



Framework for parametric assessment of operational and embodied energy impacts utilising BIM

Zaid Alwan^{a,*}, Amalka Nawarathna^a, Rana Ayman^a, Mingyu Zhu^b, Yomna ElGhazi^c

^a Faculty of Engineering and Environment, Northumbria University, Newcastle, NE1 8ST, UK

^b School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK

^c School of Architecture, Planning & Landscape, Newcastle Upon Tyne, NE1 7RU, UK

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ABSTRACT

In recent years advances in digital tools have been leading the way in the construction of cleaner, more energy-efficient buildings. Furthermore, improvements in Building Information Modelling (BIM) have resulted in various tools being used to assess building performance and overall Life Cycle Analysis (LCA). This work offers a unique insight into the development of a parametric LCA BIM tool, focusing on both operational and embodied energy perspectives through case study analysis of a commercial and a domestic building in the UK. A mixed research method was employed combining a literature review, qualitative and quantitative LCA case study analysis, and parametric modelling. The results indicate that embodied energy is much more critical in the early stages of the building's life, then is quickly overtaken by operational energy. In addition, many variations exist in energy outputs between domestic and commercial buildings. Operational energy takes a significant share in domestic buildings compared to commercial buildings. These variations are attributed to different design methods, construction materials, occupancy patterns and energy demands. The study proposes an LCA-BIM interactive user-led method of addressing energy hotspots for both operational and embodied elements, which can provide more instant identification of energy critical areas. Such an approach can offer real alternative BIM-based analysis tools during the design stages, compared to those currently being used, which focus mainly on either LCA of operational or embodied energy.

1. Introduction

The architecture, engineering, and construction (AEC) sector is recognised to be a major consumer of non-renewable energy and source of carbon emissions. It is responsible for 35% of global energy consumption and 38% of energy related global carbon emissions [1]. Of this 35%, 30% comes from the operational energy (OE) [1] that buildings use in operational activities such as heating, cooling, lighting, and building appliances [2]. Significant advances in both legislative measures and technologies have resulted in building mechanical systems becoming more efficient in terms of OE consumption [3], but this has caused the embodied energy (EE) share of whole life cycle energy, i.e. the energy required by all the processes associated with building production, to increase [2,4]. Until recently, the EE share of buildings was not always fully accounted for due to the complexity and time-consuming nature of its assessment, compared to operational energy use. However, in recent years it has become the focus of both policymakers and researchers

wishing to optimise the total energy consumption of buildings throughout the life cycle [2,5]. To enable the AEC sector to meet the 2015 Paris Agreement goals [6,7] and United Nations (UN) sustainable development goals, equal attention to both operational and embodied energy impacts is required.

Life cycle assessment (LCA) approaches are widely used to estimate the environmental impacts of buildings during their whole life cycle, from raw materials extraction to the end of life [8,9]. However, the depth and breadth of LCA analysis has been a source of confusion and frustration for researchers as well as professionals in the AEC sector, due to the variables of material harmonisation [10] and boundary conditions [11]. Accordingly, the current research discussed in this paper follows international standards, using the methodological framework which has been described in ISO 14040 [12] for estimating and evaluating environmental impact throughout a product or service system life cycle, from cradle to gate. According to this, LCA comprises four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO 14040, 2006). Firstly, the

* Corresponding author.

E-mail address: zaid.alwan@northumbria.ac.uk (Z. Alwan).

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Abbreviations		LCA	Life Cycle Assessment
AEC	Architecture, Engineering and Construction	LCI	Life Cycle Inventory
BIM	Building Information Modelling	LCIA	Life Cycle Impact Assessment
BOQ	Bill of Quantities	LOD	Level of Detail/Development
BREDEM	Building Research Establishment Domestic Energy Model	MMC	Modern Methods of Construction
CLC	Construction Leadership Council	NBS	National Building Specifications
EE	Embodied Energy	OE	Operational Energy
FSSD	Framework of Sustainable Strategic Development	PHPP	Passive House Planning Package
GH	Grasshopper	SDG	Sustainable Development Goals
GWP	Global Warming Potential	UN	United Nations
ICE	Inventory of Carbon and Energy	WPF	Windows Presentation Foundation

goal and scope definition phase establishes the goal, system boundaries and level of detail of the LCA. The second phase, life cycle inventory (LCI), involves collecting and synthesising input/output data relating to the building being studied. The third phase, life cycle impact assessment (LCIA), involves evaluating the significance of potential environmental impacts using the LCI results. Typically, LCI and LCIA are merged and simplified in building analysis [13,14]. The last phase, interpretation, deals with the demonstration of results from both LCI and LCIA. It includes summarising, drawing conclusions and recommendations, and decision-making in compliance with the goal and scope of the study.

With regard to EE assessment, generally, the bill of quantities (BOQ) is required: the quantity of individual materials or components is multiplied by the energy coefficient extracted from a specific LCA database. Numerous LCA databases are available from which to extract coefficients of materials and components, for instance: Inventory of Carbon and Energy (ICE) [15]; ecoinvent 3.3 [16]; ÖKOBAUDAT [17]; and Athena Life Cycle Inventory Product Databases [18]. However, this manual estimation approach is very time-consuming; much effort is needed to establish the BOQ and find the correct coefficients of building materials from LCA databases, which are mostly either country-specific or region-specific [19,20].

A complete LCA of whole energy consumption will normally be considered, when complete architectural construction and mechanical details for a project are identified. By then, it is often too late to consider potential substitutions of materials, components or systems to make the building more energy efficient. Early analysis in the architectural design process could be highly beneficial in enabling the minimisation of environmental impact [21]. In addition, LCA analysis needs to feature in the current digitalisation drive of buildings, as opposed to current manual calculations [22].

BIM, with its many benefits, has been a transformative tool within the AEC sector [23]. In addition, in the last few years BIM maturity within projects has been assessed with reference to LCA from associated cost [24] to Global Warming Potential (GWP) assessment [25] and sustainable project delivery. Accordingly, there are opportunities available to optimise energy consumption by further improving design and construction using BIM.

While many academic publications have focused mainly on impacts of operational and embodied energy and their associated carbon in isolation, the critical focus in this research is in terms of the challenges of a whole cycle approach for both EE and OE, and the most effective way to obtain meaningful answers within the AEC sector utilising BIM. No academic studies exist that link both operational and embodied aspects of energy in one tool for the AEC sector from a UK perspective.

1.1. Aim and objectives

The aim of this research was to develop a single parametric BIM and whole LCA-based tool that can be used to estimate both operational and embodied energy of buildings in the UK context. The research aim was delivered through the following objectives: 1) Identification and critique of existing LCA-BIM analysis tools; 2) Selection and creation of BIM-ready commercial and domestic case studies; 3) Analysis of critical materials and operations which make significant energy contributions; and 4) Proposal of a single parametric approach which can be utilised by the AEC sector, based on the case study findings.

This paper is organised into four main sections. The first section contains a literature review, including the adoption of LCA within BIM, its many challenges, and the definition of systems boundaries for the LCA-BIM case study analysis. The second section describes the

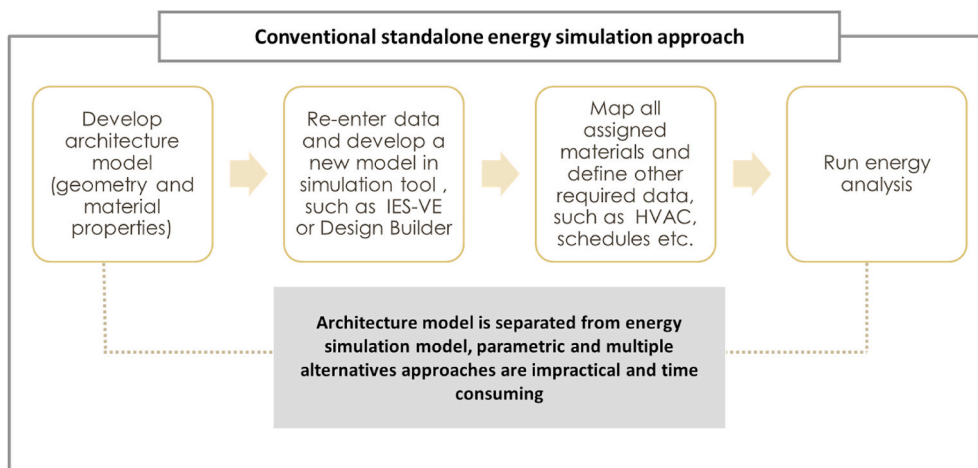


Fig. 1. Workflow for standalone BIM approaches.

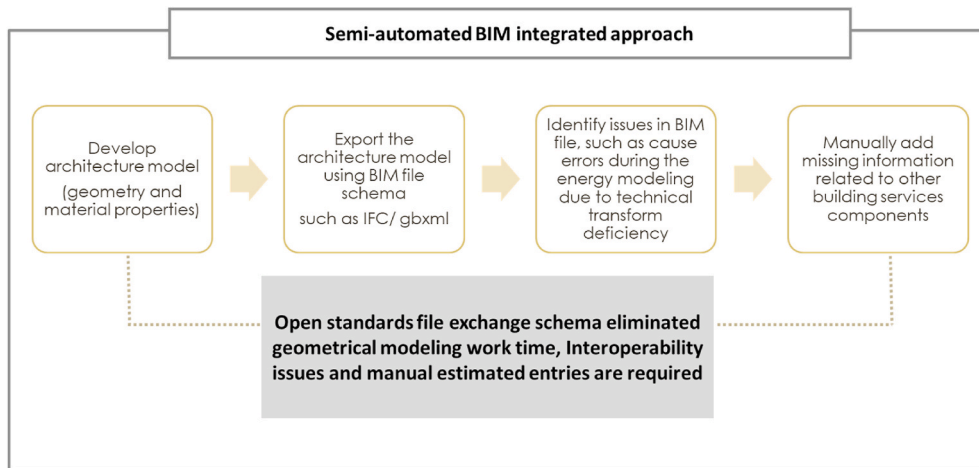


Fig. 2. Workflow for semi-automated BIM approaches.

methodology of the study in which two different UK case studies, were evaluated within BIM environments to identify energy-critical elements from both embodied and operational aspects. The case study provides useful multi-perspective insights to deal with the complex, multi-faceted issues of LCA in buildings. The third section presents the user-driven parametric framework. The final section discusses the proposed framework as a whole energy LCA-BIM decision-making tool in building projects.

2. Literature review

2.1. BIM utilisation and complexity of LCA analysis

BIM has made significant impacts in transforming day-to-day operations within the AEC industry through promoting collaborative culture, project delivery [26] and enhancing performance across the building and infrastructure life cycle [27]. Incorporating energy analysis into BIM during the design stage would provide many benefits, including giving more consideration to alternative options which would optimise the whole building life cycle energy consumption [28]. A number of innovative methods have been used recently, integrating LCA [19] and operational energy assessment within BIM processes [29], but the literature contains few research contributions on integrating whole building life cycle energy analysis and utilising BIM to optimise total energy consumption. This systematic analysis explores the challenges faced in using existing tools for whole building life cycle energy analysis in BIM-based projects. The current BIM-based sustainability and LCA processes are summarised in Fig. 1 and Fig. 2, which show standalone energy simulation systems and semi-integrated BIM approaches, respectively.

The complexity of using both of the above methods for material and energy properties leads to possible data loss. When it comes to analysing a model, designers and others have to do additional work to make sure the information is accurate. This process is time-consuming and requires IT skills which are not always available to the sector. In addition, very few studies have focused on linking workflow obstacles of green projects to potential improvements using current BIM capabilities [30]. Fully integrated LCA analysis systems do not exist; this area is often overlooked in favour of software used for design and construction planning.

2.2. Challenges in using existing BIM tools for whole life cycle energy analysis

Many researchers in the AEC sector have highlighted that estimating total energy within design projects is challenging [31,32]. LCA BIM-based energy analysis is increasing [33], and many off-the-shelf

Table 1 Interoperability and complexity of existing life cycle energy analysis tools.

Tool	Interoperability issues within BIM and complexity
Within BIM environment	
Tally® [39]	<p>Plug-in limited only for Revit Architecture:</p> <ul style="list-style-type: none"> - It is a plug-in within Revit architecture or structure model - Depends on the granularity and detail of BIM model level of development (LOD) <p>Deals with three detailed levels:</p> <ul style="list-style-type: none"> - Schematic design: showing building components weighting - Design option comparison: comparing materials impact from the BIM model - Complete LCA analysis - Limited customised development or update for the inventory data and not flexible to other system boundaries
One Click LCA [40]	<p>Can be used with a wide range of software, so not limited to one:</p> <ul style="list-style-type: none"> - Web-based interface software (IFC can be plug-in Revit, IES-VE, Graphisoft ArchiCAD, Tekla structures etc.)
On separate platform – BIM model can be used for material take-off	
Athena Impact Estimator [41]	<ul style="list-style-type: none"> - Manual entry of material quantity information; requires highly experienced LCA individual to complete information module about a 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
eTool LCD [42]	<ul style="list-style-type: none"> - Manual entry of all material, assembly, and operational inputs - Has simplified scheme for entering data results not connected to BIM model
BOQ, MS Excel, and databases such as ICE, Gabi, and US LCI	<ul style="list-style-type: none"> - Results are not connected to the BIM model - Level of complexity is flexible and can be designed to suit the conceptual design stage - High possibility of errors - Does not allow iterative process as it will be impractical and time-consuming - Reliability is not assured, and validation is required

systems exist [19]. However, their uptake has been limited due to economic and technical issues (see Table 1). Many challenges remain, as will be highlighted in this section. While tools exist, their application is limited in terms of accounting whole LCA impacts, and there are numerous issues with interoperability and BIM access to databases [34, 35]. Reluctance within the AEC sector to adopt LCA BIM is a big

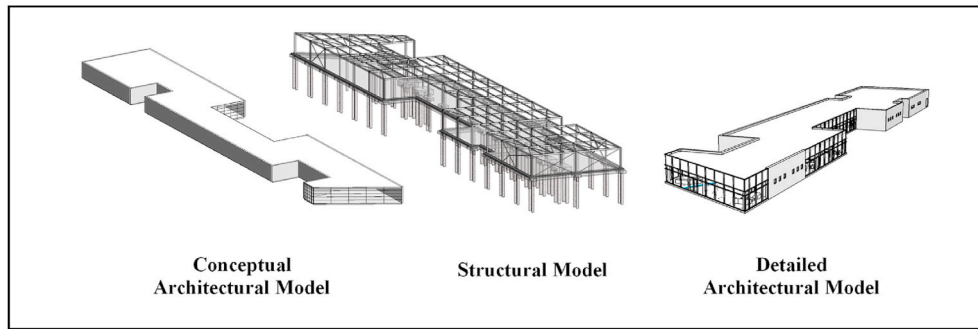


Fig. 3. BIM model of commercial case study at different stages of design from (LOD 200, 300 to 400).

challenge. A recent national UK BIM adoption survey [36] indicated that the use of BIM to meet sustainability targets is a low priority when it comes to applying BIM to a project. While the sector is under pressure to adopt global sustainability measures and meet sustainable development goals (SDG), it appears the BIM agenda still revolves around improving design quality, increasing productivity, and enabling collaboration. In reality, BIM also needs to be adopted as a framework for sustainability analysis energy reduction targets, and can be applied to different stages of projects. It has been demonstrated that the use of innovative applications in the construction industry, such as modern methods of construction and offsite manufacture, utilised within BIM [37], can help with addressing current environmental pressures; the Framework of Sustainable Strategic Development (FSSD) [38], is one example which may help the sector become more accepting of sustainability challenges.

Rather than taking the static approach of using BIM to generate a BOQ and then mapping the materials on different platforms, researchers in recent years have been investigating more dynamic, interactive methods. For example, Tally [39] and One Click LCA [40] commercial software provide a dynamic approach for LCA, but require a licence, which may be a barrier, especially for smaller-sized organisations. Several scholars have also developed dynamo and embedded Revit tools to provide integrated and dynamic approaches. Silvestre and Pyl (2020) [43] have developed the BIMEELCA tool using Revit to import inventory databases inside Revit and Windows Presentation Foundation (WPF) in order to develop a user guide interface. The tool recognises the material quantity, which could be volume, area or unit and allows the user to select from the embedded library. Bueno, Pereira, and Fabricio (2018) [44] used dynamo in order to import elements' [45] midpoint values

into Revit family components, and to calculate and extract Excel reports. A similar, but more advanced tool was developed by Genova (2019) [46], which uses a series of dynamo scripts to build a material library with the required inventory database and the quantities modelled in Revit, with visualisation options. In summary, many researchers at present are striving to provide a dynamic, flexible tool using programming languages to deal directly with the BIM model, and this trend is likely to continue with increased digitalisation and automation of the process.

2.3. Complexity of mapping life cycle input data and level of details in BIM models

The complexity and time-consuming nature of mapping life cycle input data with building material quantities are the main challenges of using existing tools [33]. The multiple manual inputs required to match the sustainability data with the material properties database is impractical because it takes a long time and means high susceptibility to errors during transfer, as highlighted in section 2.1. A critical aspect of BIM is the level of details or developments (LOD) of the model, which is typically LOD 100 for concept design, rising to LOD500 as built. Typically, studies have looked at high LODs of 300 and above, but for LCA to be effective, the analysis needs to cover the early stages of design as well [19,47]. However, not all projects consist of elements that are accurate or fully coordinated at LOD 300. Alwan and Gledson (2015) [48] provide a concept for a theoretical framework, linking LOD levels to building performance utilising green buildings certification and retrofitting.



Fig. 4. BIM model of domestic case study showing highlighting main elements to be analysed.

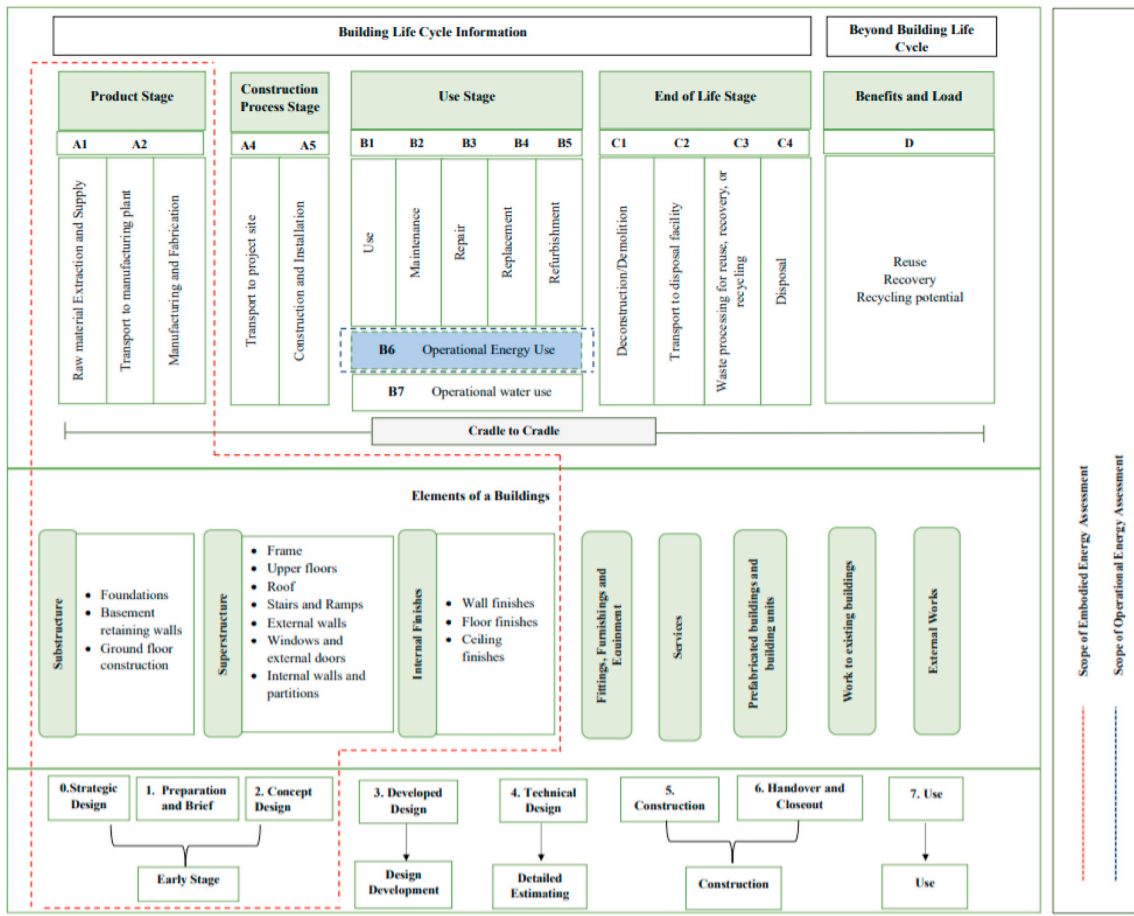


Fig. 5. Scope of the study (mapped with the aid of BS EN 15978:2011, and RIBA plan of work).

The current approach of using both manual (by professionals within the AEC sector) and commercial calculation tools is often based on BOQ and presented as a solution to energy and carbon accounting for a project’s LCA carbon impact. It is anticipated that the framework presented will address the current gaps of the LCA-BIM one platform approach and identify crucial elements for such a platform, rethinking or mitigating the impact within LCA-BIM for both EE and OE, rather than relying on last-minute accounting.

LOD is related to the inventory database of building elements, that are refined in the design process, and can be used in material calculations [19]. There are three levels of detail at building level: element level, component level and materials level. For example, the Swiss Buildings Database gives an estimate which can be used at the concept stage. For LOD 100, European Bauteilkatalog element library average values can be used, for LOD 200, 300 component level such as “gypsum board twin metal frame wall” or a “brick cavity insulated wall” are classified as one element. The last level is LOD 300 and 400 with a specific coefficient value provided to a material such as brick and rockwool insulation gypsum board for example. In the UK, the ICE database used in this study can be applied at later LOD stages only. There are limited database options that can be used at different LOD stages, therefore LOD 300, or above LOD3 as defined in NBS BIM toolkit [49], is adopted in this case study. It can be concluded that for predictive BIM analysis to work, there needs to be synergy between global databases and LOD levels. It should also be highlighted that there is more than one way of expressing LOD. The NBS definition of LOD is LOD 1, 2, 3, 4, rather than LOD 200, 300, 350, 400, which is the North American standard, and which is widely used worldwide.

3. Methodology

In order to achieve the research aim and present in one unified approach a whole life parametric energy estimation tool, both qualitative and quantitative methods using BIM were employed. In the first part, current BIM concepts of digitalisation workflows were applied to two case studies, one commercial and one domestic (see Figs. 3 and 4), focusing on both operational and embodied energy perspectives in order to identify the major energy critical elements. The second part involved the development of a parametric user-led LCA-BIM whole system platform within BIM. The outputs from the case studies were key in enabling the identification of the parametric framework to analyse key operational and embodied components. It is expected that this approach will form a combined analysis of both EE and OE, which could be adopted and used within the AEC sector.

3.1. Boundary for construction elements in BIM

The part of the method that involves identifying construction elements is essential, as the selection of the correct co-efficient for EE and OE will be limited to certain stages of the building analysis. Whole impact assessment of every single component is almost impossible, as a building might comprise 1000+ items or types of material, therefore a focus on EE of major building materials’ impacts has been adopted. As described in the introduction, LCA begins with goal and scope definition. Accordingly, systematic mapping was carried out with the aid of BS EN 15978:2011, Building Cost Information Service (BCIS) elements classification, and Royal Institute of British Architects (RIBA) building development stages, as presented in Fig. 5, which explains the boundary of the study for both EE and OE.

3.2. Assessment of operational and embodied energy within the design process

The building elements that were chosen for the EE estimation were termed critical embodied and operational “energy hotspots”, due to their larger volume and energy consumption. This was a unique feature of this research and was used in order to give a true reflection of the critical elements when considering whole energy LCA within BIM. This numerical operational modelling was developed to give a realistic measure of current energy consumption for the case studies, based on typical energy consumption in the UK context. This will most likely differ between commercial and domestic buildings due to their differing patterns of use. One commercial and one domestic case study were selected in order to explore where energy was consumed in both operations and materials LCA, thus providing valuable input for the parametric LCA framework regarding what should be included in terms of energy input ratios.

The LOD used to extract the BOQ of both building types – the domestic and commercial case studies - was categorised as graphical model elements in terms of quantity, size, shape, and location. This information also covers non-graphical data on materials, such as construction block types, windows, and glazing units’ thermal performance, as different construction approaches may result in different OE demand, for example.

The commercial case study was a virtual project developed by a BIM-specific training firm, White Frog (2020) [50] in conjunction with the BIM Academy (see Fig. 3). This virtual project was selected because it was specifically developed to replicate an actual office, and it has been widely used for training purposes by the BIM Academy [51]. It is anticipated that the findings of this research will be used in future training programmes involving AEC sector professionals. BDN Limited, an architecture firm, provided the domestic case study, which is located in the North of England. The project is exemplary in utilising Modern Methods of Construction (MMC) through 3D BIM offsite cleaner fabrication and addressing many low carbon considerations (see Fig. 4). Both case studies were representative of the UK construction sector; however, the methodology of this research can be applied to other construction types, and is not exclusive to the UK.

The characteristics and materials of the case studies were as follows: the commercial office consisted of a steel frame, glazing and precast concrete slabs as a construction option and mixed mode ventilation system. Using a steel frame means more rapid construction time and lower construction costs. A mixed mode or hybrid ventilation system has the advantage of allowing users to maximise passive cooling and utilisation of mechanical systems in extreme hot or cold conditions.

The domestic building was of lightweight insulated concrete block construction, with external expanded polystyrene (EPS) insulation board and render finish. The house was serviced by an air source heat pump and underfloor heating in the main living areas, which is typical in the UK environment where summer cooling is seldom required, but winter heating is necessary.

3.3. Establishment of embodied energy building profile within BIM through case study analysis

In this study LOD 300 was used, which is equivalent to LOD 3 as defined in the NBS digital toolkit [49] definition of deliverables. BOQs were extracted and automated using a BIM-based approach at LOD 300 and within the boundary set in Fig. 5. 3D models of the case studies were analysed, and volumes were extracted and linked to material information for different Revit files, populating the model with appropriate data taken from the ICE 2.0 database [15], a UK-based database which details the embodied energy and carbon of over 120 materials; it is free to use and not country-specific. The developed model was used to extract BOQ materials, estimates of missing information were documented and applied and then mapped to material-specific values in the ICE database

using an Excel sheet. In this quantitative method, using correct building models generated within BIM frameworks, both the quantities and density of the major building elements were established using the EE factors from the ICE database. Areas outside the research boundary (such as secondary materials and furnishing) were not included in the analysis. Finally, a parametric script on Rhino was developed to enable a dynamic iterative approach in order to eliminate the manual work required to map materials on Excel, which will be explained further in section 5.2.

3.4. Establishment of operational energy building profile within BIM through case study analysis

For the domestic case study, the Building Research Establishment Domestic Energy Model (BREDEM) [52] was used. This is a methodology tailored 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, and is preferred in UK conditions over commercial software. It allows evaluation of heating, cooling, and appliances, as well as other energy demands, such as cooking and electrical appliances.

For the commercial case study, the operational outputs analysis system, EnergyPlus™, a whole building energy simulation programme for AEC professionals, was used. It is a standalone simulation programme without a ‘user-friendly’ graphical interface and is the most recognised worldwide operational energy software. In this case, the DesignBuilder [53] research and the educational licence was used as an interface for the EnergyPlus [54] environment to allow the researchers to carry out simulations in a straightforward way by defining elements of building model geometry, requesting data, and analysing heating, cooling, and other demands on commercial buildings. DesignBuilder has been developed explicitly around EnergyPlus, enabling the use of EnergyPlus databases of building materials, glazing units and other fabrics.

3.5. Exporting results and BIM visualisations

EE and OE are measured in different units: EE in MJ/kg/m²¹ (representing Global Warming Potential (GWP)), and OE data in kW/m² generated (representing use). The most commonly used unit for energy in the AEC sector is kWh/m², so all of the data was converted into kWh for use in the next stage of the process, which concerned which elements can be controlled in a parametric design and altered within the early stages of design.

3.6. Synthesis of energy critical OE and EE elements in BIM parametric lens

A parametric script was developed and adapted for UK conditions using modelling software Grasshopper (GH), generating suitable matrices for total energy intensity. The parametric design is useful as it can be used to study the impact of geometric and material variables on environmental aspects, namely embodied energy and operational costs. Parametric tools can also be used to increase awareness in the AEC sector of the potential effects of design and material decisions, due to their interactivity. In this case, a specific LCA plug-in was designed for GH. The script is free and available at Food4Rhino.² This has been used and optimised for the first time for complete energy analysis in the UK context. The tool can be used to perform functions similar to the calculation of BOQs, and linked to a database library based on UK environmental conditions and outputs from the case studies. Crucially, it includes the ability to carry out dashboarding of the elements to limit its

¹ 1 MJ = 3.6 kWh

² <https://www.food4rhino.com/>.

Table 2
Example of specific material selection extracted BOQ from BIM model.

Main Building Element	Sub Element	Building Materials			Mass(kg)	EE Factor (MJ/kg)	EE(MJ)
		Material	Qty	unit			
Substructure	Foundation, Lowest floor, Basement retaining wall	light weight concrete	238.510	m ³	267,369.710	0.700	187,158.797
		cast in place R/ concrete	222.550	m ³	534,787.650	3.166	1,693,137.700
EE of Substructure							1,880,296.497

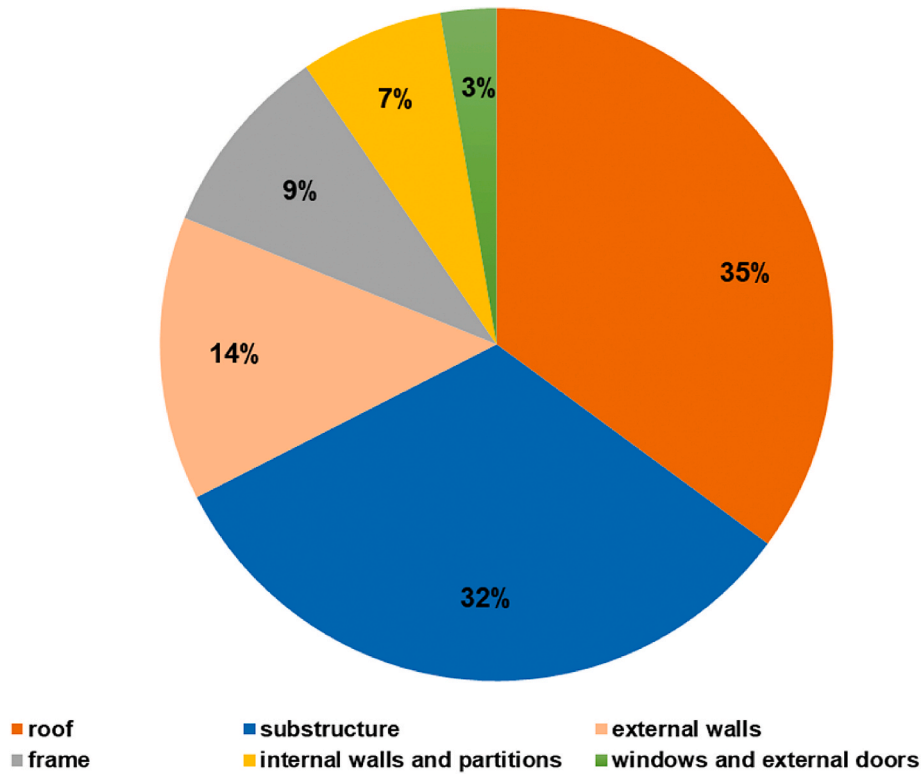


Fig. 6. BIM based embodied energy impact analysis of commercial case study, percentage of MJ units.

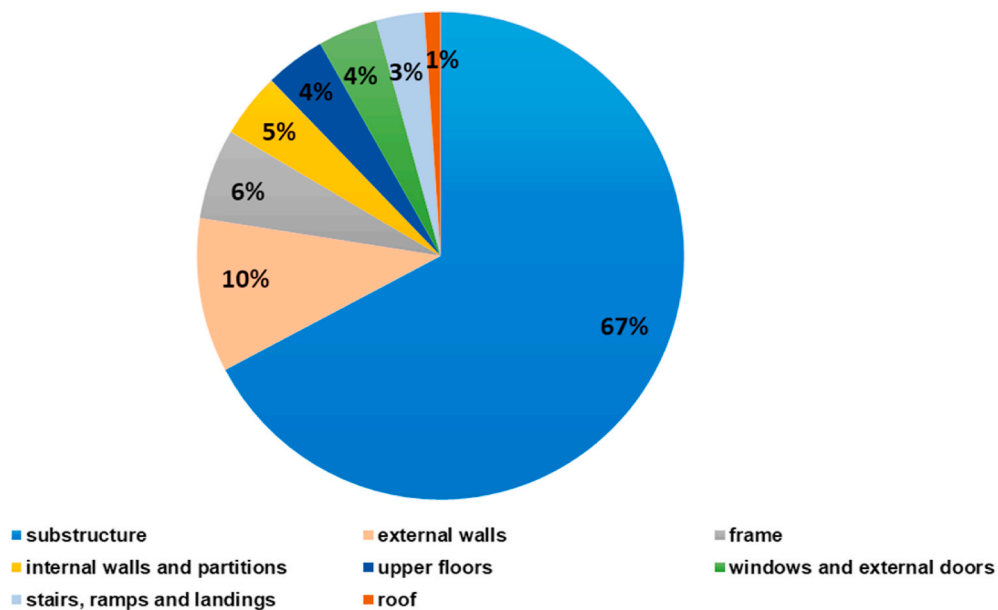


Fig. 7. BIM based embodied energy impact analysis of domestic case study, percentage of total MJ units.

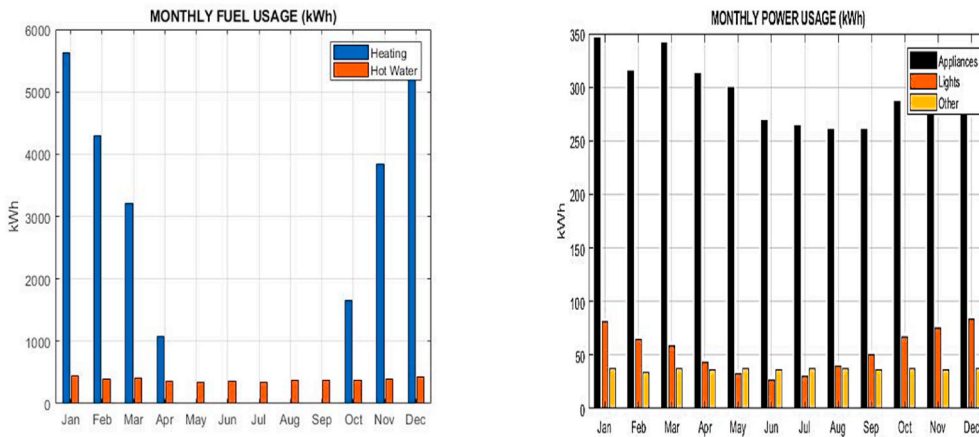


Fig. 8. OE for the domestic case study based on BREDEM analysis, example generation of energy profiles.

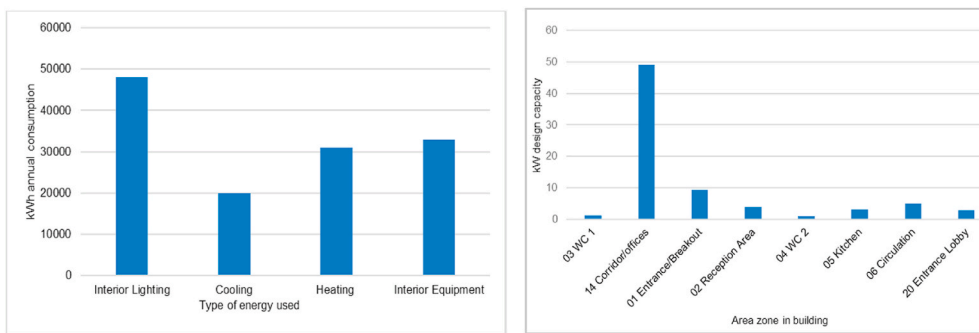


Fig. 9. OE for the commercial case study based on Design Builder analysis.

impact, and can be controlled by the user.

4. Results

The aim of this research was to adapt existing BIM concepts of digitalisation of design and construction processes, which are currently

underutilised and not used for energy analysis. The results of the LCA (both OE and EE) are presented in this section. An example of the EE outputs for the major building materials, analysed in accordance with the LCA boundary set in Fig. 5, is shown in Table 2 (see Appendix 1 for the full analysis of both sets of building results). The results indicate that the density of the material rather than its volume plays a significant role

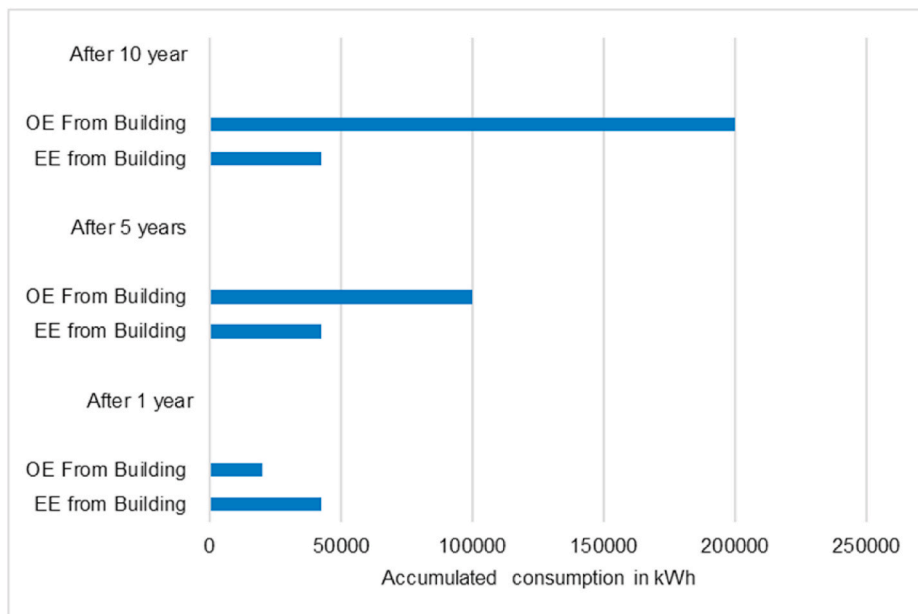


Fig. 10. Total energy of domestic case study in first year. (Assumption of OE doubling while EE remains same, Note 1 kW = 3.6 MJ).

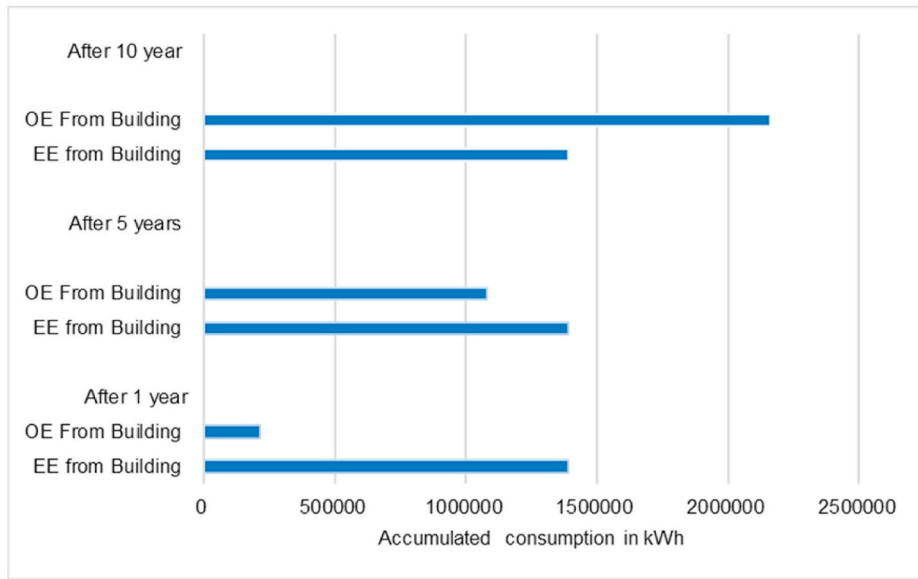


Fig. 11. Total energy of commercial case study in first year. (assuming OE rises over time while EE remains same; note 1kW= 3.6 MJ)

in its overall energy impact. MJ, which is an indication of GWP, is the obvious choice for measuring EE as a functional unit within an ICE database.

A full breakdown of the major construction elements is provided in Fig. 6 and Fig. 7, showing the EE for both the commercial and domestic case studies, extracted from the BIM model. It can be seen that the substructure was by far the biggest contributor in the domestic case study, while the roof (followed closely by the substructure) was the greatest contributor in the commercial setting. Elements near the end of the design process were unlikely to show more variation as the design process was near end of LOD 300; in both cases, concrete constituted more than 60%, which is hugely significant.

Using real case studies means a detailed account can be given of the major elements within the building fabric and their contribution in terms of energy intensity and captured energy in construction blocks. However, this is only half the picture of LCA; hence the case studies were also analysed from an operational energy perspective.

OE analyses for the domestic case study revealed that space heating

in the winter months, followed by appliances, was by far the highest contributor (see Fig. 8). On the other hand, in the commercial setting, the greatest OE impact arose from mechanical systems and heating and cooling, with different zones of the building having markedly different contributions (see Fig. 9).

It is worth noting that in order to obtain results with high accuracy, different BIM energy analysis tools were used, as set out in section 3.4 of the methodology, based on BREDEM and EnergyPlus, both of which were non-parametric and non-iterative.

Once a building is occupied, another phase of accounting for both OE and EE impact starts and continues over its lifetime. By aggregating the results for all the building elements and performing analyses at the building level over a ten-year future horizon (see Figs. 10 and 11) for both of the case studies, interesting variations emerged relating to the impact of operational and embodied elements. It was assumed that a building’s operational energy impact will be the same every year to maintain lighting, heating etc., so that it will increase over 10 years, while the embodied impact locked into the material will remain static

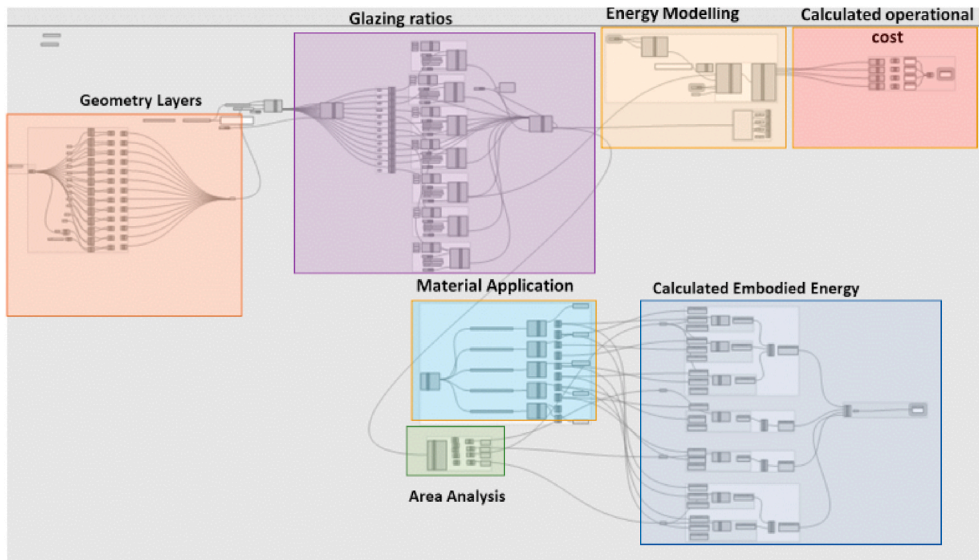


Fig. 12. A framework overview of Grasshopper script overview developed for both operational and embodied energy, linking seven key areas which have the greatest impact.

Table 3
Overview of total energy based on take-off for significant building elements and operational energy modelling based on BIM frameworks.

Case study	EE MJ(GJ)	OE (kWh)	Floor area (m ²)	EE (MJ/m ²)	OE (kWh/m ²)
Commercial	5806.728 (5.8)	150,000	1238	4690	210
Domestic	1527.023 (1.5)	19,000	210	1527	91

for 10 years, unless major renovations are carried out to the building's fabric.

This appears to be a straightforward modelling assumption. However, and more crucially, there were significant differences in the elemental accounting of building materials for commercial and domestic buildings. When considering LCA and overall energy use of buildings, it is important to take a longer-term view of both EE and OE.

5. Discussion

This section discusses the findings of the case study analysis and the challenges facing not only researchers but also AEC practitioners in accounting for overall energy and LCA processes. The case study analysis showed different hot spots for total energy use, and the results were used to develop a parametric framework within LCA-BIM. Parametric modelling is suggested as a future approach for interactive BIM energy analysis for the AEC sector.

5.1. Different characteristics of benchmarks for domestic and commercial buildings

One of the objectives of the research was to get more accurate LCA data by evaluating the impact of both operational and embodied energy of buildings in the UK context within an LCA-BIM tool. Previous research, which looked at the embodied aspects of materials alone, and did not account for operational energy use, only gave half the picture of true LCA. Without accounting for operational energy, researchers cannot reflect on the full impacts in terms of buildings' total LCA.

The work has demonstrated that this can be done from a BIM perspective in a 3D environment through operational and embodied analysis with different geometries and different building types. Figs. 6 and 7 give an overview of how domestic and commercial energy consumption patterns vary in terms of material impact and intensity. Such variations in LCA and impacts of building use were used as indicators in Fig. 12 in the development of key aspects of the resulting parametric framework.

Clear differences exist between profiles of EE and OE, as can be demonstrated in Table 3, showing an attempt at benchmarking in kWh and MJ units, which can be entered into a BIM parametric platform as indicators of use and LCA for buildings from a UK perspective. The results clearly indicate that the commercial case study had a more significant EE impact than the domestic one, suggesting that EE is more significant in commercial buildings; meanwhile, OE makes up a larger share of overall impact for domestic buildings. This suggests that it is vital to assess operational impacts at the design stage, a process that is often currently overlooked.

The results of this paper are unique in going beyond normal operational and embodied carbon impacts of buildings. The results provide a practical tool that can be used by practitioners, integrated within BIM procedures and protocols, to give a flavour of how the two measures can be synchronised as the only critical way of assessing carbon impact through a single framework for buildings, thus enabling and facilitating the move towards zero carbon buildings. The results offer a unique insight into how energy and associated carbon can have a longer-term impact over the lifetime of buildings. It is safe to assume that

information about total energy and associated carbon kgCO₂ of MJ/kg can have much greater environmental value if captured early at the design stage, rather than five or ten years after the building has been built.

5.2. BIM as an iterative unified parametric design tool for effective LCA of whole energy and feedback

While the development of parametric modelling for environmental assessment has been addressed by previous research in terms of its challenges [55], its application within BIM has been relatively underutilised and, more importantly, does not exist within commercial software packages used in BIM. The unique framework (see Fig. 12) was developed based on the outputs from EE and OE analysis of key energy outputs and hotspots of GWP in MJ and kWh in the commercial and domestic case studies. It allows users to carry out quick and timely analysis so they can use the feedback immediately for real-time design decisions affecting current and later stages of the design LOD 300 within BIM, incorporating the assessment of operational energy. The system allows users to integrate different kinds of material libraries from different countries or regions. It can also be linked back to ranges of operational energy consumption patterns and benchmarks. In addition, the calculated operational cost considers variations of the impact of day/night temperature, and especially changes in the weather over the year, by using the weather data files.

The key geometrical elements of the model were linked to the materials and simulated using parametric script linking seven key elements, as shown in Fig. 12. The results for heating, cooling, lighting, and electrical appliances were collected, and the results were aggregated together to represent the total annual operational energy consumption (OE). For calculating EE, different areas were linked to their materials, along with their mass and EE factor, to measure the layer's impact, followed by the component's impact and total EE values. This unique approach of linking most of the critical OE and EE aspects in one approach is key from a building analysis point of view.

The proposed framework is suitable for further development, with the potential to add more layers of data; for instance, to profile the differential impacts of building occupancy, use type, lifetime of building, and any future refurbishments. The results have indicated that domestic buildings' operational energy impact becomes more significant and rapidly overtakes the impact of materials over a ten-year period. Within a parametric model, operational energy use (e.g. heating and lighting) can be adjusted using a dashboarding system, and advance modelling of how design affects operational energy use (e.g. height of walls) is possible. This is likely to be highly useful to AEC professionals, who want rapid results and instant feedback without the additional effort of accessing a separate database outside the BIM domain.

Rhino/Grasshopper as a tool is used by creative designers for free form generation and creative building structures, but the software has greater analytical potential if adopted in the right way. For example, a critical look at the application of parametric methods in the practice of design reveals use is still predominantly based on aesthetic, structural, and fabrication criteria [56] while its applications for building performance and daylighting research are still growing [57].

In the proposed tool (Fig. 12), a unique integration was carried out by linking an EE database (ICE) and an OE database (Energyplus+). The Bombyx plug (energy analysis), developed by ETH in Switzerland, was adapted and used in a UK context [58]. ETH Zurich researchers have expressed interest in further collaboration and development and have made a version of this available online [59].

One positive aspect of this system is that it can be adopted to different regions, depending on local environmental factors and different types of databases. This can be facilitated through the open-source, codes, and plug-ins, which are downloadable through the grasshopper community [60]. These plug-ins cover aspects such as daylight and shading. In addition, energy profiles for occupancy loads,

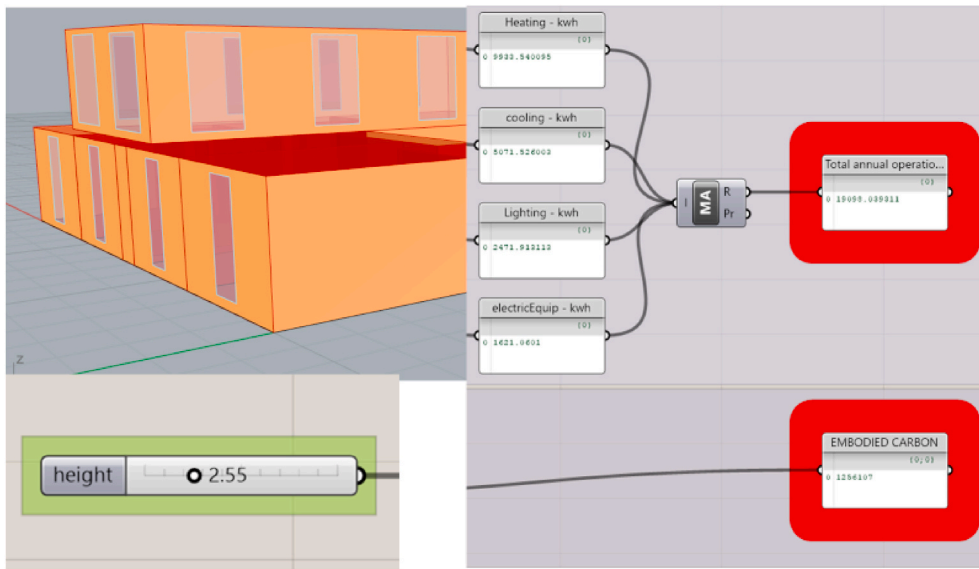


Fig. 13. Example of real-time adjustment of both OE&EE using sliders and set limits.

energy consumption, and the script are modified according to the requirements of specific geographical locations and environmental priorities. For example, hot dry regions of the world will adapt the script to have more focus on shading, while a temperate region will focus on material use and heating options. Similarly, the materials library of BIM objects and environmental impact vary depending on the databases and energy intensity associated with material production. Fig. 13 shows how the tool allows the user to manipulate elements of the design, such as height, and the impact of such changes on operational energy, within a domestic case study. The software development in this section gives an

insight into how LCA analysis can be approached within a UK context. It is not common for architecture practices to adopt standalone parametric modelling with no upper or lower material or energy range limit. The current framework offers a dashboarding system based on UK building regulations, which the user can influence for immediate results. A tool such as this one may provide important early level design input regarding which areas have the greatest impact, depending on building type, allowing the user to model, demonstrate and influence change.

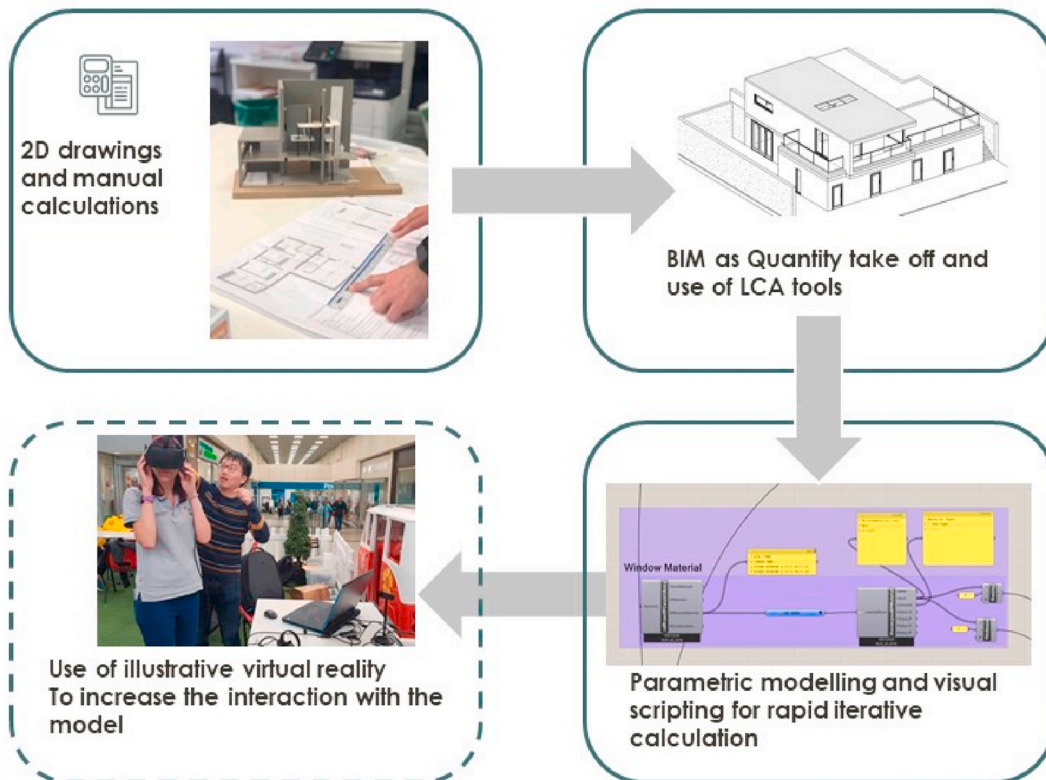


Fig. 14. Future trajectory of research ultimately applying VR to visualise LCA impact from parametric dashboard.

5.3. A plethora of different LCA datasets and benchmarks

Findings from the literature and the research suggest that while parametric whole LCA for impacts is possible, confusion lies in the range of software and datasets available, and choosing which is the best one to apply. While adaptation to calculation methods for embodied impacts is challenging, issues with material libraries for LCA calculations can be confusing for professionals in the AEC sector. Similar work was done using a European Swiss database (KBOB, 2017), and it was noted that the approach to GWP was very different to that of the UK-based ICE database. Another factor to consider is different BIM-based methodologies for environmental impacts. In the domestic case study, BREDEM energy modelling proved an effective methodology for domestic energy analysis in the UK, based on construction characteristics (Underwood et al., 2007), indicating that appliances are the main energy consideration in domestic buildings. Other methods for ultra-low carbon cases might use the Passive House Planning Package (PHPP), which could yield different results.

In different parts of the world there will be different databases for both OE and EE, and associated carbon counting, as well as different policy procedures for integration of embodied impacts. For example, in the Netherlands it is a legislative requirement to carry out a LCA; while in British Columbia in Canada, embodied carbon assessment is mandatory, all projects are required to report it, and there is a target for a 40% reduction in embodied impacts by 2030 [61]. In the digital world of global collaboration, a unifying global approach is needed to guide AEC practices.

5.4. Virtual reality to enhance BIM and digital representation of impacts

For AEC experts and other stakeholders to engage with the impacts of parametric modelling, instant and accessible feedback is needed, and this may be difficult to achieve through the cumbersome task of operating a parametric dashboard, which also needs technical skills. The research team is currently investigating better visualisation of the parametric tool within BIM, so that users and stakeholders can better relate to overall total parametric LCA within Virtual Reality (VR) (see Fig. 14). In recent years VR technology has been applied to facilitate design, construction, and management for the built environment [62]. VR programmes' ability to integrate with BIM and the live synchronisation between the BIM and the VR model enables auto-updates in real-time. In reality, terms such as GWP, kgCO₂, MJ/kg, and kWh might be hard to interpret in architecture offices, and even for many AEC professionals, and their application in an immersive environment may be more convincing. The application of VR in LCA can diminish discrepancies at the source. Furthermore, despite the different technical backgrounds of users, participants have been shown to positively embrace the ideas and aspirations of VR [63].

Visual programming, if done well, can provide immediate information that can be acted upon straight away, providing an important link between geometry and the data [64], and this novel approach may persuade the sector to consider LCA as a major priority within BIM. The use of computer-generated VR imagery, such as flythrough animations and interactive solutions, is not new to the sector [65] and has been used in marketing and design representations, although not previously as an LCA concept. Virtual models have the benefit of dynamic information input and output, which can be integrated into a BIM model. As the parametric LCA total analysis is evolving, physical live data such as climate and material and EE can be exported from the GH model in Fig. 10 and integrated in the virtual model using VR gaming technology, Unreal gaming engine [66]. The time span on the simulation can be included as a variable factor in the model and can run from LOD 200–400, to allow for lower impact EE. Observing and interacting with virtual reality does not require technological knowledge in a certain field, thus reducing barriers on communication between user and materials impact, making parametric tools much more accessible within

BIM. For instance, users are able to switch between different construction layers and materials to gain an understanding of both the visual aesthetic impact and energy performance at the same time, thus better enabling them to make decisions on the full impact of different materials and design choices.

5.5. BIM as a driver for change and cleaner fabrication

This study has demonstrated that utilising BIM to address areas of the greatest energy impact - "Hotspots" - is possible for the purpose of total energy LCA analysis in building projects. Such results can feed into ISO 14040 or the BIM Execution Plan [67], which facilitates the implementation of energy and other LCA targets in a BIM project. Furthermore, links between parametric LCA and other established BIM procedures can be made, such as the National Building Specifications (NBS) BIM library, which is recognised internationally.

The availability of standardised components for BIM objects such as NBS is becoming more common for design consideration [68], and moves for fabrication and offsite manufacturing can be BIM-integrated [37]. The dynamic framework proposed can allow for material substitution for cleaner standardised components such as walls and other equipment, allowing more opportunities for innovation and collaboration in new production processes for design and construction.

Future legislative pressure and targets for BIM frameworks should be integrated within building performance and linked to LCA. The AEC sector is at a crossroads with the new construction revolution 4:0 [69], which requires the industry to transform itself to incorporate more automation and digitalisation. The sector is already lacking in competitiveness, as highlighted by the Construction Leadership Council [70], because of its low levels of research and innovation. It is critical that such challenges are addressed, and LCA accountability which leads to sustainability by innovation could help to achieve this.

5.6. Advantages and limitations of BIM-LCA approach

The novel approach outlined in this paper involves combining both OE and EE use and linking the outputs to a range of data benchmarks, or ones set by users. This can in turn be linked to a VR domain to allow users to analyse energy consumption data in a user-friendly fashion. Currently, professionals consider each element of building design in isolation when it comes to building evaluation of construction projects and decision-making on the addition of renewables or low carbon materials. Building parametric intelligence into BIM-LCA models provides a great deal of design power in terms of allowing parametric decisions control for decision-making. For instance, within the BIM model, constraints can be built in for specific materials not to exceed certain benchmarks for EE and OE within a project, meaning low energy alternatives or carbon solutions have to be sought. The benchmarks in Table 3 could act as standards for commercial and domestic scenarios.

It is also worth noting that the framework tool is at an early design stage and is likely to mature and evolve, with more established benchmarks and better material libraries being developed, especially for EE aspects. One potential limitation to consider in terms of wider adoption of such tools is that while design iterations can be quick and link to databases, parametric design and BIM integration can be a steep learning curve for professionals in the AEC sector, almost akin to learning from 3D, and constituting a huge move from the traditional 2D approach. Finally, construction projects and the market have to be ready to adopt such a data-driven approach for it to be successful, if wider adoption is to be realised in the long term.

6. Conclusion

This research demonstrated a new, systematic approach to evaluating total operational and embodied carbon impacts in a building, utilising a BIM framework. The literature suggested that a variety of



Fig. 15. Pecha Kucha overview of the Project, https://www.youtube.com/watch?v=pOs_VcTLUFE.

databases and methods exist for assessing buildings' impact. The use of actual case studies provided a valuable insight into the impacts of different construction types, as well as different structural elements. Case study analysis showed that while it is important to assess embodied impacts at an early development stage, operational impact assessment may not be possible until the later stages (LOD 300), when mechanical systems and energy specifications are issued. Furthermore, taking a longer-term view of total impact over 10 years of energy consumption in a building (combined operational and embodied) may lead to different results. The case study analysis illustrated that embodied and operational impacts affect different stages of the workflow and cannot be assessed at the same time.

This unique approach, which has not been attempted before, enhances the feasibility of dashboarding and testing of sustainable alternatives, for both operational and embodied aspects. This method of visual scripting potentially provides more flexibility, allowing the designer to focus on the impact of major building elements. The addition of benchmarks could be used to further improve the proposed framework, and additional case studies should be investigated in different national and regional contexts.

Providing a range including upper and lower limits for AEC practitioners, as well as benchmarks, is vital for the tool to be a success. Visualisation of results is key: it is much more important to show a convincing impact of a few major hotspots in, for instance, a VR domain, rather than total energy impact in a hard-to-interpret graphic. There needs to be further integration of LCA in terms of simulation and existing BIM protocols, BIM objects and governmental drivers, otherwise a standalone LCA tool will not be effective in the long term.

CRediT authorship contribution statement

Zaid Alwan: Conceptualisation, Supervision, Methodology, Data Collection and Analysis, Writing Original Paper, Writing revised paper. **Amalka Nawarathna:** data analysis, Assisting Writing and Writing Reviewing both original and revised papers. **Rana Ayman:** 3D modelling, data analysis of building components, digital take off, assisting in paper writing. **Mingyu Zhu:** 3D modelling Virtual reality, Building optimisation, use of a variety of parametric tools. **Yomna ElGhazi:**

Material, Building optimisation, Architectural modelling and the use of a variety of parametric tools.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.job.2021.102768>.

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