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IFC-based embodied carbon benchmarking for early design analysis

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ABSTRACT

Current legislation focuses on reducing the operational carbon impact of buildings. However, the production of materials used in construction generates a considerable amount of carbon, known as embodied carbon, that accounts for a sizeable fraction of the environmental impact of a building during its lifecycle. We present a newly developed tool, pycab, which calculates the embodied carbon of a building directly at the design stage and compares it to the Royal Institute of British Architects (RIBA) 2030 Climate Challenge Target Benchmarks. As input, the tool uses standard Industry Foundation Classes (IFC) files that can be produced directly from existing Building Information Modelling (BIM) software. The pycab tool enables industry professionals to make design stage decisions that reduce the embodied carbon impact of their projects. This research demonstrates one of the many potential uses that digital tools can have in reducing the environmental impact of the construction industry.

1. Introduction

The construction industry can be viewed as one of the cornerstones of addressing sustainable development in society, considering that buildings are of high economic significance and have a substantial impact on both the environment and quality of life [40]. As one of the largest consumers of natural resources, the industry needs to adopt sustainable solutions through product, process and system development. Being an inclusive discipline spanning the energy, environmental, business and technology domains, sustainability aims to enable technological and economic development, whilst mitigating or minimising the impacts on the ecosystem. The adverse effects of construction - including resource depletion, energy use and associated emissions of greenhouse gases, waste generation and disruption of communities - push the industry towards discovering more integrative solutions. Despite progress towards sustainable buildings and construction, the industry is still lagging behind and is responsible for nearly 40% of global carbon emissions, approximately 10% of which results from manufacturing building materials and products such as steel, cement and glass [58]. In 2009, United Nations Environment Programme (UNEP) [57] declared that greenhouse gas (GHG) emissions would more than double in the next 20 years due to the rapid increase in urbanisation and inefficiencies of the existing building stock, unless mitigating measures on GHG emissions were implemented.

The construction, operation, and demolition stages of the life cycle of a building produce 12.6%, 85.4%, and 2% of total CO_2 emissions, respectively [43]. According to BS EN 15978 [7], whole life thinking involves considering all the life cycle stages of a building, from the product stage (A1-A3, cradle-to-gate), construction process stage (A4-A5, handover), use stage (B1-B7), end of life stage (C1-C4, grave) and beyond building life cycle (D, benefits and loads beyond the system boundary). Despite the high levels of carbon in the operation stage, the focus of carbon management is shifting from operational carbon to embodied carbon, as a result of improved operational energy efficiency in buildings [59] and stringent regulatory control of energy. Emissions from the operation stage are continuously reduced through multi-pronged efforts related to technology and policy aspects, including improvement of heating and ventilation and adoption of zero-energy building design [28]; this stage has also been the focus of regulation, in contrast to embodied carbon. Implementation of energy efficiency regulations in recent years has resulted in low operational energy demand and associated reduced GHG emissions of new buildings [27]. Hence, the share of embodied energy and GHG emissions due to the manufacturing, replacement and disposal of building materials has gained importance [24] and the industry is increasingly facing the need to reduce embodied carbon in the built environment. Researchers agree that challenges exist and legislative pressures are needed for carbon reduction [22,31,44,63,66]. Government policies around the world

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have been directed towards responding to this need, which include reducing embodied carbon emissions from the extraction and manufacture of materials, together with associated transportation, construction and installation processes. In the UK, for instance, a voluntary target has been proposed by construction professionals and architects [46] for the reduction of embodied carbon and operational carbon by 2030.

The UK has set an ambitious target of achieving net zero carbon reduction. To achieve this, a total reduction target of 50% within construction by 2025, and 80% by 2050, a reduction relative to 1990 carbon emissions levels [55] need to be adhered to. Embodied carbon benchmarks and targets - as part of building regulations and planning decisions - can help foster progress towards these reduction goals. LETI Embodied Carbon Primer [29] suggests carrying out embodied carbon comparisons on typical construction bays during early design stages, where decisions can be guided by benchmarks and data, in order to reach net zero targets by 2030. The greatest opportunity to affect carbon emissions in the project life cycle comes at the initial stages of projects for both new construction and renovation, through the correct gauge and management of embodied carbon; otherwise, the potential for carbon emission savings is forfeited for the remaining lifetime of the building.

Research advancements and developments are occurring globally within the construction industry, and external pressure for a smarter built environment is exerted by more ambitious energy and carbon emissions agendas across the world [6]. Utilising advanced digital technologies in the processes for the life cycle of a building helps create better-performing buildings by adding more value. Building Information Modelling (BIM) has been the main focus for sustainable solutions within the built environment, with its potential being explored in various studies. Rather than being a simple virtual model or software, BIM can be regarded as a process of creating models with semantically rich information in a common data environment (CDE) to accelerate digitalisation in the industry [42]. The significant contribution of the construction industry to GHG emissions has triggered extensive research attention focused on environmental impact mitigation technologies [41]. Even though recent studies [33,49] show that the nexus between BIM and sustainability has shifted towards increased use of sustainable principles and improved quality of environmental analyses, the need for a structured process for embodied carbon assessment and benchmarking is still not being fully addressed [65].

1.1. Aim, objectives and value

This paper aims to provide a glimpse of the future of the construction industry, with a focus on the paradigm shift in the built environment, through the question: how can we promote the use of BIM for sustainability benchmarking, carbon accountability and reporting on sustainability within the Architecture Engineering and Construction (AEC) community? Best practice in sustainability in the built environment can be achieved by analysing and acquiring energy and carbon data from current built assets and using them to predict future construction industry performance within digital and virtual reality frameworks. The wider digitisation of the built environment will revolutionise how we develop and deliver infrastructure and built assets. Traditional methods are still used today, especially by the housing industry, and the challenges of excessive waste and carbon are not purely technical, but also operational and planning related. Despite the persistent barriers caused by the fragmented nature of the industry and difficulty in obtaining the relevant data, ways of working in construction should go well beyond these traditional methods. The current systems are inefficient and as a consequence, do not lead to satisfying outcomes for society concerning environmental, economic and social aspects. The study aims to acquire embodied carbon data of a building within Industry Foundation Classes (IFC) structures as the basis for improving performance within the built environment. The main objectives to meet the research aim are: (1) to develop an automated process for calculating the embodied carbon impacts of a building through BIM, and (2) to facilitate the decision-making process to reduce this carbon impact based on alternative building materials and benchmarking. The ultimate value of this research is to reach a wider audience of practitioners in the AEC field and demonstrate how open-source digital solutions allow for greater traceability and accuracy of carbon benchmarking. While professional bodies such as Royal Institute of British Architects (RIBA) and the Royal Institution of Chartered Surveyors (RICS) have introduced targets for domestic and non-domestic buildings, no guidance exists on digital means of achieving such ambitious reductions. The proposed tool demonstrates a proof of principle, i.e., that lower embodied carbon materials can be automatically suggested at the design phase based on the overall carbon impact they have on the project. The anticipated value of this is enabling designers to make informed embodied carbon-based decisions at the design phase and encouraging them to consider lower carbon alternatives to their design choices.

1.2. Research method

The proposed research approach of linking BIM and embodied carbon assessment consisted of three main phases: model design, model development and model verification (Fig. 1). To effectively address the challenge of gathering reliable data for embodied carbon calculation, the Industry Foundation Classes (IFC) data model was utilised. As an open, vendor-neutral, international standard (ISO 16739-1:2018), IFC is usable across a wide range of hardware devices, software platforms and interfaces for many different use cases, as well as archiving project information [9].

The model design phase comprised an extensive literature review and scope definition of the proposed model. The stage of the building life cycle was limited to the product stage which includes the modules: cradle-to-gate: raw material extraction and supply (A1); transport to manufacturing plant (A2); and manufacturing and fabrication (A3). The Inventory of Carbon and Energy (also known as [56]) was used as the embodied carbon database for building materials. A major consideration in this study was to use an open-source database for carbon, thus allowing replication of the study. The database, once created, used records from 1800 sources worldwide on embodied carbon and energy [23]; therefore, it may be considered to be worldwide in application, in terms of nature and range of materials. It contains data for over 200 materials, broken down into over 30 main material categories, and the database is widely used, having been downloaded by over 30,000 professionals around the world. Due to the lack of availability of an up-to-date country-specific embodied carbon database, the materials' carbon coefficients were extracted from a proxy database (ICE V2.0 or V3.0). The materials' extraction, manufacturing methods, and energy consumption were assumed to be the same as those in the published database. Users must be aware that any model will have limitations and may need to be adjusted if a country-specific database is established in the future. For instance, the embodied carbon of a material manufactured using fossil fuels may be deemed lower if that particular material is manufactured using renewable energy in some countries. Due to its powerful IFC compliance, Graphisoft ArchiCAD® was chosen as the BIM software.

The model development phase first focused on the creation of a library to store the embodied carbon factors for project-specific building materials and components, and the template file to hold this embedded library. It then involved the development of the algorithms based on embodied carbon calculation and implementation of the software tool.

The model verification phase comprised the validation of the developed carbon calculation and benchmarking tool through a case study. It included the generation of the BIM model using the template file and exportation to IFC format, and automatically calculating embodied carbon for analysis and benchmarking.

2. Background research

Along with the discussion on the environmental impacts of the

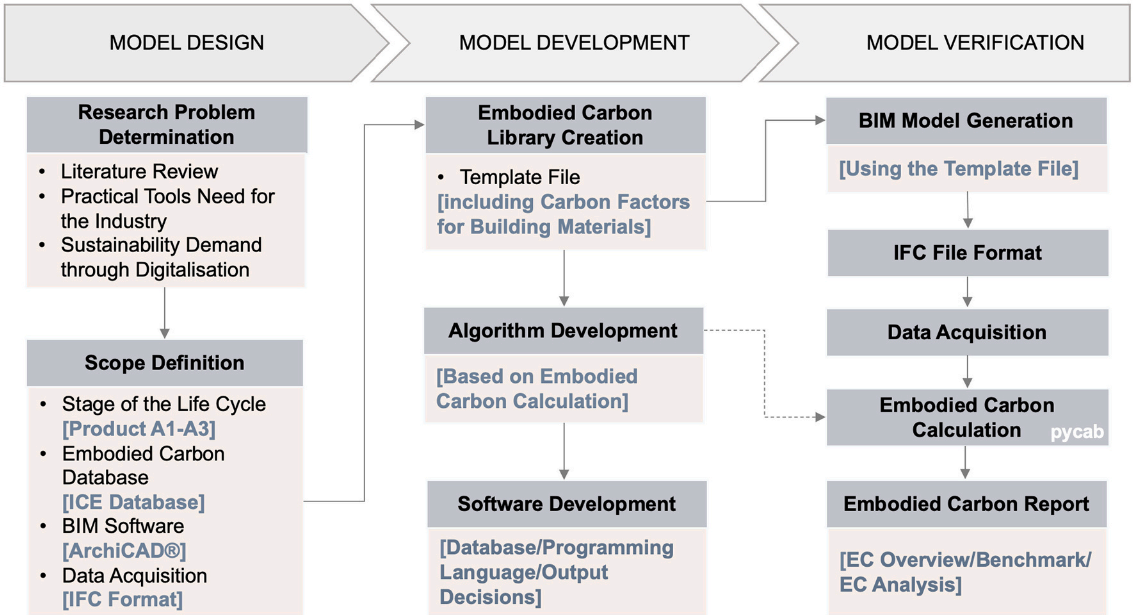


Fig. 1. Research method.

construction industry, literature on sustainability in recent years has focused on the integration of information technologies for the promotion of a sustainable built environment. Comprehensive literature review studies including sustainability, BIM, and their integration, provide information on the state of the art, research trends and directions in this domain. The areas of embodied energy [1,5,15] and building certification systems [10] have seen the maximum growth in recent years [4]. Given the increasing recognition of sustainability, due to its potential to support sustainable building development through integrated solutions, the role of BIM has been highlighted - more for the design and construction stages of the building life cycle, and less for maintenance, retrofitting and demolition - in most studies [30]. A more recent study [61] indicates that the development of BIM in sustainability draws academic attention and possesses considerable research value in connection with the largest number of high-frequency keywords in the sustainability cluster. Utilising the Delphi method, Olawumi and Chan [39] identify the three most significant benefits of BIM and sustainability practices integration in construction projects as: *'enhance overall project quality, productivity, and efficiency,' 'ability to simulate building performances and energy usage,'* and *'better design products and facilitate multi-design alternatives'*. However, despite these potential developments, it is argued that the lack of computer tools and the complications of the BIM models hinder the adoption of green BIM [62]. The main barriers are the industry's resistance to change from traditional working practices; the extended period it takes to adapt to innovative technologies; the lack of understanding of the processes and workflows required for BIM and sustainability [38]; the weak interoperability among various green BIM applications; lack of industry standards holistically covering the various application areas of green BIM and studies on the best practices of green BIM projects; low accuracy of BIM-based prediction models [33]; and lack of BIM libraries with semantic-rich objects [50].

Since life cycle assessment (LCA) is considered the most suitable way to assess the environmental impact of buildings [35], various studies are focusing on the integration of LCA with BIM. Bueno and Fabricio [8] discuss the consequences of the simplification of LCA data and methodology in the main existing tools that integrate LCA in the BIM platform using a simulation on wall systems performed in a BIM plug-in. To facilitate the assessment of carbon emissions over the life cycle of building demolition waste, Wang et al. [60] have developed a conceptual framework in which BIM provides an effective approach to harvesting data and feeding it into the LCA. In their study, Rezaei et al. [45] have developed a method to integrate BIM and LCA in both the early and detailed building design stages through Autodesk Revit® and openLCA. To demonstrate the feasibility of integrating BIM with dynamic life cycle assessment methodology, an operable and integrated BIM-DLCA model to assess the dynamic life cycle environmental impacts of buildings has been proposed by Su et al. [52]. Cavalliere et al. [12] propose a novel method for applying LCA continuously over the entire building design process to assess the embodied environmental impacts using the data provided by BIM, with as much accuracy as possible in each stage.

Studies focusing on measurement, monitoring and reduction of GHG emissions can be grouped into two, based on whether they utilise BIM or not. Zhang and Wang [67] propose a detailed carbon emission inventory for buildings and divide the life cycle of a typical building into three stages, based on material and energy flow: the materialisation stage, the operation stage, and the disposal stage. They highlight that although the operation stage appears to contribute approximately 82–86% of the total emissions, the materialisation stage is also of considerable importance in alleviating current environmental pressures. By aiming to develop a method to enable the estimation and analysis of emissions at project, activity and equipment levels in a building construction, a framework is established to provide a systematic procedure to aid decision-making for reducing direct emissions at the construction stage [48]. Luo et al. [34] suggest that a prediction formula using steel reinforcement, concrete and wall materials as independent variables can better predict CO_2 emissions in the construction materialisation stage through statistical analysis and comparison.

Based on the results of previous studies using construction system modelling and life cycle assessment, Ozcan-Deniz and Zhu [41] treated greenhouse gas emissions as an additional project objective along with time and cost, and applied multi-objective optimisation to derive optimal solutions for transportation projects. The results showed a strong positive correlation between time and cost, a moderate positive correlation between cost and GHG emissions, and a weak positive correlation between time and GHG emissions. Yepes et al. [64] echo the finding that optimal solutions in terms of monetary costs have a satisfactory environmental outcome, differing only slightly from the best possible environmental solution obtained.

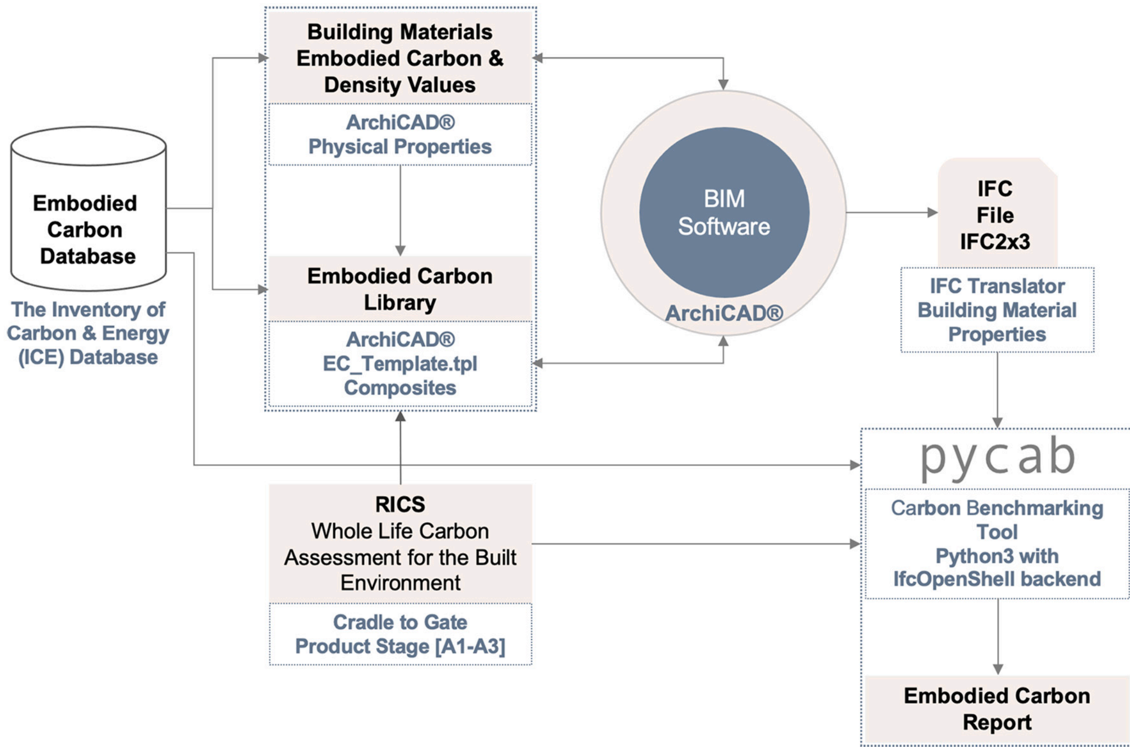


Fig. 2. Proposed embodied carbon calculation and benchmarking model.

Hafner and Schäfer [20] examined substitution factors by describing the approach of performing comparative LCA of residential buildings with different building constructions according to the actual standards BS EN 15978 [7]. Through the method demonstrated how to assess substitution factors on the building level, the study found that building with timber instead of using mineral materials resulted in a positive GHG reduction.

Construction projects using off-site manufacturing are growing in popularity and as such may have an accelerating role to play in efforts to reduce carbon emissions; several studies have focused on developing real-time carbon emission monitoring systems for prefabricated components [32,54].

Recent studies regarding embodied carbon assessment have focused intensely on BIM integration due to its potential to improve the environmental impacts of buildings. Focusing on optimised structural design in the life cycle carbon performance, Eleftheriadis et al. [18] offer a BIM-embedded approach utilising embodied carbon metrics and results from heuristic structural optimisation. To provide the connection between the BIM model and LCA results, a framework to estimate the embodied energy content (material embodied energy, transportation energy and construction energy) within the native BIM environment has been developed by Nizam et al. [37]. Autodesk Revit® application programming interface (API) is used to develop the prototype in the form of an add-on for the Revit software to act as a tool to determine embodied energy content. Based on Dynamo, Shadram and Mukkavaara [51] have presented a framework that supports appropriate design decision-making by solving the trade-off problem between embodied and operational energy through integrating a multi-objective optimisation approach with a BIM-driven design process. Another study using Dynamo and Autodesk Revit® has developed an embodied environmental impact assessment tool for the early design stage [24]. However, the calculation of the embodied impact is based on surface areas instead of volumetric models, making it less accurate for certification of the as-built model.

Cang et al. [11] present an Autodesk Revit®-based calculation method that takes the “building element” as the basic unit for schematic design, targeting energy savings and emission reductions of buildings as early as possible. A carbon emission measurement system developed by Ding et al. [14] for prefabricated residential buildings during the materialisation phase is based on BIM and a carbon emission measurement model. The system incorporates Autodesk Revit® and Microsoft Access-based databases for data management. Covering reinforced concrete construction, hot-rolled steel construction and light steel construction, Abouhamad and Abu-Hamd [2] propose a life cycle assessment framework for embodied environmental impacts of building construction systems. A BIM integrated framework is intended for early use in the design stage to assist decision-making in identifying sources of higher embodied impacts. Software tools focusing on carbon measurement, such as Tally® [53] Life Cycle Assessment App and EC3 [16], which are developed for quantifying the environmental impact of building materials, can only work with Autodesk® as plugins, rather than open-source IFC files. Relying on a specific BIM authoring tool in order to operate, imposes a limitation for users who are keen to reduce their initial material carbon impact at a minimal cost. The EC3 tool is limited to available US and Canadian vendor-specific Environmental Product Declarations (EPDs), and North American focused Tally® app makes calculations based on the conditions in the US. Tally® relies on GaBi database and modelling principles [19]. Even though GaBi datasets have been used in LCA models worldwide, there could be uncertainty in Tally@ results, which can stem from both the data and its application. In their practical review of BIM-LCA integration tools, Mora et al. [36] present the limitations of Tally®, mainly regarding the availability of the environmental data (as the number of constructive alternatives available in the plugin databases was quite limited, leading to the need for assumptions on the most similar types of building components), the recognition of the chosen materials in the Revit® project and verification of the accuracy of the LCA analysis (due to the lack of different materials, because most materials are generic (taken by the GaBi database), and it is not possible to edit the material information).

Even though recent studies include BIM-based solutions for embodied carbon assessment, there is still a need for a more inclusive approach. The main concerns of the previous efforts can be listed as

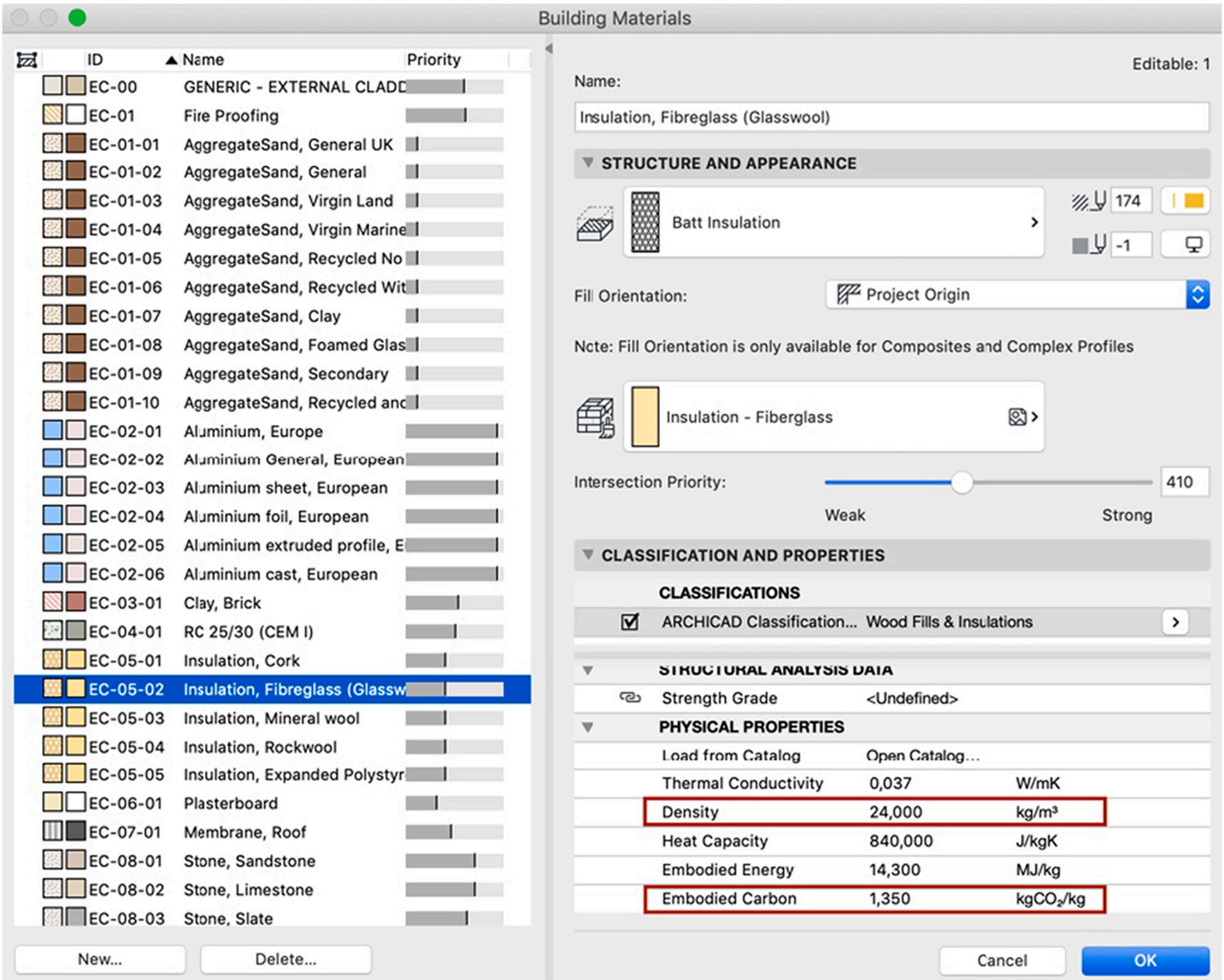


Fig. 3. Building materials.

relying on Autodesk®; working better in the early design stage, with accuracy problems likely in later design stages; concentrating on limited building elements or disciplines; and lacking benchmarking and alternative material suggestions for carbon reduction. Considering all these aspects, this work presents an IFC-based carbon benchmarking tool that automates the calculation process including all building elements, and proposes material substitution to decrease total embodied carbon.

3. Embodied carbon benchmarking model

The primary motivation of this study was to automate embodied carbon calculation for buildings and facilitate the decision-making process for lower carbon emissions through suggestions and benchmarking using IFC open file format. On the basis of previous studies concentrating on the integration of BIM into sustainability assessment [25], and operational and embodied energy analysis [3], demonstrating that while operational energy contribution increases over the lifetime of a building, embodied carbon at the production and construction stages is significant, the proposed model provides a guideline to assess the embodied carbon of buildings, which is currently unregulated by building codes. Focusing on regulated operational energy and carbon is outside the scope of the study as it is subject to greater regulations on energy efficiency and the adoption of renewables. Regarding potential concern about a possible increase in operational energy through the adoption of low carbon materials, there is no predicted increase in operational energy as the substitution materials are still high-performance materials that have to be approved by building codes which require energy-efficient materials. Moreover, even though the end of life stage is not included in the scope of the study, the ICE database considers the full lifecycle of the product including the burdens of disposal and benefits of recycling or reuse (C1-C4) despite being a cradle-to-gate database.

The proposed model can be applied in the design stages of any building type such as commercial or residential and project type including both new construction and renovation projects, as well as as-builts. This versatility not only promotes low carbon new construction and renovation but also enables embodied carbon inventory of existing building stock, which can facilitate managing these processes in the built environment in the digital age even though there could be a resistance to create BIM models of the existing buildings due to the considerable time and cost effort. The model is based on a carbon benchmarking (pycab) tool sustained by IFC structure including embodied carbon data. The main components of the proposed model are an embodied carbon database, embodied carbon library, BIM software and developed tool (pycab), as shown in Fig. 2.

The process to effectively implement the model included the

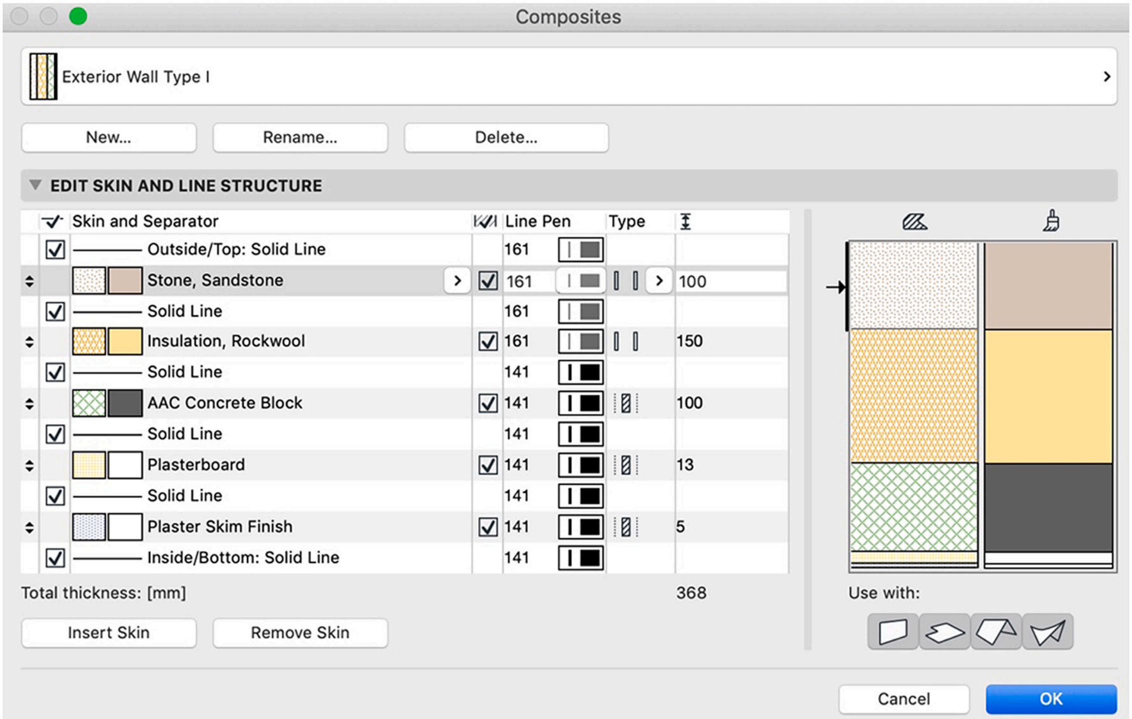


Fig. 4. Composites.

following steps: embodied carbon and density data of building materials from the ICE database were incorporated into the BIM software (ArchiCAD®) under physical properties. Based on these building materials, an embodied carbon library and template file were created. Taking these steps as inputs, BIM software created an output of the completed project in the IFC file format, which formed the input for the next step of the proposed model. A carbon benchmarking tool (pycab) developed through Python3 with IfcOpenShell backend (an open-source software library that helps users and software developers to work with the IFC file format, http://ifcopenshell.org/), generated the embodied carbon report of the project by extracting the related data from the IFC file and making a calculation according to the formula, as well as benchmarking and comparing different building materials for replacement suggestions. Assessments could then be made according to the targeted level (such as a reconsideration of building materials to decrease the embodied carbon of the building). The steps, shown in Fig. 2, for computing the embodied carbon can be applied to any building and project type.

Fig. 3 presents the inclusion of embodied carbon and density values of each building material obtained from the ICE database into ArchiCAD®. Despite their unique numbers, materials were grouped and numbered according to their main category to enable the comparison of alternatives.

The building elements (except window, door and stair) that consisted of materials were listed as composites in ArchiCAD® (Fig. 4). Here, it was important to accurately specify the thickness of each layer (material) in order to get a precise calculation. Embodied carbon factor and density for window, door and stair were provided by utilising IFC property sets.

The software was readied for the generation of the project through the template file storing all the composites/building elements with the necessary data (embodied carbon (EC), density and thickness of building materials and IFC properties for window, door and stair) for embodied carbon calculation, with the generated BIM model being exported as an IFC file with all IFC properties as well as building material properties. Using the IFC file as the input, and based on the embodied carbon calculation algorithms, the tool produces the output report. The tool loops over each IFC type (i.e., ifcwall, ifcslab, ifcroof, ….) and for each IFC type it then loops over every instance of that type (i.e., each building element), obtains the building material and the volume and then uses the formula (Area x Thickness x Density x Embodied Carbon Factor) to compute the embodied carbon contribution of each material. For each material in the ICE database, an embodied carbon code was introduced, of the form “EC-XX-YY”. The XX indicates the material category and all materials with the same XX code are assumed to be interchangeable, to serve as a guide to the designer that the materials may be interchangeable. The tool suggests alternative materials with the same material category (i.e., the same XX value). The developed tool is written in python and relies upon the open-source IfcOpenShell library (http://ifcopenshell.org/) (it also requires the commonly used matplotlib, numpy and pandas python packages).

The tool simply applies the formula of material quantity (a) x material embodied carbon factor (b) where (a) and (b) are measured against the same metric (e.g., per kg, material densities are needed). The carbon emissions attributable to the product stage [A1–A3] of the items included in the whole life carbon assessment must be calculated by assigning suitable embodied carbon factors to the given elemental material quantities [47]. After summarising the embodied carbon information, the report provides a detailed analysis which shows the carbon share by building elements and materials, as well as benchmarking with RIBA 2030 Climate Challenge Target Benchmarks. The tool also suggests alternative building materials with lower embodied carbon. It is worth noting that while there is an effort to benchmark carbon through strong fiscal measures, there is no guidance on the material cost and the structure of achieving embodied carbon targets, hence, this aspect was considered outside the scope of this tool.

4. Case study

The applicability of the developed model was checked using a case study where an architecture practice wanted to develop an early design parametric tool. Constructed in 2017 in the UK as a bespoke house under current new energy-efficient building regulations, the case study is a

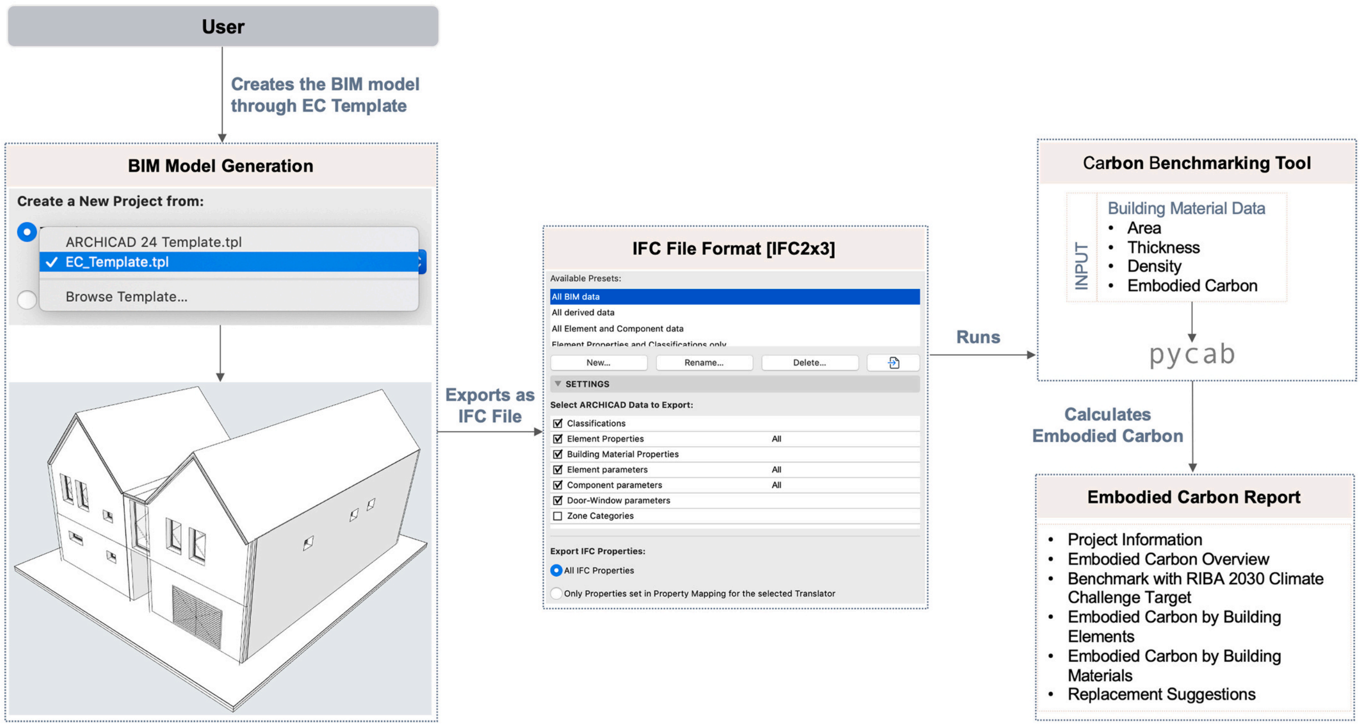
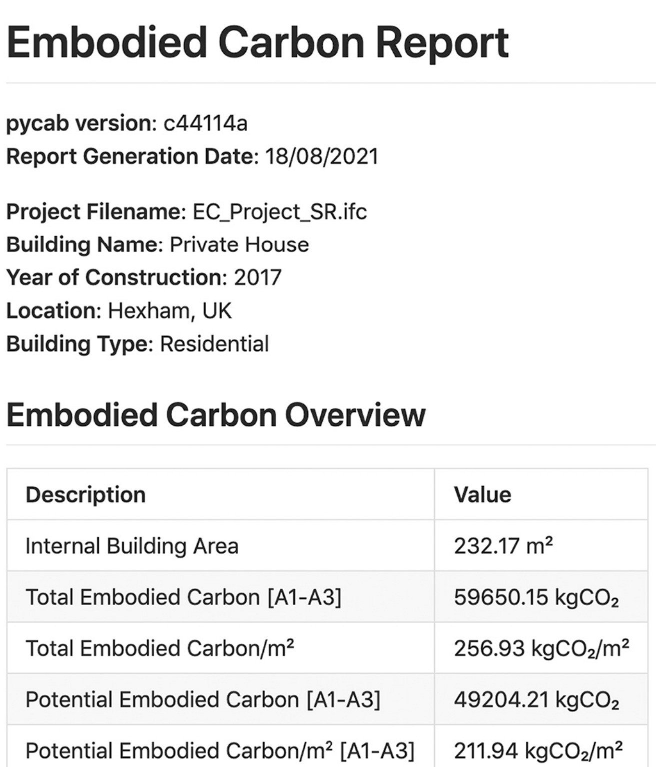


Fig. 5. Workflow diagram for user process.



Embodied Carbon Report

pycab version: c44114a
Report Generation Date: 18/08/2021

Project Filename: EC_Project_SR.ifc
Building Name: Private House
Year of Construction: 2017
Location: Hexham, UK
Building Type: Residential

Embodied Carbon Overview

Description	Value
Internal Building Area	232.17 m^2
Total Embodied Carbon [A1-A3]	59650.15 $kgCO_2$
Total Embodied Carbon/m^2	256.93 $kgCO_2/m^2$
Potential Embodied Carbon [A1-A3]	49204.21 $kgCO_2$
Potential Embodied Carbon/m^2 [A1-A3]	211.94 $kgCO_2/m^2$

Fig. 6. Embodied carbon report – overview.

two-storey residential building. Considering the share of housing in the construction industry and its affecting factors in urban scale, the selection of a residential building is of great importance for sustainability, and is expected to increase awareness of embodied carbon reduction for all parties from citizens to authorities. The steps for the user process are given in the workflow diagram (Fig. 5).

Based on 2D drawings (floor plans, sections, elevations, roof plan and details) of the project, the BIM model was generated through the embodied carbon template file in ArchiCAD®, which contains the material library and can be used for any project and building type. As the template file included project-specific building elements and corresponding building material information, the created BIM model stored all necessary data for embodied carbon calculation. The project information, such as name, building type, and the location was also entered into ArchiCAD®. In order to have all these data in the IFC file, all IFC properties including building materials properties should be selected in the translation process. The BIM model was exported as IFC2x3 schema.

The pycab programme (https://github.com/BahriyeIlhan/pycab) was run in the terminal using the command:

python3 pycab.py –ifcfile IFC_FILE.

The programme then extracted the quantities (area and thickness) and values (density and embodied carbon) of each building material from the IFC file and made the necessary calculation by applying the formula. The output report was generated as a markdown file and was also converted to html; these files can be opened with a standard editor/browser. It first summarised the project information and embodied carbon overview (Fig. 6).

After providing general information (name, construction year,

Table 1
Breakdown of whole life carbon vs RIBA's current benchmarks and targets for medium-scale residential buildings [29].

		Current Benchmark			2030 Target		
Stage	%	Min.	Avg.	Max.	Min.	Avg.	Max.
Products/materials [A1-A3]	21	210	275	368	42	110	179
Transport [A4]	2	20	26	35	4	11	17
Construction [A5]	<1						
Maintenance and replacements [B1-B5]	9	90	118	157	18	47	76
Operational energy [B6]	67	670	878	1172	134	352	569
End of life disposal [C1-C4]	1	10	13	18	2	5	9

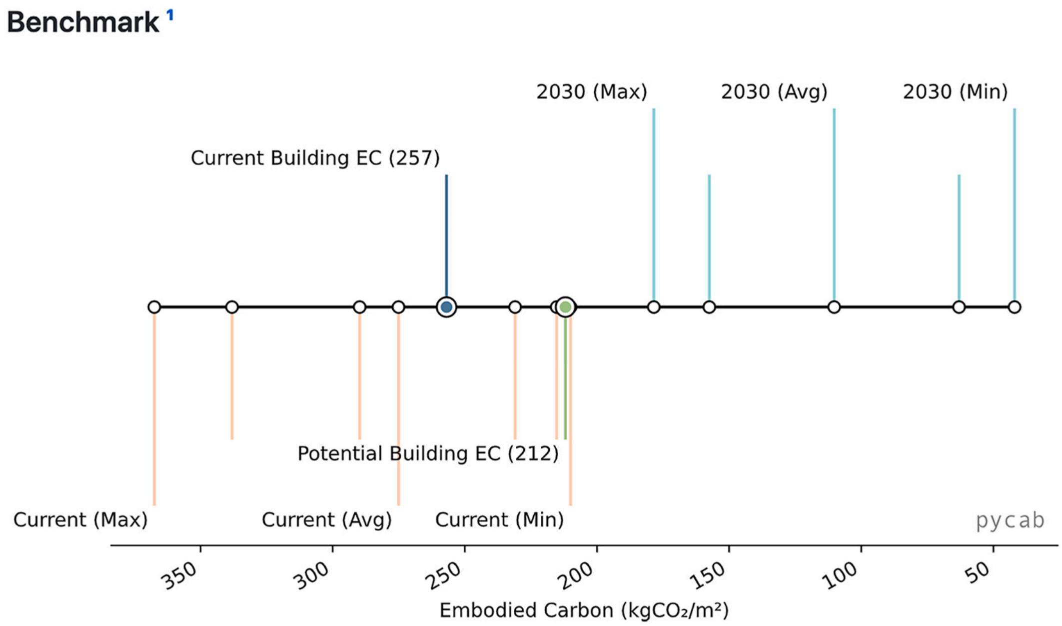


Fig. 7. Embodied carbon report – benchmark[1].

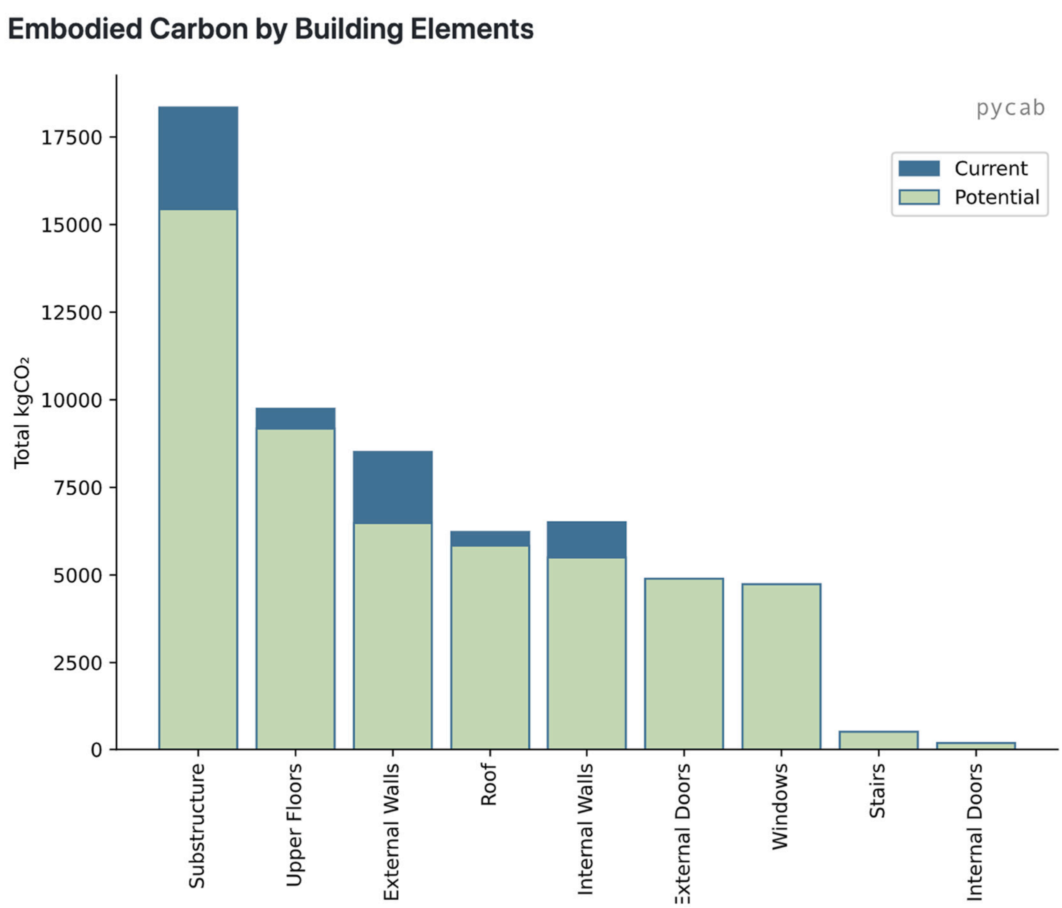


Fig. 8. Embodied carbon report – EC by building elements.

location and building type) for the project, total and per square metre embodied carbon values for the product stage were presented. It also provided the potential embodied carbon amount if alternative building materials were to be used instead, with replacement suggestions being given in the last section of the report.

The report included current and potential embodied carbon benchmarking with RIBA 2030 Climate Challenge Target Benchmarks. The RIBA Climate Challenge sets embodied carbon current benchmarks and 2030 targets for domestic and non-domestic (office and school) building types, for stages A-C. The share of A1-A3 was calculated based on the

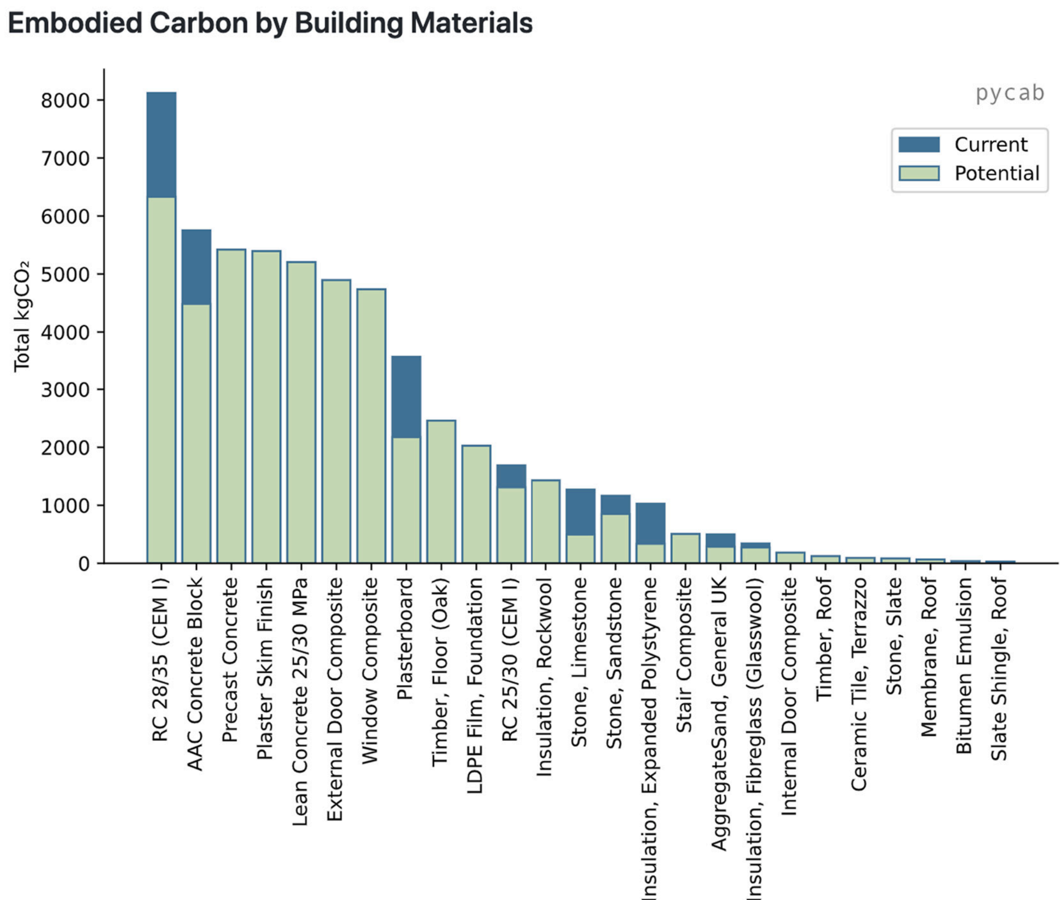


Fig. 9. Embodied carbon report – EC by building materials.

breakdown of whole life carbon for medium-scale residential buildings, which is given in Table 1.

Fig. 7 visualises these numbers and shows the rating of the current building embodied carbon (blue line) and potential building embodied carbon (green line) versus RIBA's current benchmarks and targets for medium-scale residential buildings. The building's current embodied carbon (257 $kgCO_2/m^2$) is smaller than RIBA's current average benchmark (275 $kgCO_2/m^2$) and the potential embodied carbon (212 $kgCO_2/m^2$) can be achieved by replacing the current building materials with alternatives which have lower carbon factors. Although it still has some way to go to reach 2030 targets, the potential embodied carbon almost reaches the current minimum benchmark (210 $kgCO_2/m^2$).

The report continues with the detailed embodied carbon analysis. While Fig. 8 shows the embodied carbon impact of each building element in total embodied carbon, Fig. 9 indicates the share of embodied carbon for each building material used in the project.

The results revealed that the substructure of the building had the highest embodied carbon impact, followed by upper floors, external walls, roof, internal walls, external doors (including the garage door) and windows, respectively. Due to their timber construction, both the stairs and internal doors had a much lower embodied carbon impact. Corresponding to the building elements, the building material with the highest embodied carbon was reinforced concrete. Autoclaved aerated concrete (AAC) concrete block, a component of the external walls, was the second highest contributor to embodied carbon, followed by precast concrete used on upper floors and plaster skim finish applied on plasterboard (for both walls and ceilings). As part of the substructure, lean concrete also had a relatively high embodied carbon impact. The aluminium material of the garage door moved the external door composite to a higher place on the list. Similarly, the window composite, due to its metal frame, accounted for a substantial amount of embodied carbon. Building materials, including plasterboard, oak, low-density polyethylene (LDPE) film, rockwool and expanded polystyrene, limestone and sandstone, made a smaller contribution to the building's total embodied carbon. The remaining materials made a negligible contribution to the building's total embodied carbon; this was partly due to their low embodied carbon density and partly due to their small volume.

At the end of the report, alternative materials are proposed for a replacement to reduce the total embodied carbon of the building. The programme checks if there is a substitute building material with a lower carbon factor and calculates the new potential embodied carbon of the corresponding material. It is critical to have interchangeable materials with the correct ID numbers under the related category, so that sensible replacement suggestions can be made. Fig. 10 lists a total of nine possible material replacements, from the highest embodied carbon saving to the lowest. The embodied carbon contribution of concrete formulated with Portland cement (CEM I) is a lot more than concrete with pozzolanic additions. In this project, the exchange of these materials would result in 1791$kgCO_2$ savings in the total embodied carbon. Replacing plasterboard with timber panels may have a high impact in terms of reducing embodied carbon. Similarly, using concrete blocks instead of AAC concrete blocks can substantially affect the total embodied carbon. Due to its lower carbon factor, slate is suggested for all other stone types used for the façade of the building. A review of design decisions regarding the quantity of limestone and sandstone, along with consideration of other relevant factors (e.g., aesthetic concerns), could take place for optimal results. Having the lowest embodied carbon factor, rockwool can be chosen where appropriate. Even though it may not be possible to apply all these suggestions to the project, for several reasons (such as cost, aesthetics, owner demand and irreversible

Replacement Suggestions

1. RC 28/35 (CEM I): 8121 $kgCO_2$ / 6330 $kgCO_2$ (Saving 1791 $kgCO_2$)

ID	Name	EC/m³
EC-13-01	RC 28/35 (CEM I)	312.80
EC-13-03	RC 28/35 (Pozzolanic Ash)	243.80

2. Plasterboard: 3574 $kgCO_2$ / 2174 $kgCO_2$ (Saving 1400 $kgCO_2$)

ID	Name	EC/m³
EC-06-01	Plasterboard	312.00
EC-06-02	Timber, Panel	189.75

3. AAC Concrete Block: 5753 $kgCO_2$ / 4484 $kgCO_2$ (Saving 1269 $kgCO_2$)

ID	Name	EC/m³
EC-14-02	AAC Concrete Block	210.00
EC-14-01	Concrete Block	163.68

4. Stone, Limestone: 1273 $kgCO_2$ / 495 $kgCO_2$ (Saving 778 $kgCO_2$)

ID	Name	EC/m³
EC-08-02	Stone, Limestone	247.50
EC-08-03	Stone, Slate	96.25

5. Insulation, Expanded Polystyrene: 1027 $kgCO_2$ / 335 $kgCO_2$ (Saving 692 $kgCO_2$)

ID	Name	EC/m³
EC-05-05	Insulation, Expanded Polystyrene	78.96
EC-05-04	Insulation, Rockwool	25.76

6. RC 25/30 (CEM I): 1689 $kgCO_2$ / 1309 $kgCO_2$ (Saving 380 $kgCO_2$)

ID	Name	EC/m³
EC-04-01	RC 25/30 (CEM I)	296.70
EC-04-03	RC 25/30 (Pozzolanic Ash)	230.00

7. Stone, Sandstone: 1165 $kgCO_2$ / 849 $kgCO_2$ (Saving 315 $kgCO_2$)

ID	Name	EC/m³
EC-08-01	Stone, Sandstone	132.00
EC-08-03	Stone, Slate	96.25

8. AggregateSand, General UK: 499 $kgCO_2$ / 285 $kgCO_2$ (Saving 214 $kgCO_2$)

ID	Name	EC/m³
EC-01-01	AggregateSand, General UK	15.68
EC-01-03	AggregateSand, Virgin Land	8.96

9. Insulation, Fibreglass (Glasswool): 342 $kgCO_2$ / 272 $kgCO_2$ (Saving 70 $kgCO_2$)

ID	Name	EC/m³
EC-05-02	Insulation, Fibreglass (Glasswool)	32.40
EC-05-04	Insulation, Rockwool	25.76

Fig. 10. Embodied carbon report – replacement suggestions.

processes), the process enables stakeholders to witness the contribution of building materials, and can raise awareness about correct material selection for future projects.

5. Conclusion

The push for the reduction of overall carbon emissions in design, construction and operational processes, is driving the industry towards more technology-integrated solutions. The applications developed in this approach benefit from the potential of BIM to improve the processes of building life cycle assessment for managing this move and implementing feasible methods and systems. Improving understanding of how digital applications can be used to visualise and address embodied carbon can be a big step change towards taking action to substitute materials and reduce the upfront carbon impact, which is currently entirely unregulated.

The use of BIM for embodied carbon assessment in this study enables early decision-making and much-needed benchmarking of material choices, demonstrating how digitalised processes can contribute to the success of low carbon building. As an iterative process, which can help in proposing alternatives; the tool is not considered as a design tool, however, its interaction with BIM software will make it much more accessible to practitioners to assess carbon at early stages for improved design decisions and appraisals. The results indicate that carbon savings in the superstructure and the external walls were most significant in the particular case study examined, although this may be different in other building types. The findings support arguments that benchmarks are needed and help address the lack of methodologies available to industry experts for demonstrating the benefits of benchmarking to clients and building operators.

In recent years, BIM utilisation within industry has been rapidly growing, and an increasing number of buildings are now designed with a complete BIM model in place. The tool presented in this research ideally fits into the framework of modern building practice. However, for existing buildings without a BIM model, while this tool could be used to assess their embodied carbon, the cost and time involved in the creation of an as-built BIM model may be prohibitive unless other uses are planned (e.g., management and maintenance).

The need for such BIM-based tools will become even greater when it comes to decision-making on mega projects, as shown by the recent case where the City of London planning authority refused permission for a major 300 m tall tower, citing high embodied carbon as one of the reasons [26].

As Edwards et al. [17] suggest, AEC practitioners may be able to develop BIM models utilising a standardised and integrated library that contains whole life cycle energy information for each material. This would not only enable easier energy life cycle comparison of different materials, but it would also provide an automated and more transparent process for material/product substitution. However, there may still be resistance to adopting complete automation of the process, linked to issues including:

- The lack of a legislative framework governing the integration of carbon data, particularly embodied carbon, in BIM frameworks.
- Clear roles and responsibilities and skills development of key personnel to utilise the full digital technologies needed to assess full upfront carbon.
- Lack of findings from case studies of major projects or refurbishments modelled in BIM environments which can help influence change.

The findings of the current study may represent how such research can contribute to the knowledge base and encourage further work in this area, thus alleviating some of these concerns. Targeting only embodied carbon at the product stage, the proposed tool can be considered as a proof of concept that embodied carbon data can be automatically processed and used to guide the design. Not including operational energy or disposal stages, the model can be enhanced through the inclusion of other aspects of building materials such as cost, recycling or reusing. Moreover, looking at operational energy alongside embodied carbon could be a future direction for this research.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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