2018/19 ECR Project

Digital Energy Estimation Tool (DEET):

Final Report

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Digital Energy Estimation Tool (DEET)	Faculty of Engineering and Environment Northumbria University , Newcastle upon Tyne
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Abstract

Buildings have an impact on the environment at all stages of their life cycle; material production, construction, operation & repair and demolition stage. The impact in terms of energy and carbon is well documented at present with approximately 40-50% of global energy consumption for operational energy requirements and 30% of global Greenhouse Gas (GHG) Emissions.

While operational energy efficiency has traditionally received considerable attention from the government, building related professional bodies and research community, the embodied energy portion of Built Environment assets tended to be neglected. Therefore, recent attention has been shifted towards increasing the knowledge of whole lifecycle energy efficiency.

Methods to estimate whole life cycle energy consumption are well recognised, but they are time consuming and comprehensive analytical procedures. Numerous studies have looked into developing tools to make the estimation process simple. However, none of them have resulted in estimating whole life cycle energy or making it easy for stakeholders or professional to engage with. In this research project with the financial assistance from CDBB the research team has developed a unique parametric design based methodology for estimating total energy use in a building utilising BIM (Building Information Modelling) frameworks and protocols. Results from the work have indicated that embodied energy can be much more significant in the first few phases of the buildings life cycle, and material selection can be addressed within a parametric model. In addition the funding allowed for a unique multi-disciplinary research approach for technologies such as BIM and virtual reality can be used to communicate the message of addressing the overall aims of CDBB in enhancing the performance of the built environment and the cities and communities it serves.

1. Main Text - Introduction

The expansion in current global economy and higher living standards rapidly increase the demand for global energy (BP P.L.C., 2019). In 2018, global energy consumption has increased by 2.3%, nearly twice the average rate of growth since 2010, causing the global energy-related CO_2 emissions to rise by 1.7% (IEA, 2019). Energy consumption and carbon emissions of the building sector average approximately 30% of global energy and 20% of global CO_2 emissions (IEA, 2010). In the UK, building sector alone consumes nearly 40% of total energy consumption (MHCLG, 2014). Therefore, the energy performance of buildings legislation (England and Wales) has now become more stringent with many amendments to optimise the energy consumption of buildings. Due to such huge impacts the UK government has set 50% lower emissions from the construction sector as its main aims of the construction 2025 flagship strategy (HM Government 2013).

Within a whole life cycle of a building, two types of energy are consumed namely; operational and embodied. Operational energy is the energy consumed to run a building by operating processes such as heating and cooling, lighting, ventilating and appliances; whereas embodied energy of a building is the energy consumed by all the processes associated with its production i.e. extract raw resources, process materials, assemble product components, transport between each step, construction, maintenance and repair, deconstruction and disposal (Ding,2004). Until recently, the main focus was only on operational energy which is consumed in the use stage, owing to its larger share and impact over the life cycle. However, as buildings become more energy efficient in terms of operational energy, the embodied energy and associated carbon arising during the other life cycle stages have now come into focus (Dixit, et.al., 2010; Ibn-Mohammed et al., 2013). The optimization of energy consumption of buildings requires equal attention on both operational and embodied energy. Estimation of embodied and operational energy is the main drive towards a comprehensive analysis of energy consumption facilitates to identify appropriate energy optimising measures (Praseeda, Reddy, and Mani, 2016).

According to the Energy Performance of Buildings Regulation (2012), in new buildings, energy analysis should be carried out at an early stage of the design process where more opportunities are available to optimize the energy consumption. Therefore, estimating energy consumption in the early stages of building design has received a substantial importance today for energy and emission reduction efforts. However, estimating whole life cycle energy consumption during early design stage of a building is a complicated task which depends on number of factors such as building characteristics, materials use, energy systems characteristics, control and maintenance, weather parameters, and behaviour of occupants (Asadi, Amiri and Mottahedi., 2014). Therefore, achieving an accurate estimation of total energy consumption is challenging.

Life cycle assessment (LCA) is a widely recognised and accepted method for the assessment of burdens and impacts throughout the lifecycle of a building (Praseeda, Reddy, and Mani, 2016). Even though, many developments such as energy modelling tools, models, software and frameworks have been developed to simplify the life cycle energy assessment of buildings, only fewer researches have attempted to estimate both operational and embodied energy of buildings (Koezjako et.al, 2018; Giordano et.al., 2017; Lolli,Fufa and Inman, 2017., Praseeda., Reddy., and Mani., 2016; Giordano et.al., 2015). It emphasises that still there is a need for a systematic approach for estimating whole building life cycle energy.

During the last decade, Building Information Modelling (BIM) had significant growth within Architecture, Engineering and Construction (AEC) industry enabling to improve decision making and performance across the building and infrastructure lifecycle (Tulubas Gokuc and Arditi, 2017). Incorporating energy analysis into BIM during early design stage would certainly provide many benefits including giving more room to create alternative options which optimize the whole building life cycle energy consumption.

In view of that, this project proposes a BIM enabled approach to predict total energy consumption of commercial and residential buildings in the UK. It enables the generation of real-time energy data, both embodied energy from building components through 3-D computing paradigm at an early building design stage, coupled with operational energy input, bringing a new approach to total life analysis of energy and carbon. Such data will allow more accurate prediction of impacts and material substitution by linking both operational and embodied energy in one tool.

2. Life Cycle Energy Assessment of Buildings

LCA is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product’s life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal (ISO,2006). As previously mentioned, it is a widely recognised and accepted method to calculate the environmental impacts of a building which has an impact on the environment at all stages of its lifecycle (product, construction process, use, end of life).

LCA methodological framework comprises of four stages; 1) goal and scope definition, 2) life cycle inventory analysis, 3) life cycle impact assessment and 4) life cycle interpretation as shown in Figure 1 (ISO,2006).

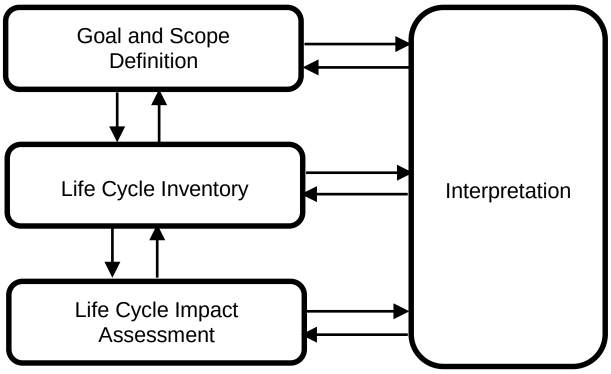


Figure 1: LCA methodological framework (ISO 14040:2006)
Source: International Standard Organisation, 2006

The depth and breadth of the LCA depends on the goal and scope of the LCA. Accordingly, the goal and scope definition phase include establishing the goal, system boundary and level of detail of the LCA. The second phase of the LCA involves the life cycle inventory analysis (LCI). It involves the collection and synthesis of input/output data relating to the system being studied. The life cycle impact assessment phase (LCIA) includes evaluating the significance of potential environmental impacts using the LCI results. Finally, the life cycle interpretation phase deals with the interpretation of results from both LCI and LCIA. It includes summarising, drawing conclusions and recommendations and decision-making in compliance with the goal and scope definition (ISO,2006).

LCA of buildings is quite challenging mainly due to the time consuming nature of data collection during LCI phase. There are many LCI databases available, for instance; Bath Inventory of Carbon and Energy (ICE) (Hammond and Jones,2011), EcoInvent 3.3 (EcoInvent Association,2016), ÖKOBAUDAT (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety,2013), Athena Life Cycle Inventory Product Databases (Athena Sustainable Materials Institute,n.d). However most of these databases are either country specific or regional specific and rely on generic data and require a platform for LCA calculations.

There have been variety of assessment tools developed within the building sector to simplify LCA calculations. They are used as decision- making aids which stimulate communication, make energy and environmental efficiency quantifiable and ultimately set goals and monitor performance (IEA,2005). According to IEA Annex 31, these assessment tools are categorised as;

a) Energy modelling software
b) Environmental LCA tools for buildings and building stocks
c) Environmental assessment frameworks and rating systems
d) Environmental guidelines for design and management of buildings
e) Environmental product declarations, catalogues and reference information
f) Certifications and Labels

Table 1 provides few examples for such assessment tools.

Table 1: LCA Tools

Assessment Tools	Examples	References
Energy Modelling Software	COMFEN, DesignBuilder, Ecotect, EnergyPro, eQUEST, IES Virtual Environment, Simergy, TAS, sefaira Concept	AIA,2012
Environmental LCA tools	ATHENA Environmental Impact Estimator, Simapro, Building Environmental Assessment Tool (BEAT), BEES 4.0, Envest 2, Eco-Quantuam, EQUER, GABI	Bernardi et.al., 2017
Environmental assessment frameworks and rating systems	Building Research Establishment Environmental Assessment Methodology (BREEAM), the Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), EcoEffect	Bernardi et.al., 2017
environmental product declarations (EPDs) from different EPD program operators	the International EPD system, The Norwegian EPD Foundation, EPD Danmark, AENOR	Eco-Platform, 2014
Certifications and Labels	Energy Performance Certificate(UK), European Eco Label, Energy Saving Trust Recommended	Defra,n.d

With the support of some of the above mentioned energy modelling software, a number of studies have been conducted over the last few years incorporating both operational and embodied energy in building life cycle energy assessment, for instance, the studies of Giordano et.al., (2017) and Koezjakov et.al., (2018) can be shown. Giordano et.al., (2017) have carried out two studies to assess both the embodied and operational energy in a net zero energy building during its earliest design stage and in different types of tall building façade systems located in 5 different climate zones. Both these studies have used Initial and Recurring Embodied Energy Assessment (IREEA) worksheet tool for embodied energy and IES Virtual Environment Software for operational energy assessment. Koezjakov et.al., (2018) have assessed the relationship operational energy demand and embodied energy in Dutch residential buildings. The analysis has been performed using 3SCEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model and a constructed Embodied Energy Database Management System (EEDMS).

3. Existing BIM based Tools for Energy Analysis

Most of the important decisions related to energy efficiency are made early in the design process as more energy savings can be achieved later on in the project (Cemesova, et al., 2015). And importantly, Energy performance regulation (2012) mentions that energy modelling should be carried out at an early stage of the design process of new buildings, in order to inform further development of the design and construction. As a result, number of tools have been developed to support the operational and embodied energy estimation and analysis process. The below sections will first highlight the use benefits of the use of BIM-based energy analysis over conventional energy approach, then it will review existing operational and life cycle energy analysis tools.

3.1 Benefits of BIM-Based Energy Analysis at early design stage

In the building industry, the concept of BIM has gained increasing acceptance over the last years, increasing collaboration among building design and construction project members (Eastman et al, 2011; Schlueter and Thesseling, 2009). According to the US National Institute of Building Sciences Facilities Information Council (2010), “BIM is a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition”.

In the traditional project delivery method, the work of architects, structural engineers, MEP engineers, contractors, and various other building consultants occurs in relative isolation to one another. However, BIM-based project delivery method, information available to the various parties can all be shared and integrated around a central building information model (Azhar, et.al., 2011). In addition, immersive virtual environments (IVEs) combine pre-construction mock-up that presents a sense of real space to the future users and building information models that allow for testing of different design alternatives (Heydarian et al., 2015).

In conventional energy modelling approach, traditionally created 2D drawings were used to create an independent model in an energy modelling tool (US GSA, 2015). This may lead to misinterpretation of the drawings, inconsistencies, simplified model, and large amount of time needed to create an energy model (Reeves, Olbina and Issa, 2015). In contrast, BIM-based energy analysis assists to automate this process and create consistent and more complex energy models which provide faster and accurate results compared to the traditional methods (Azhar et.al., 2011; US GSA, 2015). In BIM-based project delivery, energy analysis can be integrated into building design, construction, and operation/maintenance more efficiently as energy performance is analyzed using the central BIM model without having to recreate building geometry in certain energy analysis platforms (i.e., gbXML-enabled tools). According to US-GSA (2015), use of BIM -based energy analysis provides several benefits including: more accurate and complete energy performance analysis in early design stages, improved lifecycle cost analysis, and more opportunities for monitoring actual building performance during the operation phase. In addition to them, it will assist to assess the energy benefits of various design alternatives and thus help designers and owners make better decisions related to materials and products selection that have low environmental impact (Donn, Selkowitz and Bordass, 2012).

3.2 Operational Energy Analysis

Operational energy analysis is an assessment of the overall building energy performance (BEP) and also known as building energy modelling (BEM). There are various existing BEM tools available for the use of architect and building services engineers in order to evaluate the design decision during the preconstruction design stages in informing building design performance analysis and validation (Hyun, Marjanovic-Halburd and Raslan, 2015). These tools can be used during conceptual and early design stage in order to:

1. Understand climate and weather of the project location
2. Inform the massing and orientation phase
3. Design and selection of materials for building fabric
4. Simulate the energy use of building services (Zanni, 2016 and Reeves, Olbina and Issa, 2015)

Table 2 summarises the existing BEM tools that can be used to above purposes during early design stage of a building development.

Table 2: Operational Energy Analysis Tools

Purpose	Design/ Energy variables	BEM tools
Climate and weather	Daylight availability Solar access/intensity Wind direction/intensity Temperature range Humidity	Autodesk Vasari Sefaira Autodesk Revit PHPP IES-VE EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS Climate consultant
Massing and orientation	Overshadowing Building height and footprint Irradiance over building's planes Thermal performance Daylight Ventilation	Sefaira Autodesk Revit plug in IES-VE EnergyPlus eQuest PHPP iSBEM
Building fabric	Glazing and shading Daylighting Insulation properties of building skin: Solid and voids (U-Values and G-values) Airtightness (at 50 Pa) Ventilation and free cooling Overheating	IES-VE Sefaira EnergyPlus (engine) PHPP DesignBuilder (operated by energy plus) Open studio (operated by energy plus) EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS EnergyPlus
Building services	Energy consumption Heating, cooling, and hot water Electric load IT and small power consumption Energy source Artificial lighting Occupation schedules	IES-VE Bentley Hevacomp Modelica Sefaira EnergyPlus (engine) DesignBuilder EcoDesigner EDSL TAS TRNSYS Assessment (SWERA) Solar Deployment System (SolarDS) Open studio (operated by energy plus)

Source: Zanni, 2016 and Reeves, Olbina and Issa, 2015

In the UK , only few tools such as IES-VE, DesignBuilder and EnergyPlus engine are approved and compliant for the high accuracy as they are accredited by UK's National calculation method (NCM) (BRE, no date). But, still the use of those tools are reported to be non-user friendly specially for architects, too complex and require high detailed input, beside it is not compatible to the architects' iterative working need for exploring multiple alternatives at early stage that requires manageable input (Arayici et al., 2018).

In previous studies it can be recognized that there are two approaches for energy simulation within BIM workflow, conventional standalone approach and semi-automated BIM integrated approach (Kamel and Memari, 2018). Figure 2 and 3 illustrate the workflow for both approaches reflects the effort and time required by the user to compare the energy performance of different design alternatives. The integrated approach, which can be semi-automated using open standards such as gbxml and IFC for model transfer (Noack, F. et al., 2016) is attempting to eliminate duplication of work required for geometrical modelling . However, it has been highlighted in several studies that deficiency still exist in the functional exchange of those models to different platforms to allow multiple iterative trials required for fast and simple optimization (Arayici et al., 2018). It can be argued that both approaches have limitations for practical use in early conceptual design stages for the purpose of exploring and comparing different alternatives. This can be reasoned by the required manual entry of complicated input variables that are already estimated by stakeholders in early stages in conventional approach. These challenges and limitations motivated the use of simulation and use of parametric approaches and visual scripting methods on platforms such as grasshopper plugin for Rhino and honey bee plug in (energy plus engine), (Shadram and Mukkavaara, 2018), which will be explained further in the proposed framework.

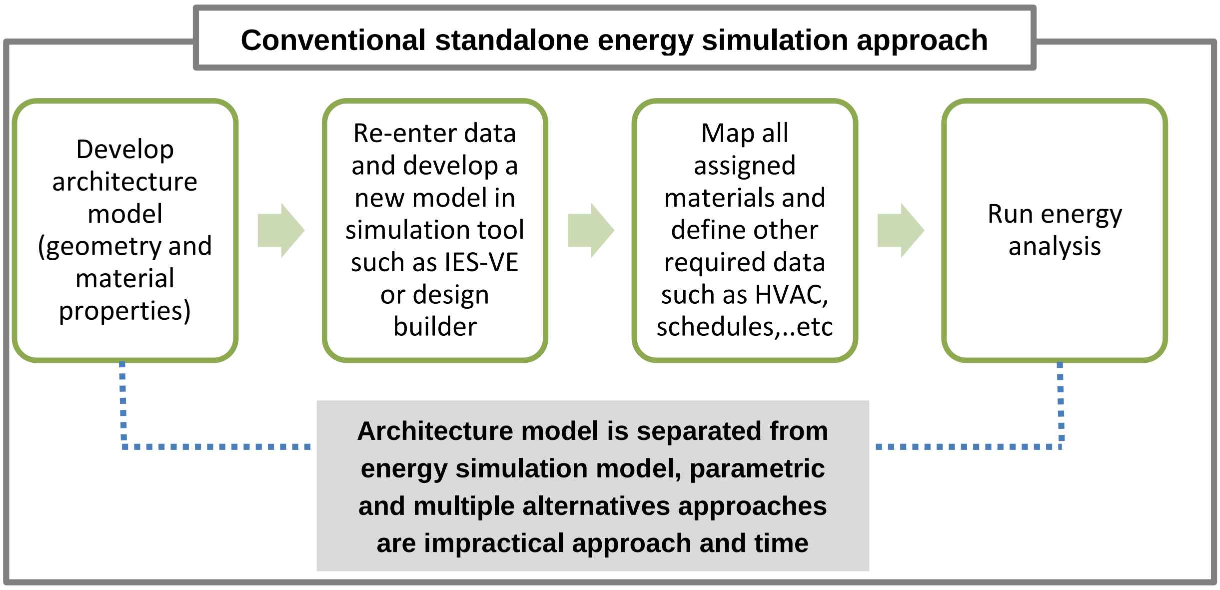


Figure 2 Workflow for standalone BEM approaches

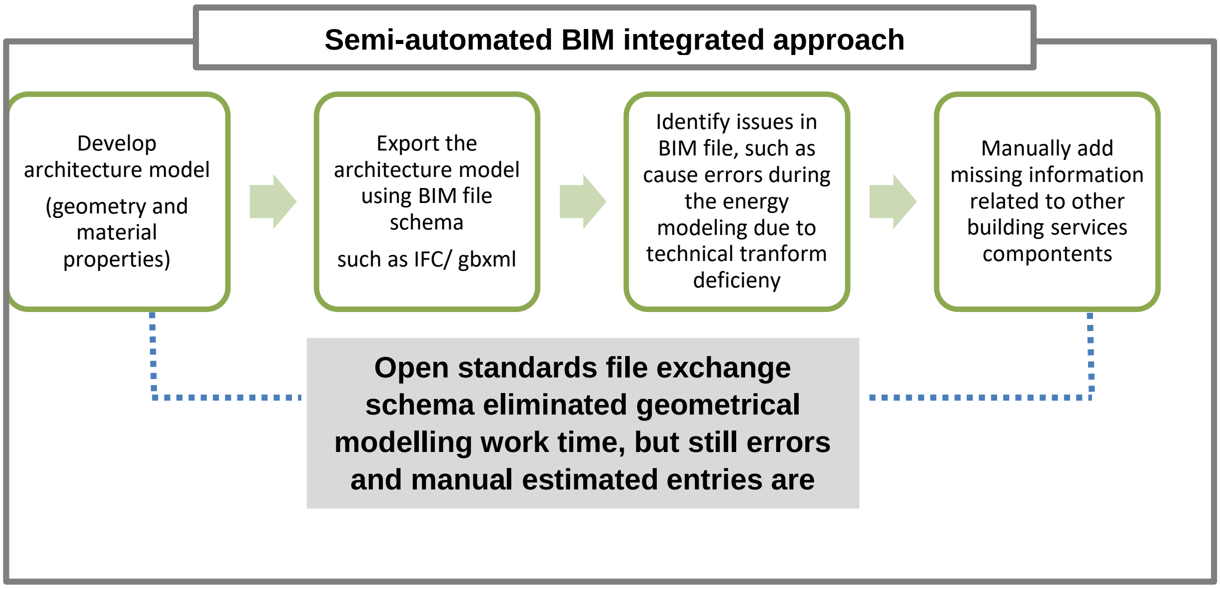


Figure 3 Workflow for semi-automated BEM approach

3.3 Life cycle energy analysis including Embodied Energy

Numerous studies in the last ten years have been conducted for general BIM-LCA integration and estimation of embodied energy in particular (Soust-Verdaguer, Llatas and García-Martínez, 2017) (Nizam, Zhang and Tian, 2018), also all databases and estimation methods are comprehensively covered previously (Azari and Abbasabadi, 2018). In addition, work by (Alwan and Jones 2014) demonstrated that embodied energy plays an important role in buildings footprint through manual methods, and automated predication can make the process much easier. Table 3 presents few tools/Methods which can be used to estimate life cycle energy including embodied energy during early design stage of a building. The required input and system boundaries of each tools are also summarised in the table.

The approaches are divided into three; illustrated in figure 4 and explained in the next second. One important variable of performing LCA and uptake of those tool is the required level of experience to deal with LCA tool (Soust-Verdaguer, Llatas and García-Martínez, 2017). The sophistication level highly depends on the tool/Method. (KTH + ALL PARTNERS' CONTRIBUTIONS, 2010) classified the different levels of performing LCA and the experience of the practitioners as follows : " basic calculation, developed in excel, tool that consider simple input output". Athena and eTool LCD (Impact Estimator and EcoCalculator) are classified medium level of sophistication while tools such as Simapro requires development of advanced calculation, which required high level of experience of LCA. Therefore, also the level of complexity of input for each tool is assessed in Table 2, as it is an important variable that affects the decision of the architects to use them.

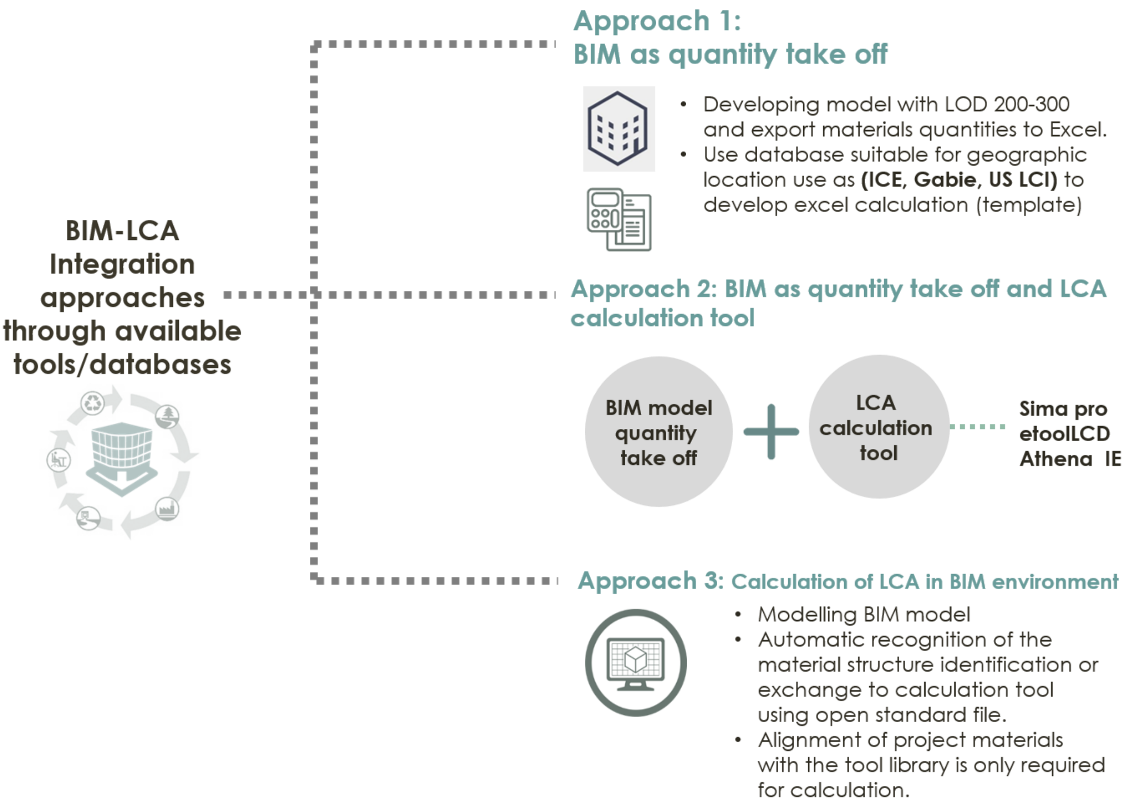


Figure 4 BIM-LCA Integration approaches under DEET

Table 3 Analysis of LCA Tools, which can calculate embodied energy and more LCA outputs

Tool	Input required	System boundary and region of database
Tally (Kieran Timberlake, 2014)	**Automatic Quantity take-off from model:** Only required to assign the unit of material calculation/ Material take off options (Length, area, volume) **Automated family identification:** All objects are automatically available in the interface according to modelled families. **Required material mapping:** Required the material mapping of the existing materials to the material library database in the program.	**Allow cradle to grave system boundary.** - Usually user rely on industry average transportation and construction impact. Ignores construction details and asks for lump sum value. -Material database used is German database GABi and filtered to North America market and manufacturers.
One Click LCA (One Click LCA, n.d)	**Import open standard BIM schema file either IFC or gbxml and file additional project information.** Similar to tally.	**Allow cradle to grave system boundary.** -complies with European standards and has template for North American Market as well -Have different schemes for use in UK and international schemes as well
Athena Impact Estimator (Bowick, O 'connor and Meil, 2010)	- **Manual entry of project material take-off** - **Assembly information** (geometry, assembly/material choice, loading) - **Operational energy information** (annual operating energy) - **Building information** (location, life expectancy, occupancy type, floor area, height)	High detailed tool with high range of LCA scoping according to: 1. Object of assessment eg. Core and shell 2. System boundary, Life cycle activities To according include scenario for database Suitable for Canadian and US regions.
etool LCD (Hermon and Higgins, 2015)	Similar to Athena IE	Similar to Athena IE, but have different schemes for use in the UK and international European and US schemes as well
Ms Excel and data base such as ICE, Gabie, US LCI	-Manual entry of material quantities that can be -Manual search through data base to get coefficients of the embodied energy values for excel calculations.	**Flexible method** as User can determine the system boundary. Level of complexity is also determined by the user.

The First approach is using BIM model as a quantity take-off to Excel sheet and develop a calculation template excel sheet. In this case the use the user develop equations and apply coefficients according to standards calculation methods to create green templates as proposed by (Lee et al., 2015) (Peng, 2016). In this case the use of Inventory of Carbon and Energy (ICE) database for UK, GaBi (Germany,US,Europe) or US LCI (US) will be selected according to the project geographical coverage and Excel calculations are developed. The second approach is similar to the first one as the method in the utilization of BIM model as a quantity take off, but the difference is using already developed LCA tool such as Simapro for LCA analysis , Athena Impact estimator, or etoolLCD(Eon et al., 2017). In the first and second approach the contribution of BIM integration eliminated the material quantity take off only, but still the exchange of material quantities requires manual entry for LCA modelling.

The third approach is presented by the use of two recently launched tools; tally (Kieran Timberlake, 2014) and one click LCA (One Click LCA, no date), both attempt to deal with LCA in the BIM environment. Detailed study was conducted by (Köseci, 2018) comparing interoperability potentials and deficiencies in the use Tally and one click LCA. The required input, system boundary considered and interoperability and level of complexity for both tools are summarized in Table 2. It is concluded that Tally and one click commercial LCA tools have eliminated the possibility of errors that can be caused from manual quantity take –off entry and provided automatic material identification which just require user material mapping/alignment with existing library. However, both doesn't allow users for update and change in the embedded material database. It is recommended use those tools in detailed and structured ways in the developed design stage, as they produce detailed and comprehensive LCA which can be advanced and time consuming for the use in conceptual design. As they are both in development phase, further investigation is required to validate the reliability and accuracy of those tools.

Also, this approach has risk or the user ignorance to the effect of the level of detail (LOD) presented in the model on the output. Most of the case studies used in previous papers use range of LOD 200-300 as reviewed by (Soust-Verdaguer, Llatas and García-Martínez, 2017) . However, the use of BIM models with LOD 200, and LOD 300 (Lee et al., 2015; Yang et al., 2018) were shown to be adequate , recent study by (Cavalliere et al., 2019) encouraged the understand and link LOD to the use of the different databases as illustrated on Global warming potential GWP . To summarise the section, it is everything that tools do exist however, they have not been fully utilised by professionals in the AEC sector due to their complexity

3.4 Challenges in Using Existing Tools for Whole Life Cycle Energy Analysis of BIM based Projects During Early Design Phase

BIM facilitates energy efficient design within the energy consumption assessment throughout the entire life cycle of buildings (Häkkinen and Kiviniemi,2008). However, there are many challenges in using tools mentioned in Table 3 for assessing whole life cycle energy during early design stage of BIM based projects due to lack of interoperability of existing tools, lack of input data during early design stage and difficulty in determining an adequate granularity and development process for building BIM models.

Recent review paper by (Nizam, Zhang and Tian, 2018), categorized the characteristics of the different types of studies in terms of applicability of framework on other projects, interoperability represented in the exchange of material sustainability data and BIM quantity take off, calculation method and finally the included and excluded system boundary. It provided a critical review of BIM-LCA integration with different approaches, which revealed challenges of the different methods. The challenges that were concluded from the analysis of different efforts and approaches of calculating embodied energy and or more LCA environmental impact calculation through BIM.

The first challenge identified is the complexity and time-consuming nature of mapping the LCI input data with building material quantities (Soust-Verdaguer, Llatas and García-Martínez, 2017). The multiple manual input required to match the sustainability data with the material properties database question the practicality of use due to the need for long modelling time and high susceptibility in errors during transfer. A study by (Jarde and Abdulla, 2012), accessed the embodied energy and carbon for two different alternatives of houses, the first is mud-brick and second is cement block. The manual calculation presented in the study to estimate the embodied energy and carbon for two alternatives reflects the complexity and time consumption required to compare results, which highly affect the uptake of this approach by architects in early design.

The second challenge is the lack of interoperability between BIM model and LCA tools which limited the role of BIM model in the framework as just an automatic material take-off, the general method of this approach is illustrated in figure 2. Several, scholars have attempt to build their proposed methods with this approach. A comprehensive framework was provided by (Shadram et al., 2016) to estimate embodied energy during building design, with the use of Power pivot – " an Excel add-in which can used to perform powerful data analysis and create sophisticated data models"-, as main data integration platform. In the same vein, (Jarde and Abdulla, 2012) conducted LCA though BIM by proposing to export IFC from BIM model and use IFC analyser to prepare quantities required by LCA tool.

Tool	Interoperability with BIM environment and complexity
Within BIM Environment	
Tally (Kieran Timberlake, 2014)	**-Automatic family identification and material take-off recognition only mapping of material in model to the selected database.** **Plugin limited only for Revit** - It is plug in within Revit architecture or structure model - Depends on the granularity and detail of BIM model LOD **Deal with 3 detailed levels:** - Schematic design: showing building components weighting - Design option comparison: comparing reports but the after mapping of materials once and executing the results report are available in the BIM model - Complete LCA **Closed commercial product:** Limited customized development or update for the inventory data and not flexible to other system boundaries.
One Click LCA (One Click LCA, n.d)	**-Automatic family identification and material take-off recognition only mapping of material in model to the selected database.** **Provides different software solutions:** -Early design optimization and benchmarking in conceptual phase -Full life cycle assessment **Not Limited to only one commercial software:** Can be used with wide range of software not limited to one - Web based interface software (IFC can be plugin in Revit, IES-VE, Graphisoft ArchiCAD, tekla structures etc.)
On separate platform- BIM model can just be used for material take-off	
Athena Impact Estimator (Bowick, O 'connor and Meil, 2010)	- Manual entry of material quantity information and required high experienced LCA individual to complete information module about product, construction installation, use, end of life. - Very complicated for the use of screening and simplified LCA that is suitable for early design conceptual phases
etoolLCD (Hermon and Higgins, 2015)	- Manual entry of all Material, Assembly and operational inputs. - Have simplified scheme in addition to detailed which provided flexibility to level of complexity required for the stage. - Calculations are not connected to the BIM model i.e. any changes in the model Material typology or quantities are not reflected automatically or highlighted to be changed in LCA calculation.
Ms Excel and data base such as ICE, Gabie, US LCI	- Calculations are not connected to the BIM model i.e. any changes in the model Material typology or quantities are not reflected automatically or highlighted to be changed in LCA calculation. - Level of complexity is flexible and can be designed to suite the conceptual design stage. - High possibility of errors - Doesn't allow iterative process as it will be impractical and time consuming - Reliability is not assured and validation is required

The third challenge is determining an adequate granularity and development process for building BIM model. (Lee et al., 2015) proposed a framework for automated LCA within BIM model without data exchange. This framework utilizes the use of parametric modelling and inter-object data relationship which associate embedded impact factors of the materials in Revit family (∗.rfa) file. After preparing a revit family for each building element by using a family writer tool, the file is used by the modeller in the

BIM authoring tool (Revit). This requires a development of model of LOD 300 or higher in addition to the need for high skilled modeller to use the developed built in family. Another effort in automating calculation of LCA impact factors without exchange of data is proposed by (Jrade and Jalaei, 2013). Similar to (Lee et al., 2015), the provided framework which adds unique keynote i.e. parameter in each Revit material family. Manual preparation of the material library is required before use by filling keynotes for the plenty potential materials. Despite, these studies provided automatic calculation within BIM environment with no exchange of files between different platforms, the method provide complex and impractical use in the industry current state. This is reasoned by the current lack of ready to use material library and requirement for high skilled modeller of the use of detailed built-in family. Also, this approach has risk or the user ignorance to the effect of the level of detail (LOD) presented in the model on the output. Most of the case studies used in previous papers use range of LOD 200-300 as reviewed by (Soust-Verdaguer, Llatas and García-Martínez, 2017) . However, the use of BIM models with LOD 200, and LOD 300 (Lee et al., 2015; Yang et al., 2018) were shown to be adequate. Recent study by (Cavalliere et al., 2019) encouraged the understand and link LOD to the use of the different databases as illustrated on Global warming potential GWP .

In summary, as illustrated in figure 5 taking into consideration of the challenges and limitations of BIM and energy estimation discussed above, the proposed framework should consider a user-friendly interface, minimize the several manual entries, and not requiring high experienced LCA practitioner to deal with assigning the right sustainability data for materials and systems used.

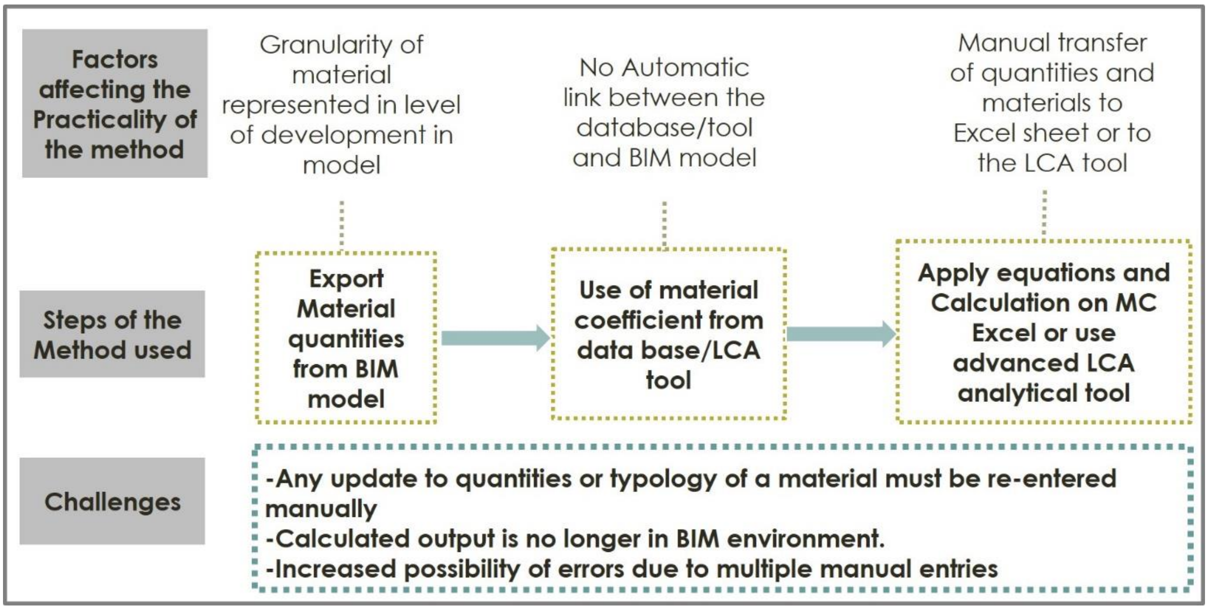


Figure 5 BIM as material take-off

4. Methodology

In this section a brief overview will be given of the methods deployed to achieve the original aims of the research project. It is clear from systematic analysis in section 3, the challenges faced by the sector in order to create an optimum method of applying BIM within life cycle analysis of buildings. The findings revealed in figures 4 and 5 which have been the outcome of literature will be used as the basis for developing this methodology.

4.1 Life Cycle Assessment Methodology

***Setting up the scope* for operational and Embodied Energy Assessment Methodology**

As detailed in the original aims of the work plan, a scope has to be set to identify the parameters of the components that can be measured. Measurement of the overall energy impact of all components is almost impossible as a building might have 1000 plus items. This section provides a road map of both operational and embodied energy within a buildings' life cycle and what can be measured within the constraints of the study and the limitations of measurement techniques. The rational which will be explained in this section is to focus on material parts of the building that can termed as "energy hot spots" due to their larger energy consumption.

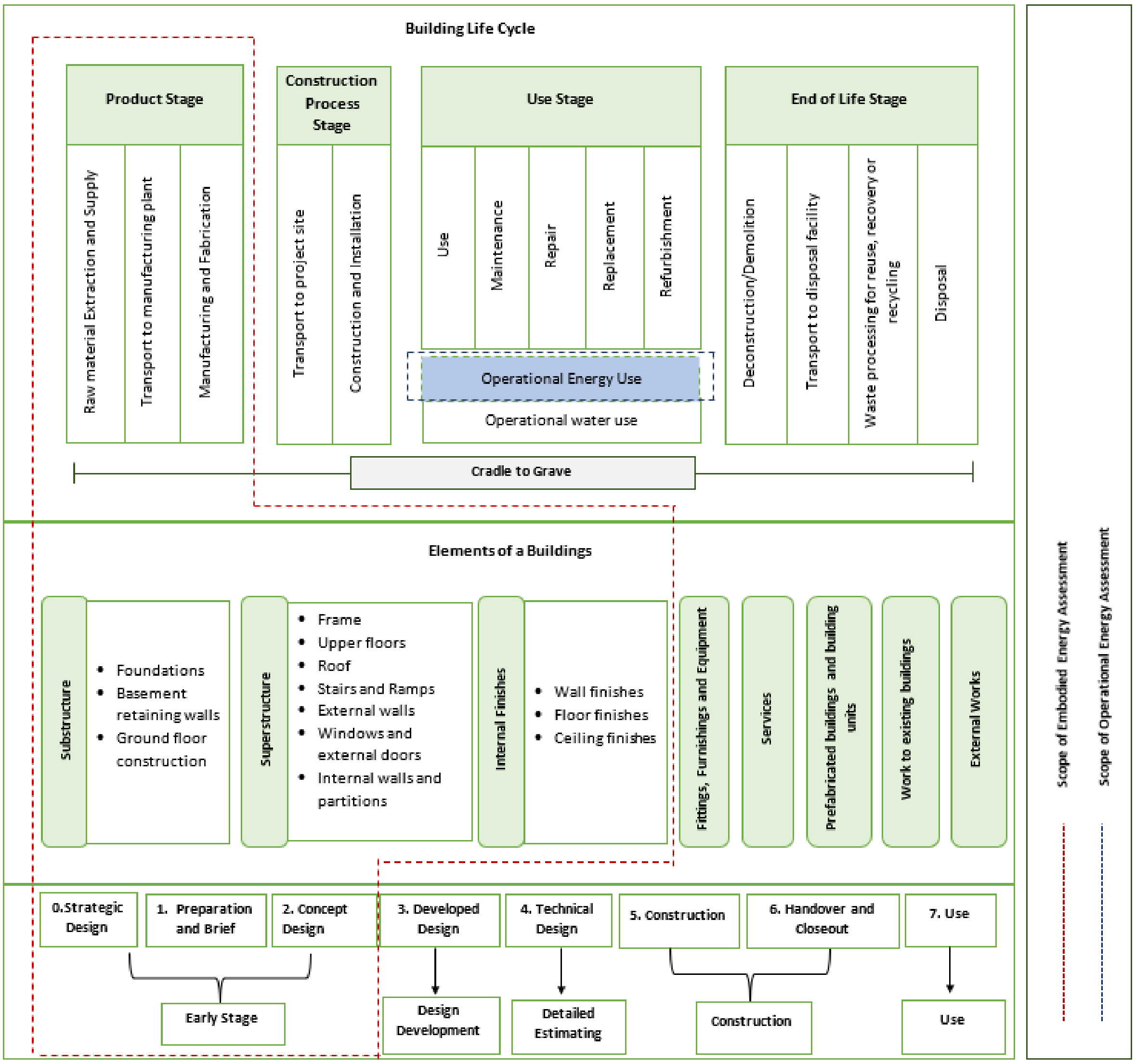


Figure 6 Boundary for the research methodology

Figure 6, illustrates the operational and embodied energy assessment boundary of this study. Since more energy saving opportunities lie in the early stage of a building development, the assessment stage was confined to the early design stage. According to the RIBA Plan of Work, early design stage comprises of a) strategic design, b) preparation and brief and c) concept design phases (RIBA, 2013). Identification of client's requirements, development of project objectives and preparation of concept design occur at this stage, allowing the decision makers to choose best energy efficient materials, systems and finishes.

Embodied energy share of life cycle assessment was currently limited to the cradle to gate boundary, which includes product stages (raw material extraction and supply, transport to manufacturing plant, manufacturing and fabrication), due to limited data availability. Further, it was limited to the carbon intensive elements of a building. As recommend by RICS (2012), substructure, superstructure, internal finishes and external works need to be included in EE and EC estimation. Accordingly, it was chosen substructure, superstructure and internal finishes for this study. External works were disregarded due to unavailability of information. EE coefficients of building materials used in these building elements were taken from the Inventory of Carbon and Energy (ICS) version 2.0 (Hammond and Jones,2011). This was chosen as it is an open access database which has been drawn mainly on data from UK and Europe. EE estimation adopted the process introduced by RICS (2012) for EC estimation. Accordingly, it included I) determining the constituent materials required for each element, II) calculating the weights of building materials used per m^2 of each element, III) identifying the EE coefficients of each material and apply them on material quantities to derive EE content of each material, IV) adding EE of all materials to establish overall EE per element m^2 and multiplying them by total m^2 to derive elemental EE, V) adding EE of all substructure, superstructure and internal finishing elements to establish the total EE. The materials used in each element were identified from the concept design drawings of each case study and eventually the EE were measured in MJ and MJ/m^2, and finally converted to kWh for consistency with operational energy units.

Operational energy tends to be the most visible and understand aspect of the building or asset as its responsible for day to day operations without which the building cannot operate, aspects such as heating and lighting and maintenance. In the three case studies presented it was demonstrated this aspect was measured either using standard coefficients for consumption or using established measurement such dynamic modelling tools which gives a precise account of the energy use.

4.2.1 Identifying Operational energy for Domestic energy case study

This numerical modelling was developed to give a true reflections of current energy consumption for the case studies, and the nature of energy consumption in the UK will be different between commercial and domestic buildings. For the domestic case studies, the Building Research Establishment Domestic Energy Model (BREDEM) was used and applied. It is a methodology for calculating the energy use and fuel requirements of dwellings based on their characteristics. It is suitable for use in research work, such as stock modelling. It shares some features with the SAP methodology, but allows users to adjust inputs which are fixed in SAP, making it better suited to certain analysis tasks. In the case of this research project, BREDEM 2013 model was used and full details of the technical specifications of BREDEM can use seen in the appendices section.

The software used is very much similar to standard assessment procedure SAP which is responsible for producing the energy performance certificates for domestic housing. However, SAP has fixed use of imports and therefore make it not possible to use it for analytical purposes in terms of research. The benefits of using and applying such established systems is that it is give details of a comprehensive domestic energy approach which covers the following:

- Calculate the energy consumption for lights appliances and cooking
- Calculate the energy requirements forward to heating
- Calculate the dwelling thermal mass
- Calculate the internal heat again
- Calculate the space heating requirements

The calculation method can provide estimation of various consumption patterns which are converted into fuel costs or CO_2, and the beauty of the modelling is that can allow greater control of issues such as lighting appliances and cooking which are very much specific to the domestic setting. It can also allow control over types of water heating building orientation and calculation of solar heat gains and internal heat gains.

4.2.2 Identifying Operational energy for Commercial energy case study

The nature of building use and energy consumption tends to be vary from domestic sector, therefore the commercial case study was modelled using a variety of standard co-efficient such based on TM46 (CIBSE Technical Manual 46). In this case as there was only one commercial building to analyze , this was done using Design builder modelling software, under educational and research license which was based on 3D geometry, imported from Revit Architecture. This was considered the most suitable option as it gave total operational energy consumption based on exact geometry.

4.2 Tool Development Methodology

The need for decision support tools that integrate LCA and energy simulation into early design of buildings led to the emergence integrated platforms in BIM and parametric design tools. Most of existing tools focus on evaluating the design alternatives after the decision making (Attia, Gratia, De Herde, & Hensen, 2012). The concept of parametric design in architecture, promise to deal with complex designs and provide an Integrated platform for many disciplines in the same time, promoting the concepts of BIM. Thus each discipline is dependent on one another in a very complex using vast geometrical connections (Eltaweel & Su, 2017).

The research team developed a bespoke parametric design tool which addresses both operational and embodied energy based on established benchmarks already in use in the industry such as, BREDEM CIBSE. Operational energy benchmarks and EnergyPlus platform, this was based on method outlined in Figure 4, mainly using option 3. The ultimate aim was to design a tool prototype that could be changed and modified by professionals operating within the AEC sectors. It is hoped that this project is a start of something more detailed in terms of overall whole energy analysis and building formants therefore using such a platform allows the user to effectively control the inputs and modify them as the needs of the client and level of detail required changes. It is also hoped that such a tool will be use of the early design stages which changes could be made to influence decisions on the type of materials to use. Hence effectively what ultimately an easy to use mechanism which could be used to educate as well as inform various stakeholders. The final stage is to represent the data that was generated into components that non-experts can relate to and this is best delivered to a virtual reality platform.

5. Case Studies

The research project had unique benefit of engaging with practitioners in the North East region who were very much interested in the outcomes and the research methodology to improve their operating processes and address sustainability issues, and supplied full technical details of building designs. In order to get an overall account of the role of built assets within the built environment three different building types were chosen, two domestic, and one commercial building, in order to get different representation of construction materials and operating patterns. a full description of the case studies and the results of the analysis can be seen in appendices section (appendix 1, together with results of the analysis).

One of the tasks that the research team had to develop was the creation of construction models in a 3-D from a 2 D environment. This allows much better data handling and extraction for further analysis in terms of total energy use. In this case two-dimensional plans were used to develop a three-dimensional model such as gbXML and Industry Foundation Class (IFC). This allowed easy categorisation and standardisation of material use which could be then analysed and exported to both operational and embodied energy analysis. This scheme was applied to all the three case studies analysed both for material and energy consumption.

6. Development of the Digital Energy Estimation Tool (DEET)

The parametric design has the great advantage of studying the impact of geometrical and material variables on environmental aspects (embodied and operational energy impacts). The proposed design-integrated approach aims to show how the assessment of coupled embodied and operational impacts can make architects aware of the potential effects of their design and material decisions parametric tools provide an interactive tool for both geometrical and material decisions.

In early design stages, parametric models generally can provide a low Level of Geometry (LOG) compared to BIM models. The Life Cycle Assessment (LCA) and operational assessment are specified according to the level of details provided and the predefined material composition of building elements. The parametric approach presented in this section a proof-of-concept for the coupled (LCA) and operational energy assessment of the building in early design stages.

Despite the recent investigations of the parametric tools, there is no ready-to-use applications, and scripts are largely customized to deal with the architect needs. Rhino/Grasshopper is one of the most widely used platforms that are used by designers today. It is a free open source; where users can customize the tool based on their needs and contribute to the source code. As defined by (Roudsari, Pak, & Smith, 2013), Honeybee is the extension of Ladybug which extends users' ability to work directly with validated simulation engines such as EnergyPlus (US Department of Energy), RADIANCE, and Daysim (Reinhart & Walkenhorst, 2001) to provide energy and daylighting modelling.

It imports standard EnergyPlus Weather files and provides designer-friendly interactive graphics to support the decision-making process during the initial stages of design. It allows users to work with validated energy and daylighting engines such as EnergyPlus, Radiance and Daysim. Integration with the parametric tools of grasshopper allows for almost instantaneous feedback on design modifications, and as it runs within the design environment, the information and analysis is interactive. The analysis are done in four steps in Honeybee, which are; preparing simulation geometry, checking the input file, running the simulation(s) and visualizing the results (Reinhart, Geisinger, Dogan, & Saratsis, 2015; Roudsari et al., 2013).

A 2D single line plan drawing was modelled in Rhino and then linked to Grasshopper as shown in figure 7 (a b). The three dimensional model was modelled in grasshopper with variable range of WWR and space heights. All building elements, ground, walls, roof, windows, etc. were separately analysed in terms of areas. The material decision and geometrical variables; WWR and space height; have instantaneous feedback from the embodied energy and operational cost, hence the total cost estimation of the building over a life time span for each design and material proposal.

The material definition depends on a selection from the honeybee and therm libraries. Each surface is composed of single or multiple layers of materials to form a component. The selected material is changed from a drop down menu using an item selector component (material decisions). These material decisions were scripted to affect both embodied and operational energy analysis.

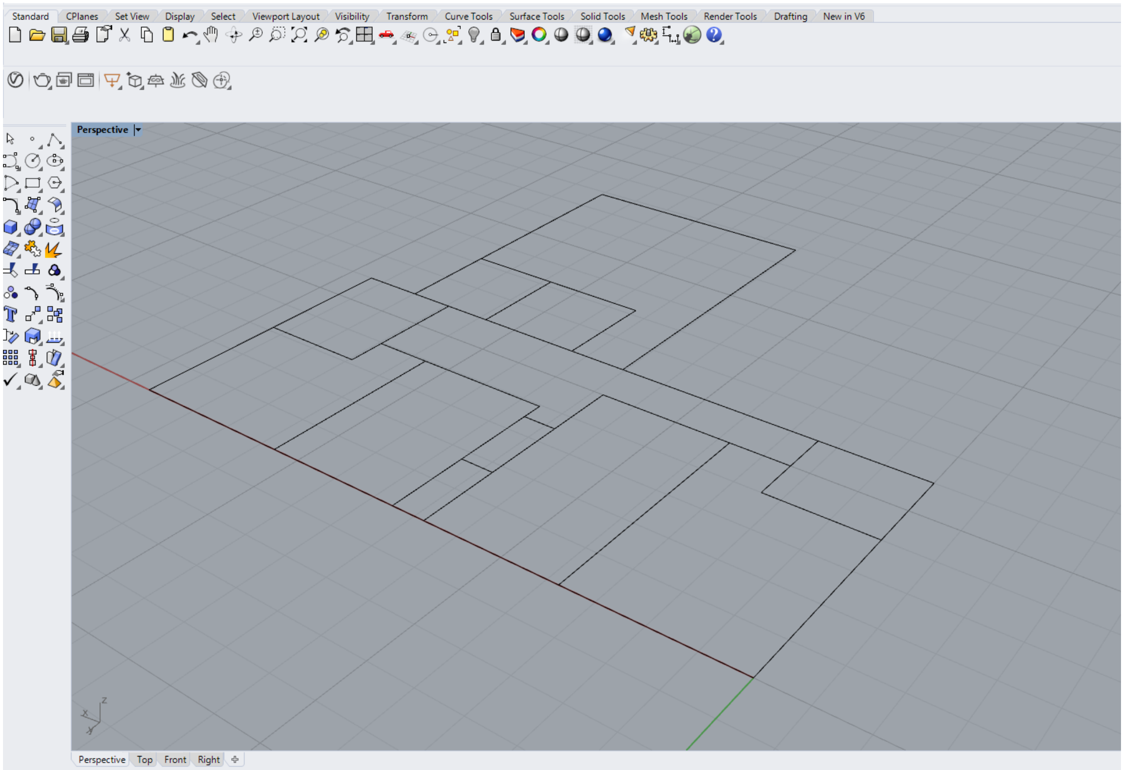


Figure 7 (a) stages of geometrically modelling objects

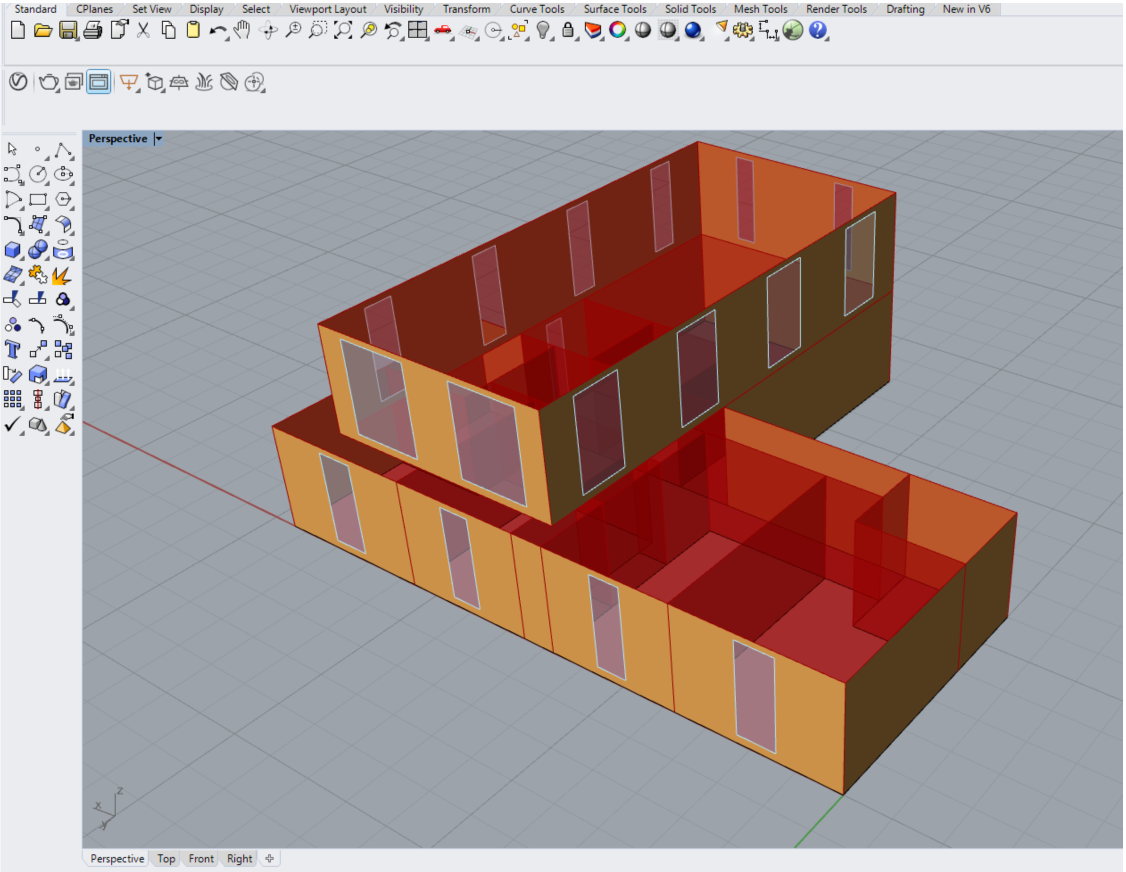


Figure 7 (b) changing the geometry of modelling objects

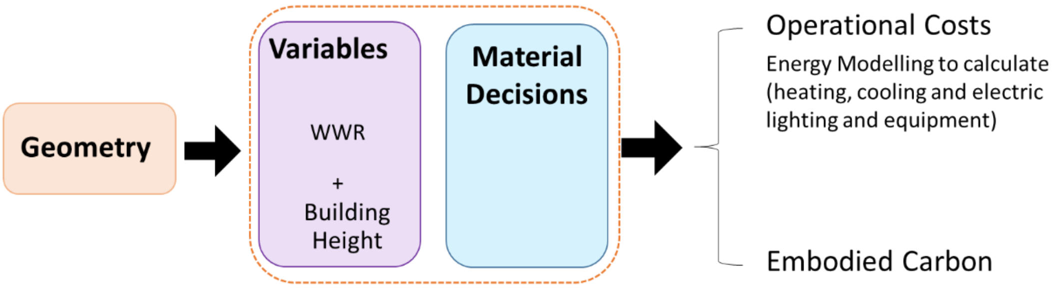
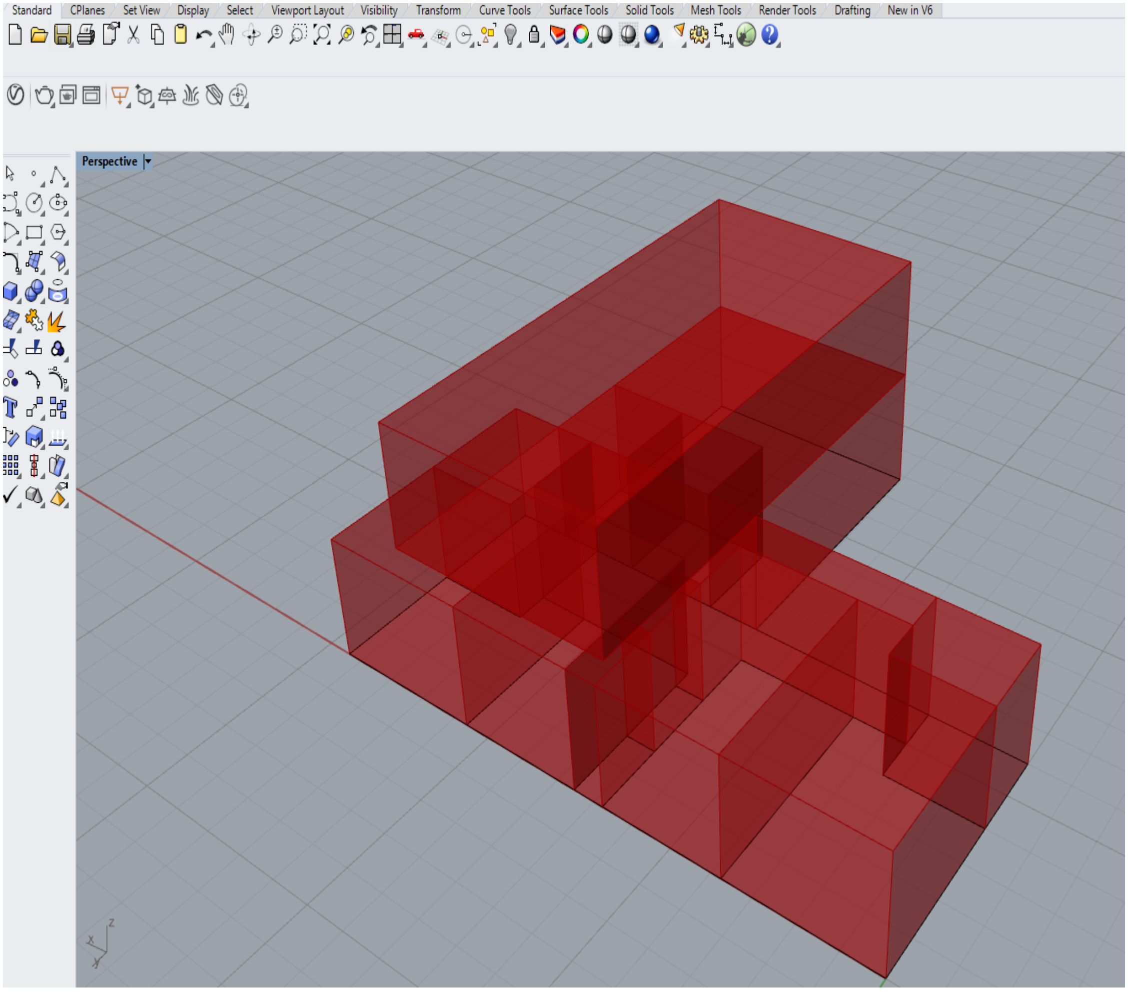


Figure 7 (b) linking geometry with total energy use



LCA analysis

Generally LCA-based softwares for the environmental evaluation of construction materials and buildings are complex and time-consuming (Agustí-Juan, Hollberg, & Habert, 2018). LCA plugins into Grasshopper such as BOMBYX and Tortuga represents a recent simplified methods and tools to consider environmental criteria from early design stages.

In recent years, academics developed an open source plugin for LCA called Bombyx. Bombyx plugin allows for simplified whole building Life Cycle Assessment (LCA) see Figure 8 of buildings during design, the research team has developed this work further. It depends on connecting the geometry drawn in rhino with named layers with corresponding geometry containers in grasshopper to analyse the area and then specify thickness, material and reference service life for each layer. The impact of layers, elements, components and the whole building is calculated per year and then the global warming potential GWP. (Agustí-Juan et al., 2018) developed a Design-integrated simplified LCA method in grasshopper for evaluating digitally fabricated building elements from early design stages.

BOMBYX WORKFLOW				
Input set 1	**calculate**	**Input set 2 for each layer**	**calculate**	**OUTPUT**
Geometry layers NFA factor (1)	Net floor area	Material Thickness Reference service life Reference Study period	-layer impact -element impact -component impact -building impact Building per year and NFA	global warming potential (GWP) Penr UBP

Figure 8 Building components within Bombyx

Energy and Operational Costs analysis

Operational energy estimation is analysed based on annual consumption using Honeybee for the expected energy consumption for lighting, cooling, heating and electrical equipment. There were two modelling methods taken in consideration while performing energy analysis and calculating operational costs.

The first method depends on modelling each zone with the extruded height variable. All extruded spaces were joined and transferred into zones. Window Openings were applied to each zone with a variable WWR. Zones and window openings are transformed into honeybee zones. All linked to weather data file according to the project location. These honeybee zones are decomposed into the building components and their areas are calculated to be further processed in the LCA analysis. This is a simplified method as it depends on the default material settings for the operational energy. The overall view can be seen in figure 9, which gives an overall figure of what was achieved under the tool development phase.

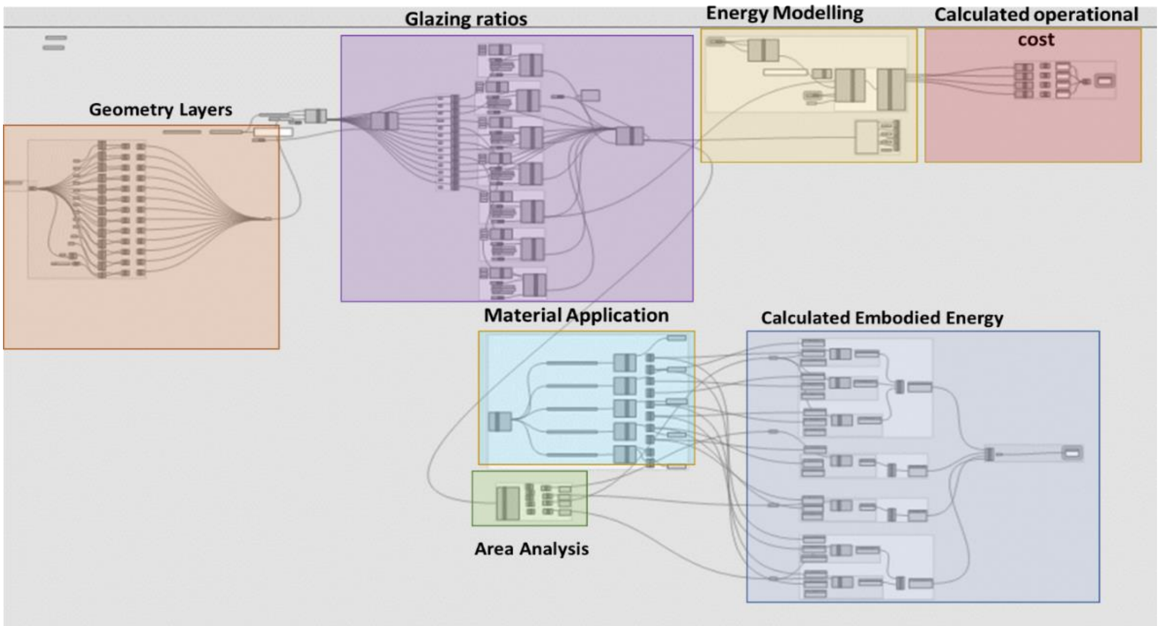


Figure 9 overall road map of parametric model

The second method depends on creating honeybee surfaces with linked material construction. Then Honeybee surfaces and glazing are transformed into honeybee zones. Although this method requires more scripting and modelling work, the energy analysis is more accurate and the material decisions affect both the operational and embodied energy. The final phase of the work which is currently being developed is to view the tool and through the lens of virtual reality (figure 10), allowing these concepts to be better appreciated by stakeholders.

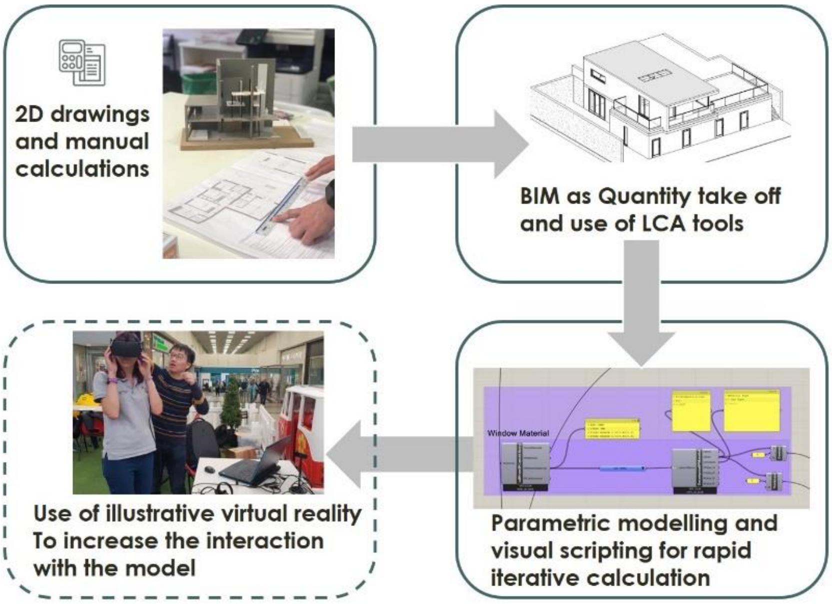


Figure 10 clockwise moving from 2D plans to VR interaction for analysing energy use and geometry

7. Impacts and potential impacts for a Digital Built Britain

The aim of this proposal as set out on the original application was to develop a prototype tool for total energy use within the built environment and thus enhancing building performance through BIM principles. The knowledge developed through findings of this project will specifically enhance the CDBB themes of sustainability, exploitation of digital resources and leveraging data and information. The rigorous application of new and innovative approaches deployed through the methodology has helped address the societal benefits, specifically in terms of considering citizens needs and communicating digital information with regards to building materials and impact of energy and carbon in the short and medium term. An overall aim of the CDBB is to digitalise our entire built assets and find innovative ways of delivering more capacity out of our existing social and economic infrastructure, and this would be addressed through the lens of BIM as a tool for sustainability and better understand of the complex issue of energy use within assets.

As has been demonstrated in recent events in the media, the topic of energy use and climate change is at the forefront of current and future policy both at a governmental level and at a societal level. The development of an interactive parametric design tool that is hoped to be used by both citizens and decision makers will enable the exploitation of new and emerging technologies, and data management to enhance the natural and built environment, thus driving up commercial competitiveness and productivity within the Built Environment sector. Furthermore, one of the successes of this approach has been to apply concepts such as virtual reality to prioritise the important and societal benefits of addressing carbon and energy use in the built environment asset which has been largely neglected in the past. This approach taken will give CDBB’s mission greater importance in terms of addressing issues such as citizen quality of life and well-being. An example of engagement with citizens through the meet the engineer and scientist example, is demonstrated in the (appendices) section.

A final thought of working within multidisciplinary team, of ECRs Cambridge-based and beyond, allowed stronger links to be established and developed which is currently leading to collaboration across different disciplines. This can result in achieving goals of DFTG by collaborating with other interested parties and bodies such as the Cambridge Centre for Housing and Planning and exploring issues such as digital twins and carbon use.

8. Discussion and Conclusions

This section will give a short overview of the main findings that were achieved and then concluding remarks and suggestions that could help in taking this project concept forward in line with CDBB road map.

From green buildings, prospective BIM as a tool has operated as platform for motivation and adoption in the AEC sector, from tools such as LEED and BREEAM (Mohamed 2018), to adopting strategic modern sustainable construction methods (Alwan et al., 2018). The work further consolidates this approach and makes direct links between BIM use and digital estimation of energy with built environment assets.

The findings have suggested that embodied energy contribution can play an important role in the first few years of the building lifecycle and the work established and adopted a framework to identify the parameters that can actually be measured. This was a very exhaustive an intensive process, but was crucial in identifying which elements can be identified as energy hotspots. While it is still early to identify the longer term impacts of this research, it is safe to say that the original objective of real time data analysis from building components can be achieved through the BIM lens and associated energy and environmental impact be assessed. This report really gives an outline of the processes needed to create a digital parametric tool that can be tested by users, can be optimised and developed to suit the needs of individual stakeholders. Thus the main output is a digital product or platform, that can be applied to the built environment and future assets and infrastructure. This study did not represent a qualitative or quantitative analysis of a particular issue rather of been based approach for addressing total energy use within infrastructure or assets.

Throughout the work packages classification in the digital built environment field was achieved and BIM framework in order to clarify links for future development and links to CDBB aims. The project achieved the development of data rich 3D construction templates that addressed more efficiently the decision making potential of BIM processes. A final outcome of the work was the realization of how such aspects such as energy and carbon in the built environment assets can be visualized with virtual reality to give it greater acceptance. This work is still underway.

One of the challenges that was faced by the research team was the generation of reliable data from the geometry and the use of the appropriate coefficients for embodied energy which can vary from country to country or might be out of date in the future. For example, if a particular manufacturing process what was the change, or the operational energy was to switch to renewable energy, this was demonstrated in one of the case studies by using two different data sources different results can be obtained for embodied energy for example.

In terms of the next steps the research team is currently engaging an intensive process of obtaining user feedback to further develop the parametric tool. The aim and hope is establishing it as a digital portal which can be accessed by designers while simpler version can be developed for consumers and users who are interested in the energy and carbon impacts of building components. Further funding would be obtained to optimize and deliver interesting and ambitious future research proposals for example utlistizing the tool within VR environment. It is hoped that on a wider international level the work will fit into the global CDBB mission of global engagement. Worldwide there has been growing interest in embodied energy and carbon analysis: work by Ranathungage (2018) has indicated that rapid rate of construction in the developing world is contributing to embodied energy and carbon. Therefore, the spotlight is shifting towards the impact of embodied energy and carbon that construction materials play in the sector globally.

Acknowledgements

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