create the string of instructions, the software will do what it is programmed for as many times as you ask it ("Lesson 1: The Basic Plug-In," 2018).

API (Application Programming Interface) is a procedure that a developer can talk to software. Accordingly, Revit API is a way Revit developers can add or change Revit functionalities through coding programming languages ("Lesson 1: The Basic Plug-In," 2018).

3.1.3. Revit Custom tool (plugin)

A computer custom tool is a sequence of tasks automated by developers using coding procedures to do a task. In the case of a Revit custom tool, it is an automated combination of many Revit tasks, for instance, moving, copying, and selecting objects ("Lesson 1: The Basic Plug-In," 2018). For instance, if a user wants to move a desk to the left for 2 inches, Revit does have that functionality and the user would be able to complete the task. However, if the user wishes to move the desk 2 inches to the left, create an instance of itself, also move the instance 3 inches to the top, and do all this by just one click, Revit API should be leveraged to create a plugin and add this automated functionality to Revit.

There are two ways to develop a Revit custom add-in. The First is to utilize Visual Studio software or any other integrated development environment (IDE) as the programming platform and develop custom tools using either C# or Visual Basics as the programing language. The second procedure is using Revit macro and developing the custom tool in Sharp Development IDE. This study implements the first procedure and visual studio software to create an embodied energy custom tool.

3.2. The custom tool development procedure

The custom tool development process was started with selecting what software are going to exchange information. Revit as a BIM tool and Excel as a software to create a customizable database have been selected. The Revit design data are in IFC format and to make them readable for other software we need to parse IFC data to the other software data format. Using the Revit API, the material's schedule data were parsed and extracted from Revit to Excel. Then a calculation procedure was designed and developed to calculate the smallest embodied energy values. A list of lowest embodied energy materials along with the embodied energy values for two scenarios was the outcome of applying the computation procedure on the design data. Finally, the outcome of the computation was parsed and transferred back to Revit using the Revit API and Excel API.

The flowchart in Figure 1 shows how the data exchange between the BIM tool and a customizable database was designed and developed. It shows there are many processes (blue rectangles) along with a Revit database as the BIM tool. Section 3.3.1 in this report will clarify each process in depth. The computation procedure, the second blue rectangle in Figure 1 flowchart, has its design process and flowchart. Figure 2 shows the flowchart for the calculation procedure embedded in the tool. Similarly, section 3.3.1 will explain this process as well.

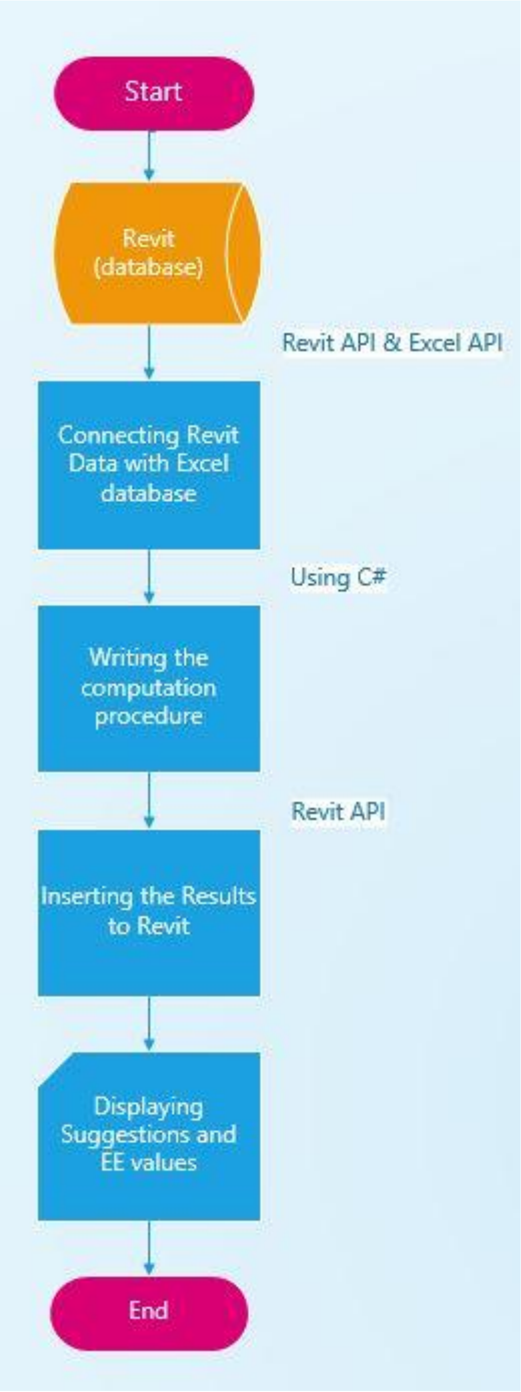


Figure 1: The custom tool development flowchart

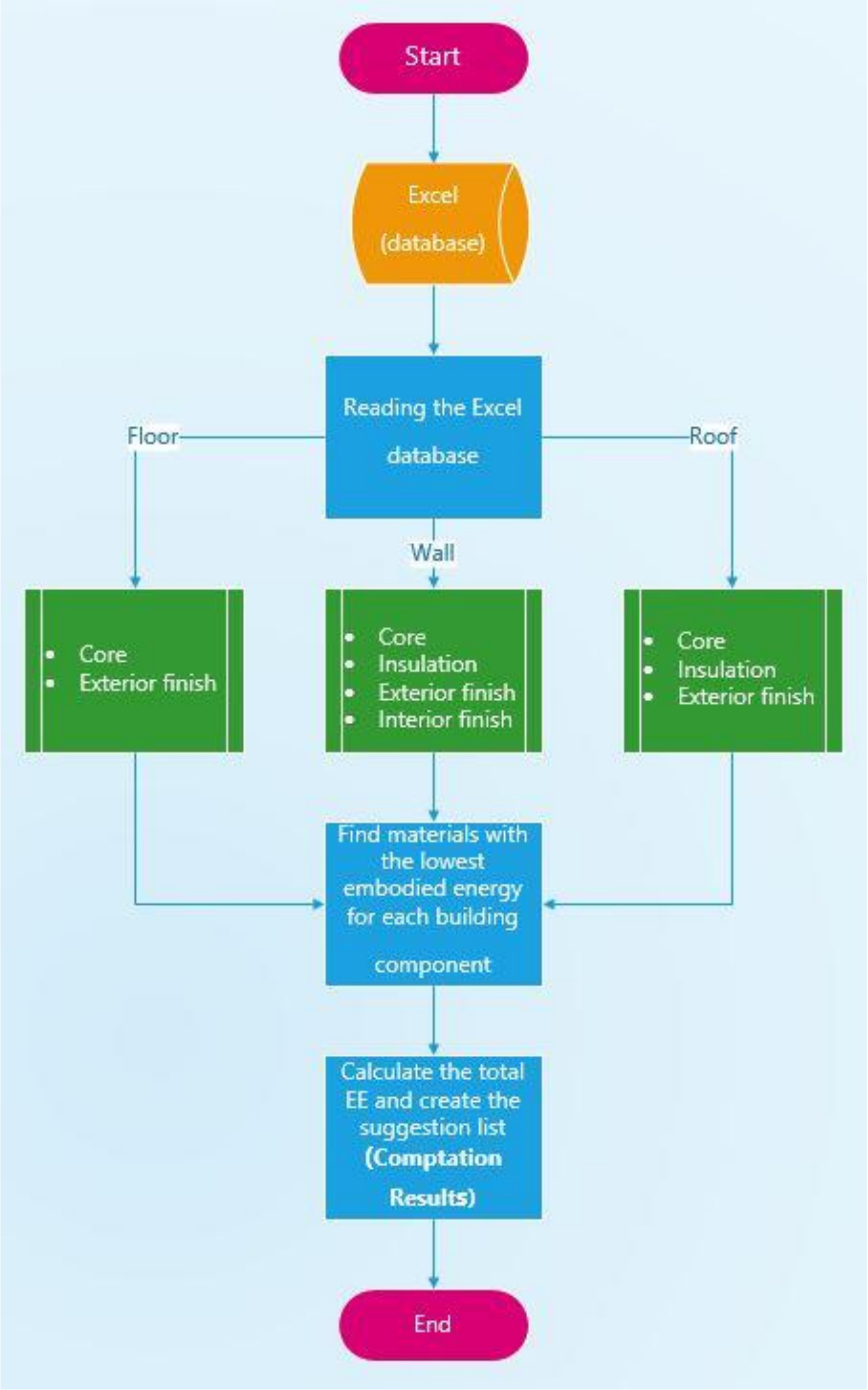


Figure 2: The custom tool computation procedure flowchart

3.2.1. How the tool works

Once the user activates the custom tool, the quantity take-off (bill of materials) including three schedules (wall, floor, roof) will be exported from BIM software (Revit) to the spreadsheet (excel). Without leveraging from Revit API, exporting Revit schedule to excel spreadsheet is not possible. The spreadsheet has already been fed with the embodied energy values of twenty commonly used building materials.

The computation procedure embedded in the tool would match the list of materials exported from Revit model with those available and already exist in the spreadsheet. For example, each assembly may contain different layers, including core, claddings, insulations, and finishes. For the core layer, the computation procedure would solely match the materials which can be used in the core layer. Subsequently, the tool would go through all the layers and select the most optimum embodied energy combination of materials (the smallest values for each layer). Then, the designed procedure calculates the embodied energy of each assembly separately. It multiplies the volume or weight of exported assemblies with the embodied energy values per pound or cubic feet of material alternatives. Finally, the tool suggests the selected optimum alternative (materials with the lowest embodied energy values) to the user in Revit. After the embodied energy of each assembly is calculated and added together, the plugin returns and shows the user the embodied energy value (numerical information) of the BIM model. Last but not least, after the most optimum combination of materials is found, the custom tool shows the user the embodied energy value of each assembly (wall, floor, roof) both for the existing and suggesting materials. Figure 3 shows the workflow of this Revit custom tool.

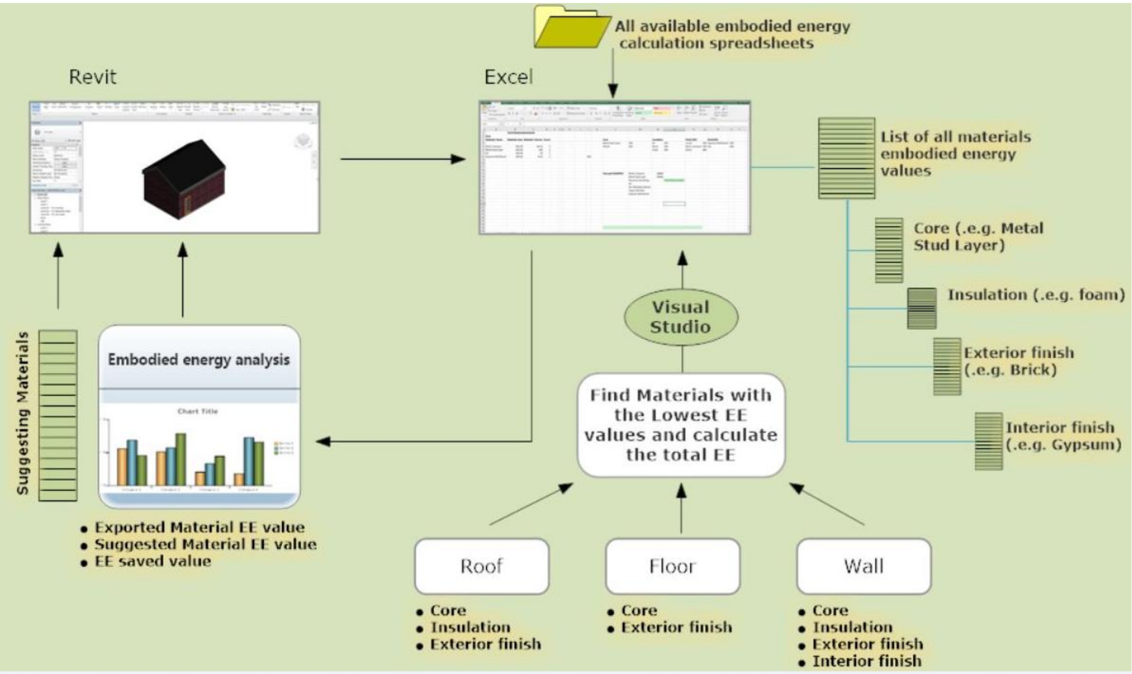
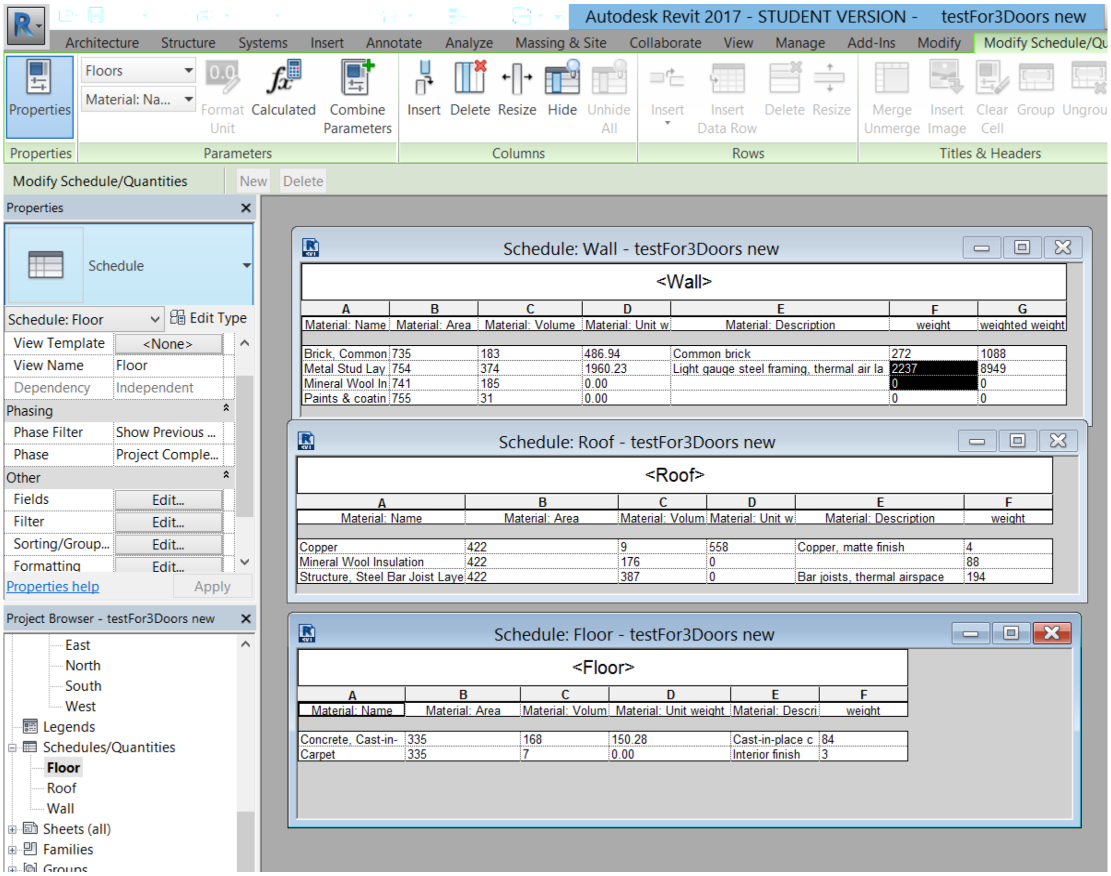


Figure 3: The workflow of the custom tool

4. FINDINGS

4.1. Setting up the BIM model for testing the tool

A BIM model has the potential to show the quantity take off of the material used in the BIM model. The first assumption of the tool is that the quantity take-off schedule of the model has been manually sorted and divided into three different schedules, including wall, floor, and roof. Figure 4 shows these three schedules.



Properties

Schedule

Floors

Material: Na...

Schedule: Floor

View Template: <None>

View Name: Floor

Dependency: Independent

Phasing

Phase Filter: Show Previous ...

Phase: Project Comple...

Other

Fields: Edit...

Filter: Edit...

Sorting/Group...: Edit...

Formatting: Edit...

Schedule: Wall - testFor3Doors new

<Wall>

A	B	C	D	E	F	G
Material: Name	Material: Area	Material: Volume	Material: Unit w	Material: Description	weight	weighted weight
Brick, Common	735	183	486.94	Common brick	272	1088
Metal Stud Lay	754	374	1960.23	Light gauge steel framing, thermal air la	2237	8949
Mineral Wool In	741	185	0.00		0	0
Paints & coatin	755	31	0.00		0	0

Schedule: Roof - testFor3Doors new

<Roof>

A	B	C	D	E	F
Material: Name	Material: Area	Material: Volum	Material: Unit w	Material: Description	weight
Copper	422	9	558	Copper, matte finish	4
Mineral Wool Insulation	422	176	0		88
Structure, Steel Bar Joist Laye	422	387	0	Bar joists, thermal airspace	194

Schedule: Floor - testFor3Doors new

<Floor>

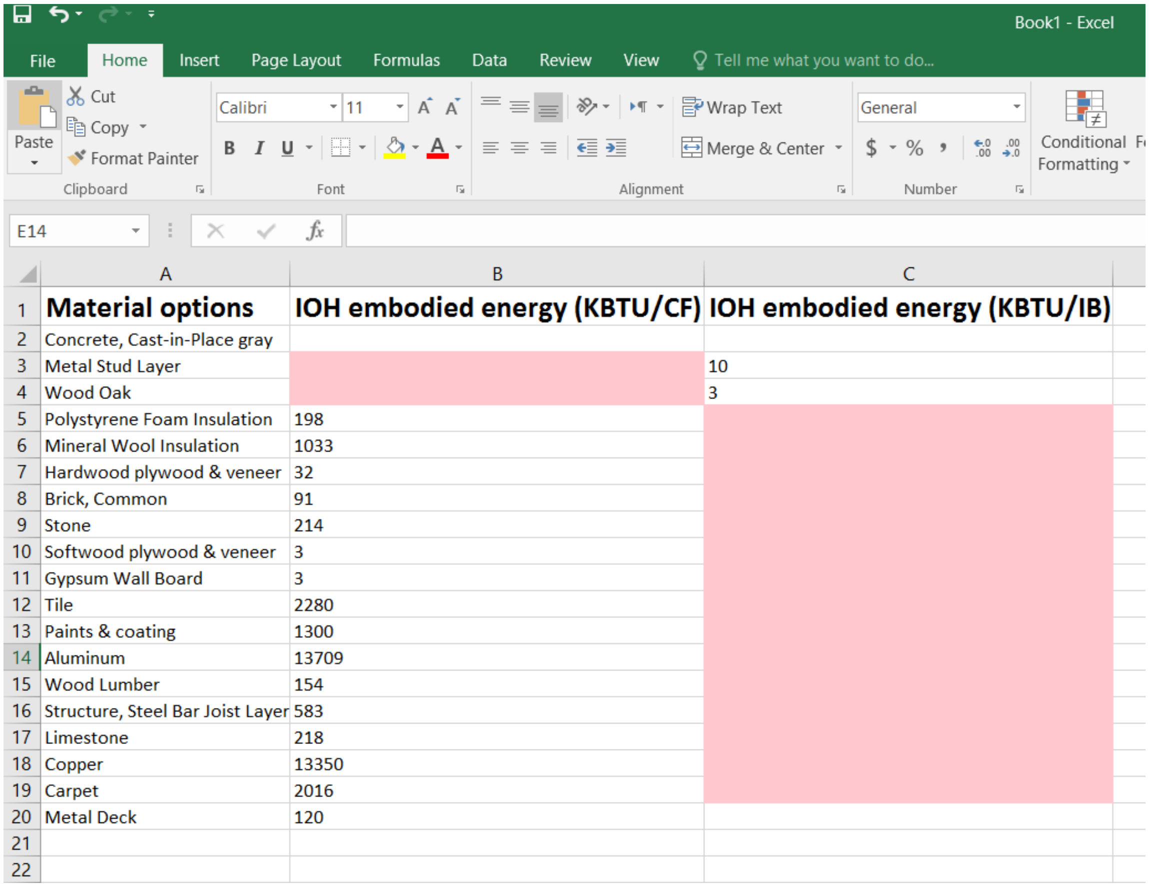
A	B	C	D	E	F
Material: Name	Material: Area	Material: Volum	Material: Unit weight	Material: Descri	weight
Concrete, Cast-in-	335	168	150.28	Cast-in-place c	84
Carpet	335	7	0.00	Interior finish	3

Figure 4: The material take-off schedule of the BIM model

4.1.1. Building envelope layers

The second assumption is that the wall assembly has four layers including, core, insulation, interior finishes, and exterior finishes. Accordingly, the floor assembly has two layers, including core and insulation. And finally, the roof assembly has three layers, including core, insulation, and exterior finishes. For testing the tool, twenty commonly used building materials and their embodied energy values based on the IOH database have been added to a spreadsheet. These materials are available material alternatives for layers in each building envelope assembly.

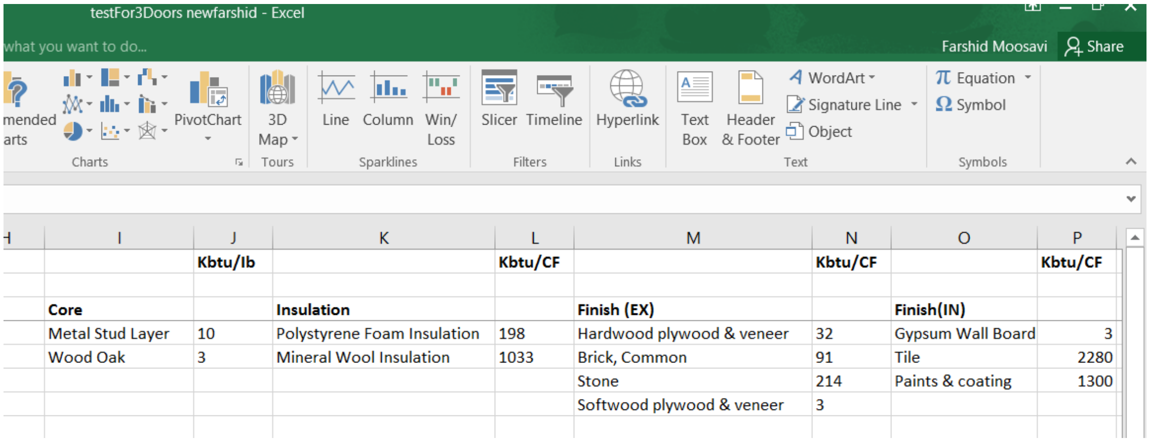
Figure 5 shows the twenty commonly used building materials and their embodied energy values based on the IOH model (Dixit et al., 2015). The units of embodied energy values on Dixit et al., (2015) was KBTU/IB (Kilo British Thermal Units per pound), however, for these research we needed KBTU/ CF (Cubic Feet) because except for wall core layers, all other exported quantities from Revit are in cubic feet (volume). Therefore, according to the density of these twenty materials (Cafe, 2008), we created our spreadsheet (Figure 5) with preferred units.



	A	B	C
1	**Material options**	**IOH embodied energy (KBTU/CF)**	**IOH embodied energy (KBTU/IB)**
2	Concrete, Cast-in-Place gray		
3	Metal Stud Layer		10
4	Wood Oak		3
5	Polystyrene Foam Insulation	198	
6	Mineral Wool Insulation	1033	
7	Hardwood plywood & veneer	32	
8	Brick, Common	91	
9	Stone	214	
10	Softwood plywood & veneer	3	
11	Gypsum Wall Board	3	
12	Tile	2280	
13	Paints & coating	1300	
14	Aluminum	13709	
15	Wood Lumber	154	
16	Structure, Steel Bar Joist Layer	583	
17	Limestone	218	
18	Copper	13350	
19	Carpet	2016	
20	Metal Deck	120	
21			
22			

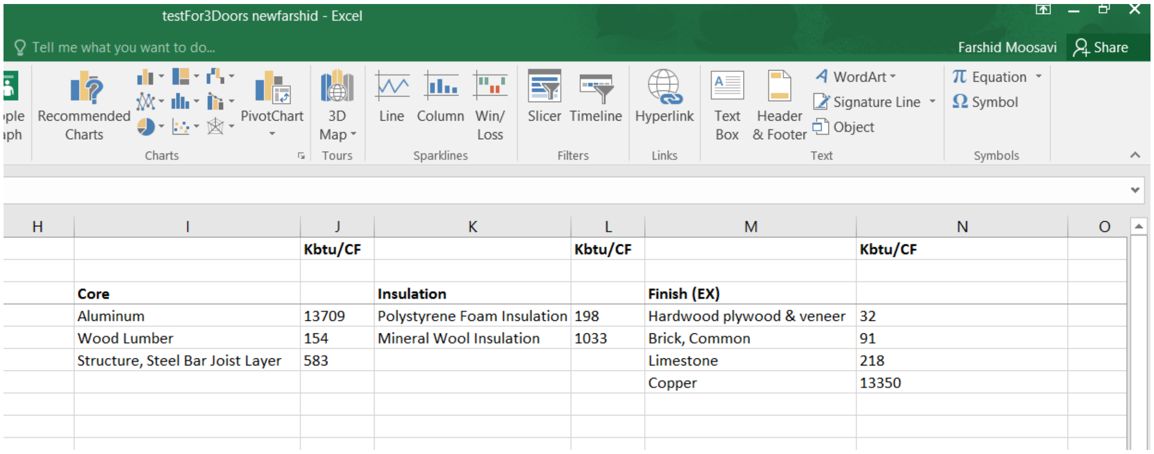
Figure 5: Twenty commonly used building materials for testing the tool

Figure 6, 7, and 8 show all the material alternatives on the spreadsheet and its three workbooks (Wall, Floor, Roof).



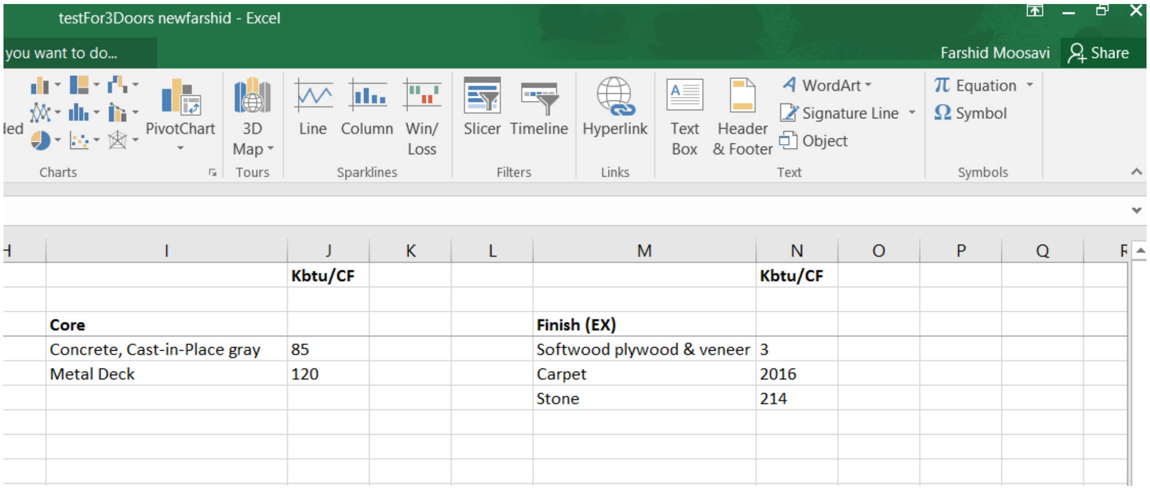
I	J	K	L	M	N	O	P
	Kbtu/lb		**Kbtu/CF**		**Kbtu/CF**		**Kbtu/CF**
Core		**Insulation**		**Finish (EX)**		**Finish(IN)**	
Metal Stud Layer	10	Polystyrene Foam Insulation	198	Hardwood plywood & veneer	32	Gypsum Wall Board	3
Wood Oak	3	Mineral Wool Insulation	1033	Brick, Common	91	Tile	2280
				Stone	214	Paints & coating	1300
				Softwood plywood & veneer	3		

Figure 6: The material EE values that can be used for Wall layers



I	J	K	L	M	N
	Kbtu/CF		**Kbtu/CF**		**Kbtu/CF**
Core		**Insulation**		**Finish (EX)**	
Aluminum	13709	Polystyrene Foam Insulation	198	Hardwood plywood & veneer	32
Wood Lumber	154	Mineral Wool Insulation	1033	Brick, Common	91
Structure, Steel Bar Joist Layer	583			Limestone	218
				Copper	13350

Figure 7: The Material EE values that can be used for Roof layers



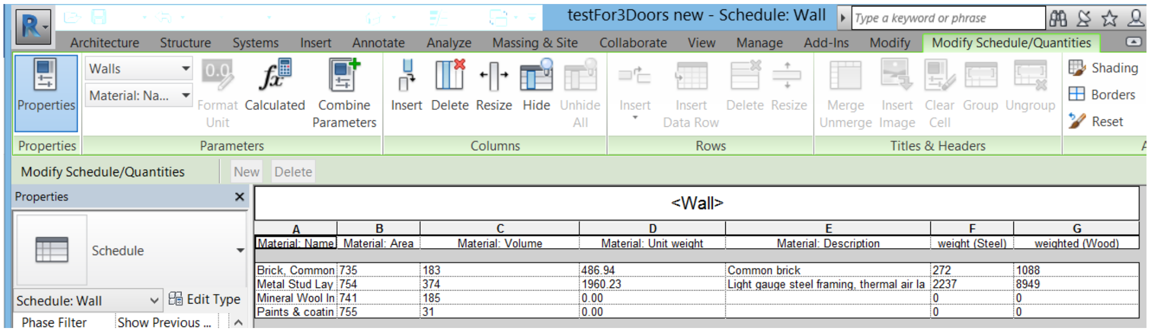
I	J	K	L	M	N
	Kbtu/CF				Kbtu/CF
Core				**Finish (EX)**	
Concrete, Cast-in-Place gray	85			Softwood plywood & veneer	3
Metal Deck	120			Carpet	2016
				Stone	214

Figure 8: The material EE values that can be used for Floor layers

4.1.2. Wall schedule core layer

As was mentioned, wall schedule has four layers including core, insulation, finish exterior, finish interior. It has been assumed that for core layer the drywall system is selected, and the only two material options are metal stud and wood lumber. Revit schedules quantifies wall materials according to their volume or weight. However, for quantifying the steel or wood used in drywall systems, Revit does not consider the gaps between studs. It also does not consider the two studs for the bottom and top track. Therefore, we manually calculated how much steel or wood could be used in the pound for a single stud. For the metal stud, we calculated steel gauge 20 with a thickness of 0.07 inches and a weight of 3.3 pounds per square feet. ("Sheet Metal Gauge Chart," 2018) For the wood scenario, we used lumber with a density of 45 pounds per cubic feet and the thickness of 100 millimeters. Eventually, to calculate the weight of the steel or wood based on the Revit calculated information (Volume and Material: Unit weight), a formula

(Weight = Material: Volume * Material: Unit weight * 0.5 1/kip * 0.0111 * 1000 * 2.2) has been added to the Revit wall schedule. Figure 9 shows the Revit wall schedule after manually adding weight factors. Thus, the unit entered for the wall core layer alternatives is KBTU per pound.

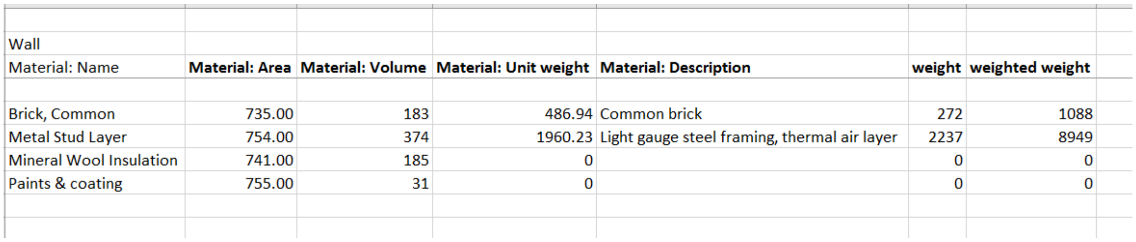


<Wall>

A	B	C	D	E	F	G
Material: Name	Material: Area	Material: Volume	Material: Unit weight	Material: Description	weight (Steel)	weighted (Wood)
Brick, Common	735	183	486.94	Common brick	272	1088
Metal Stud Lay	754	374	1960.23	Light gauge steel framing, thermal air la	2237	8949
Mineral Wool In	741	185	0.00		0	0
Paints & coatin	755	31	0.00		0	0

Figure 9: The Revit wall schedule after manually adding weight factors

Once the custom tool is activated and before its process is finished, the user can see the list of materials (Spreadsheet) used in the BIM model. Figure 10 shows the Revit model materials for wall assembly. The units are not shown in the spreadsheet, because of some errors that happened while developing the custom tools. However, when values are multiplied to calculate the embodied energy with Revit API, their units are correct and just not visible in the spreadsheet. In Figure 10, the units for "Material: Area", "Material: Volume", Material: Unit weight", "weight (steel)", and "Weighted weight (wood)", are square feet, cubic feet, pound per cubic feet, pound, and pound.



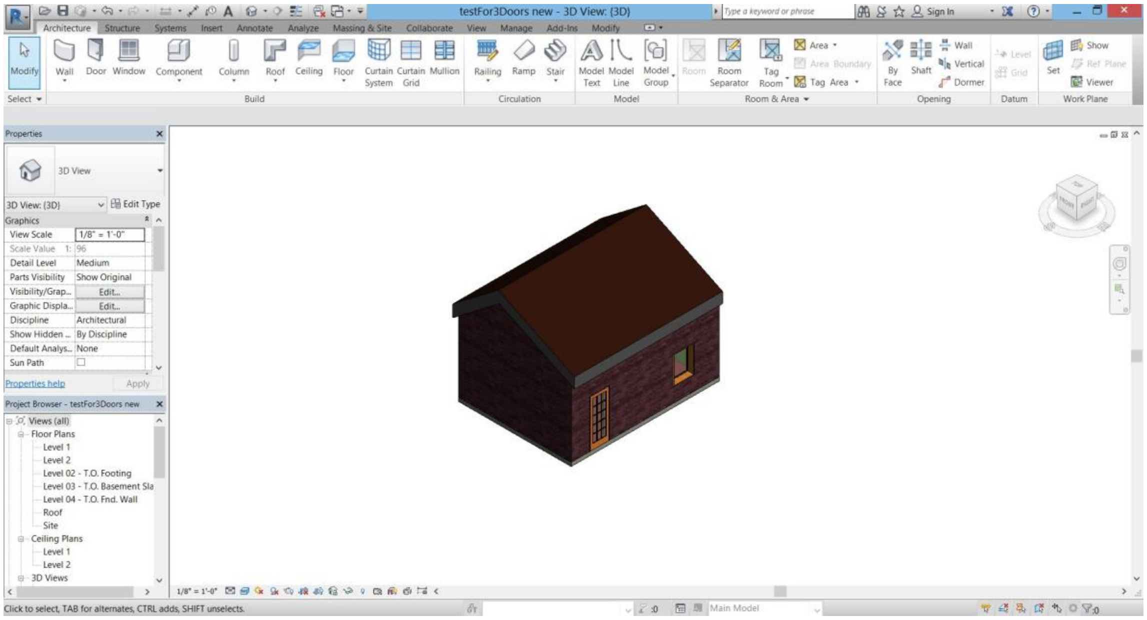
Wall

Material: Name	Material: Area	Material: Volume	Material: Unit weight	Material: Description	weight	weighted weight
Brick, Common	735.00	183	486.94	Common brick	272	1088
Metal Stud Layer	754.00	374	1960.23	Light gauge steel framing, thermal air layer	2237	8949
Mineral Wool Insulation	741.00	185	0		0	0
Paints & coating	755.00	31	0		0	0

Figure 10: The filled excel sheet (wall workbook) once the user activated the tool

4.2. Running the custom tool on a BIM model

To run the custom tool, and eventually compare the result of its application with that of Tally, a BIM model of a small house with the gross area of 335 square feet has been chosen. Figure 11 shows the 3D model of this house in the Revit software. Figure 12 shows the result of applying the proposed tool in this BIM model. It displays both the existing and suggested materials along with their embodied energy values in the assembly and project level. It also shows the comparison of the embodied energy values of both suggesting and existing materials in a graph.

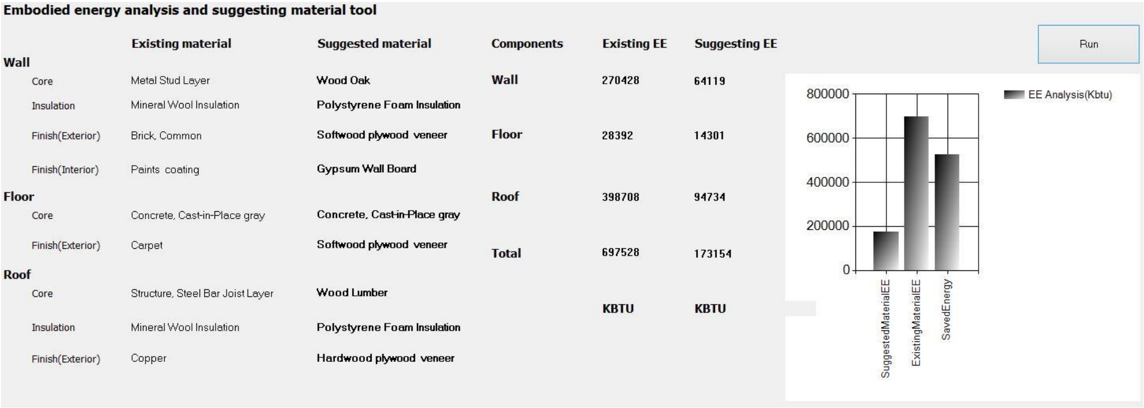


3D View: {3D}

Graphics	
View Scale	1/8" = 1'-0"
Scale Value 1:	96
Detail Level	Medium
Parts Visibility	Show Original
Visibility/Grap...	Edit...
Graphic Displa...	Edit...
Discipline	Architectural
Show Hidden ...	By Discipline
Default Analys...	None
Sun Path	☐

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 11: The 3D representation of the BIM model used for testing the tool



Embodied energy analysis and suggesting material tool

	Existing material	Suggested material
Wall		
Core	Metal Stud Layer	Wood Oak
Insulation	Mineral Wool Insulation	Polystyrene Foam Insulation
Finish(Exterior)	Brick, Common	Softwood plywood veneer
Finish(Interior)	Paints coating	Gypsum Wall Board
Floor		
Core	Concrete, Cast-in-Place gray	Concrete, Cast-in-Place gray
Finish(Exterior)	Carpet	Softwood plywood veneer
Roof		
Core	Structure, Steel Bar Joist Layer	Wood Lumber
Insulation	Mineral Wool Insulation	Polystyrene Foam Insulation
Finish(Exterior)	Copper	Hardwood plywood veneer

Components	Existing EE	Suggesting EE
Wall	270428	64119
Floor	28392	14301
Roof	398708	94734
Total	697528	173154
	KBTU	KBTU

Figure 12: The custom tool results after the user hit the Run button

4.3. Running Tally on the BIM model

Tally, the commercial environmental assessment Revit tool has the potential to show the embodied energy analysis, along with other environmental assessment of a given BIM model. To compare the result of applying the custom tool with that of Tally on the BIM model, First, tally applied on the BIM model with existing materials. Table 2 shows the embodied energy values for the entire BIM model and each building envelope component (Wall, Floor, Roof). The total embodied energy value calculated by Tally is approximately 245000 KBTU less than the embodied energy value calculated by the custom tool. Second, to see and compare the performance of the tool in suggesting materials, Tally applied to the BIM model after assigning suggested materials. Table 3 shows the Tally's embodied energy values for the entire BIM model with the custom tool material suggestions.

4.4. Embodied energy calculation results

The first outcome of running the custom tool on the BIM model is that it is possible to connect design data from Revit with customizable EE database and save energy through suggesting the lowest embodied energy materials. The amount of possible saving (524374 KBTU) is shown in Figure 12. Wall and roof layers have a bigger proportion in this energy saving due to high embodied energy values for copper, mineral wool, and steel materials.

The second outcome of the tool is the automation of the processes of embodied energy calculation, the comparison between different material alternatives to find the suggestions, and showing the result back to the user. Although the whole analysis occurred under the scene and the user was not able to see that, it takes less than a minutes to inform the user about both the analysis and suggestions. The automated processes mentioned earlier are not very complicated in nature, and if the data is available, the user would be able to do the calculation. However, the automation is the most valuable outcome of the tool, as it reduces the time required for an architect with all provided data to run the calculation.

Last not but least, the embodied energy database used for this calculation contains 20 commonly building materials, and the custom tool showed it could be valid for 20 materials. However, if the user provides a database with more material alternatives or even a database driven from other embodied energy methods like process based, does the custom tool work accordingly? We believe yes, and the reason is that the computation procedure embedded in the tool is solely looking for values (numbers) to run the analysis.

5. DISCUSSION

Comparing the results of the application of the proposed tool with that of Tally on a BIM model (Table 1) showed both hybrid IO-based and tally database are correlated. Positive correlation means custom tool EE value and Tally EE value increase when the other one increases. However, the slope of the line in Figure 13 is less than 45 degrees, and the custom tool has a bigger embodied energy values, possibly due to the system boundary difference between IO- based hybrid and process-based.

Table 1: EE values for custom tool and Tally

	Custom Tool EE (KBTU)	Tally EE (KBTU)
Floor	28392	12718
Wall	270428	157658
Roof	398708	272896
Total	697528	443272

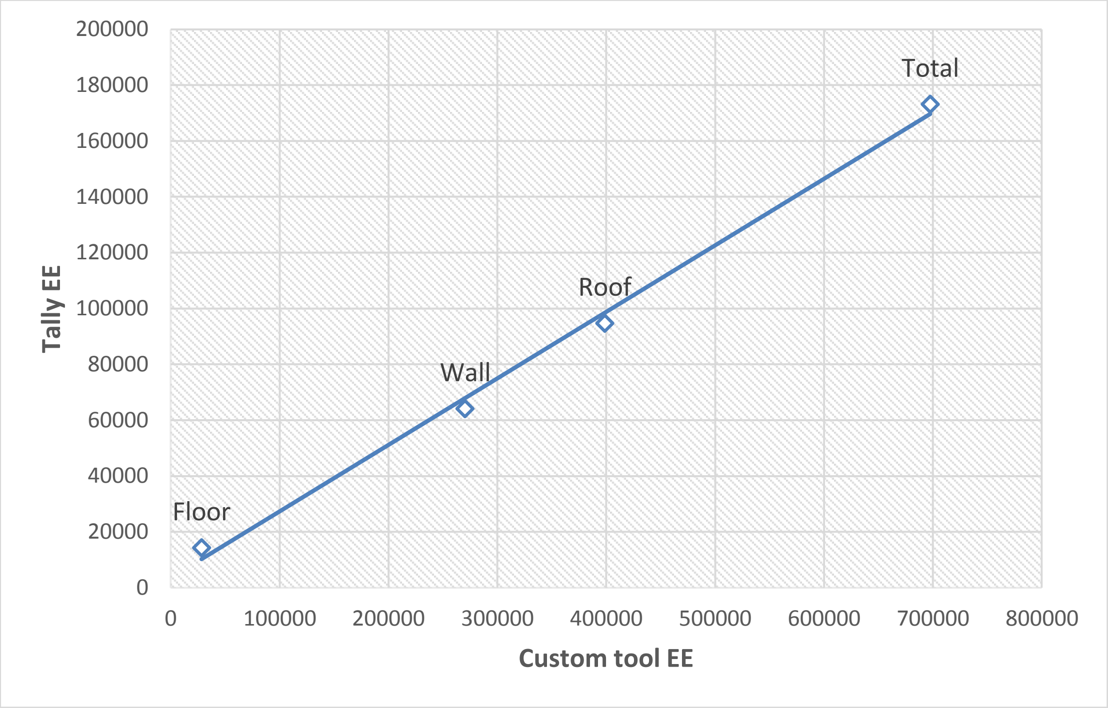


Figure 13: The Chart of EE values for tally and custom tool (Existing material)

Once the custom tool suggested the low EE materials, those materials have been mapped to Tally and run to see how Tally would result with the custom tool material suggestions. To compare both tools energy savings using custom tool material suggestions, for both building envelope level (floor, wall, and roof), and the whole project level (Table 2), this procedure happened. The energy savings have been separately calculated first, and then the results were divided by the EE calculated in the case of using BIM existing materials for both tools. According to Table 3, the insignificant differences for three building envelopes and the whole BIM model shows for both EE databases, the custom tool suggesting capability has the potential to save a significant amount of energy.

However, to generalize this functionality, more EE databases should be inserted into the tool and tested.

Table 2: Comparing the EE values for existing and suggesting materials from Tally and custom tool

	Custom tool Existing EE Material (KBTU)	Tally Existing material EE (KBTU)	Custom tool Suggesting EE Material (KBTU)	Tally Suggesting material EE (KBTU)
Floor	28392	14301	12718	7072
Wall	270428	64119	157658	33285
Roof	398708	94734	272896	42443
Total	697528	173154	443272	82800

Table 3: Energy saving percentage for the custom tool and Tally

	Custom tool EE saving (KBTU)	Tally EE saving (KBTU)	Custom tool EE saving (percentage)	Tally EE saving (Percentage)
Floor	14091	5646	49	44
Wall	206309	124373	76	78
Roof	303974	230453	76	84
Total	524374	360472	75	81

6. CONCLUSION

This study was carried out to investigate if it is possible to enable an embodied energy calculation tool for architects and designers.

The objectives of this study were:

1) Create a data exchange model between a BIM tool and a customizable database to enable embodied energy computation.
2) Create and demonstrate an embodied energy tool that suggests material alternatives to help optimize embodied energy

The data exchange model between a BIM software and a customizable embodied energy database has been successfully developed and tested. The literature review has pointed out the uncertainty of databases in current embodied energy calculation tools. This thesis has demonstrated that it is possible to exchange data between a BIM tool and a customizable database and allow users to select the database of choice. The literature review has also revealed passive functionality (not suggesting) of current embodied energy calculation tools. Our proposed custom tool has shown that there is a possibility to help optimize embodied energy by suggesting the low embodied energy materials. This research validated this possibility thorough mapping the custom tool's suggestions on Tally (the most common environmental assessment tool) and comparing the results (embodied energy values) with existing materials.

In the process of enabling the embodied energy calculation tool, there were challenges that we faced. The biggest challenge was transferring the design data from

Revit to the Excel, due to the data format difference between the two software. Thus, Revit API and Excel API have been implemented to parse BIM data (IFC format) to the Excel data format. Calculating the weight of materials used in drywalls was also a challenge, because Revit could not calculate the volume of the gaps created between studs. To solve that issue, the weight of a stud was calculated separately and then multiplied by the number of studs used in each wall.

6.1. Future studies

The scope of the BIM model covered a few building envelope assemblies. Future studies can try the tool with all building components. The embodied energy database inserted for testing the tool was limited to product stage. Future work may add services and processes to the system boundary. Further research can combine this research results with operating energy calculation tools to quantify and optimize the total life cycle energy consumption. It could also combine with other LCA tools to report environmental impacts such as global warming, carbon emission, and acidification. As far as the custom tool automation procedure, the steps of inserting EE data, and selecting the database of choice have not been automated and been done manually by the user. Future study can investigate possibilities to automate more processes. Some errors occurred while developing the tool in the Visual Studio software. Those errors have been resolved for the 20 building materials exist in the inserted EE database. Using other EE databases with more material options could result in unresolved and more complicated errors.

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