# Use of Digital Analysis Methods in Determination of Embodied Carbon of Buildings in the UK

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**Abstract.** The built environment sector has a key contribution towards global carbon emissions but also holds a huge potential for reducing its environmental impact. With the world's focus on sustainability and achieving net-zero carbon emissions, it is crucial to make consistent efforts to lower carbon emissions from the built industry. The carbon footprint of a building is mainly the sum of both operational and embodied carbon emissions throughout its life cycle. The substantial progress in reducing operational carbon emissions has now shifted the emphasis toward embodied emissions. Life Cycle Assessment (LCA) is a remarkable innovation in the environmental impact assessment of the built environment, allowing the user to perform whole-life carbon assessment and embodied carbon assessment. This study provides a detailed review of the LCA standards and protocols, methodologies, digital tools, and databases available in the UK. It also explores the challenges associated with the utilization of digital tools in the building sector. This study evaluates the whole-life embodied carbon of a case study educational building, considering the product phase (A1-A3), construction phase (A4-A5), use phase (B4), and the end-of-life phase (C1-C4). The most popular manual approach using the Inventory of Carbon and Energy (ICE) database, the Institute of Structural Engineers (IStructE), and the Royal Institute of Chartered Surveyors (RICS) guidelines are utilized for the evaluation of the embodied impact of the building. The study demonstrated that the product stage (A1-A3) has the highest share among other life cycle stages in the embodied carbon of the buildings. It consists of around 82% of total embodied carbon, whereas the rest is shared between other life cycle stages. This study also explores the reliability of embodied impact assessment of one of the most popular digital LCA tools, One Click LCA. In this study, One Click LCA is utilized for the evaluation of embodied carbon of the product stage (A1-A3) of the same case study building. It is found that the traditional method using the ICE database overestimated the embodied carbon from A1-A3 stages by 30.9% when compared to One Click LCA. The embodied carbon from stages A1-A3 of the case study building accounted for 1426.234 tCO$_2$e for the ICE database and 984.48 tCO$_2$e for One Click LCA. Due to the use of EPDs by One Click LCA, the tool exhibits reliability in the embodied carbon evaluation of the case study building. However, some of the challenges relating to the unavailability of region-specific data and lack of regular updates in available EPDs still underlies within the tool.

**Keywords:** Embodied Carbon; Life Cycle Assessment (LCA); Digital tools; ICE; One Click LCA.

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## 1. Introduction

Climate change and its associated global temperature rise have been the most pressing issue currently. The detrimental effects of climate change, coupled with escalating carbon emissions and increased energy usage, highlight the need for proactive control measures. Consequently, the Intergovernmental Panel on Climate Change (IPCC) has established an objective to limit the increase in global temperatures to 1.5°C. To achieve this, a 45% decrease in carbon emissions is required compared to the levels in 2010 by the year 2030, with a state of net-zero emissions by 2050 (IPCC, 2021). The issue of sustainability in the built environment sector has garnered worldwide attention. This sector is not merely responsible for 39% of worldwide carbon emissions (Dean et al., 2016), but it also significantly affects the environment by depleting resources and producing substantial amounts of solid waste (Onat and Kucukvar, 2020). Countries worldwide are actively working to decrease emissions associated with the construction sector, recognizing its significant potential for reducing carbon. A framework has been laid out by the UK Green Building Council (UKGBC) to create nearly carbon-neutral structures, with the aim of reaching its net zero target by 2050 (UKGBC, 2019).

### *1.1 Carbon Emissions related to Life Cycle of Buildings*

Buildings contribute to energy consumption and Green House Gase (GHG) emissions through each stage of their entire life cycle. Every type of greenhouse gas (GHG) possesses a distinct Global Warming Potential (GWP). Utilizing their energy usage and GWP as benchmarks, emissions of GHGs are transformed into carbon dioxide equivalent (CO$_2$e). This process facilitates the computation of the carbon footprint associated with the constructions (Mohebbi et al., 2021). The overall emissions can be

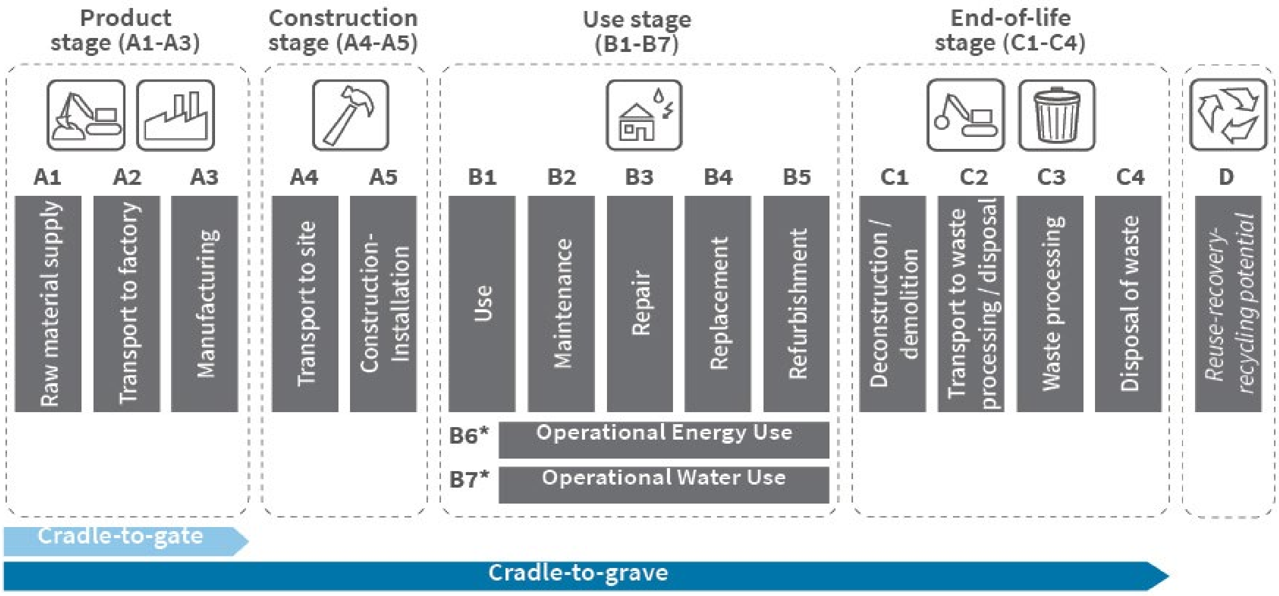

**Figure 1: Life cycle stages reproduced from BS EN 15978: 2012**

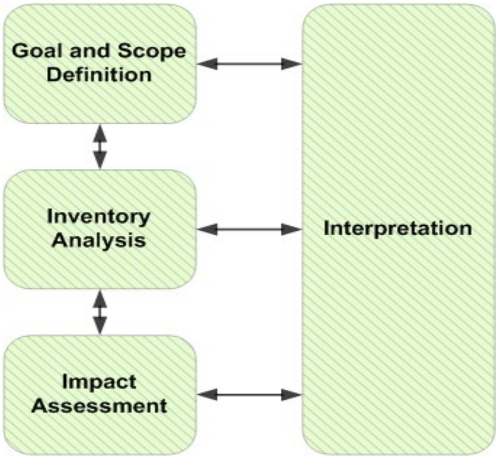

**Figure 2: Life Cycle Assessment steps reproduced from ISO 14044:2006**

classified into two primary groups: embodied carbon across the life cycle and operational carbon. Embodied carbon pertains to carbon emissions associated with manufacturing, transporting construction materials, construction procedures, and services, as well as waste material transportation and recycling (Dixit, 2019). On the other hand, operational carbon covers energy consumption for upholding comfortable indoor conditions within buildings. This includes aspects like heating, ventilation, air conditioning (HVAC), hot water, lighting, and the usage of household appliances (Cabeza et al., 2014).

Due to the prolonged lifespan of buildings, most of the energy usage occurs during their operational phase. Out of the 39% of global emissions, operational emissions contribute to 28%, while the remaining 11% is attributed to the materials used and the construction process (Webster et al., 2020). Given the large share of operational carbon in the overall carbon footprint of buildings, noteworthy progress has been made in reducing operational emissions. Various regulations regarding operational emissions for both new and existing buildings have been put into effect by the UK government, which has resulted in the establishment of standardized methodologies for assessing operational emissions (Ekundayo et al., 2012). Even though operational carbon has a larger impact compared to embodied carbon, the significance of embodied carbon in the overall carbon footprint of a building should not be disregarded. Unlike operational carbon emissions that occur gradually over a building's lifespan, embodied carbon emissions are released within a relatively short period during the construction, maintenance, demolition, and recycling phases and have an immediate environmental impact (Zhang and Wang, 2017). Moreover, certain research suggests that enhancing energy efficiency in buildings can lead to a rise in embodied energy, which can be attributed to the adoption of advanced technologies and construction materials, as observed in nearly Zero Energy Buildings (nZEB) (Copiello, 2016).

### *1.2 Life Cycle Assessment*

Numerous investigations have utilized the Life Cycle Assessment (LCA) methodology to measure embodied carbon, as it enables a thorough assessment of environmental impacts across different phases of a building's life cycle (Nawarathna et al., 2018). LCA is a globally acknowledged and standardized method, regulated by the International Organization for Standardization (ISO) 14040/14044 and utilized to calculate the environmental impact of a product/service during its life cycle (Müller et al., 2020).

LCA gives the complete picture of the overall emissions of the buildings considering both the operational emissions as well as the embodied emissions. As a result, LCA is increasingly utilized to measure the impact of buildings throughout their life cycle (Röck et al., 2018). Furthermore, LCA provides several benefits, including design optimization, certification, building approval, research, and benchmarking, all of which support the facilitation of low-carbon design. Figure 1 is a pictorial representation of the various life cycle stages of buildings according to BS EN 15978: 2012.

ISO 14040 provides a set of standard principles and a framework, whereas ISO 14044 provides requirements and guidelines for environmental management and conducting life cycle assessments (ISO-14040, 2006; ISO-14044:2006). These principles, frameworks, and measures of LCA, define four primary steps in the LCA process such as (shown in Figure 2):

i. Goal and scope definition

It involves the definition of functional description, lifespan, and system boundaries (which determine the physical scope of the building and the life cycle stages to be considered in the assessment), and selecting environmental impact categories to be evaluated.

ii. Inventory analysis

It involves gathering building-related information to construct a life cycle inventory (LCI), which consists of a thorough inventory of activities and materials involved in the building's life cycle such as transportation, construction processes, energy consumption, and water consumption.

iii. Impact assessment

It encompasses weighing the potential environmental consequences of construction, known as the Life Cycle Impact Assessment (LCIA) (Khan et al., 2022). Multiple tools for Life Cycle Assessment (LCA) or manual computations through spreadsheets can be utilized to monitor materials, scenarios, and their corresponding impacts.

iv. Interpretation

It entails comprehending and deriving conclusions from the LCA outcomes and categorizing the impacts in terms of building components, materials used, and life cycle stages considered.

After quantifying the impact, it becomes possible to make informed decisions regarding the reduction or offsetting of emissions. Thus, the reliable assessment of the overall environmental impacts of a building is essential for effectively reducing its environmental footprint. It involves comparing different alternatives, developing and executing low-carbon solutions, and keeping track of performance. In the absence of reliable measurement methods, informing policy decisions and setting appropriate scopes becomes difficult, impeding effective decision-making (Luo, Yang and Liu, 2016).

To assist with initial design choices and streamline the LCA procedure, several LCA tools have emerged alongside the evolution of the LCA methodology. However, the industry's uptake of these tools is limited, as indicated by various literature due to the underlying challenges such as lack of standardization and disparities among various databases in use, which is later discussed in the Literature Review section. However, there exists a gap in knowledge pertaining to the reliability and accuracy of digital LCA tools within the UK context.

Thus, this study aims to explore the following research questions:

- What is the present state of the digital LCA tools in the UK and the associated challenges with their implementation?
- What is the level of accuracy and reliability of the popular digital LCA tools adopted for buildings?

To address the research questions, this study aims

i. To investigate the current state of digital tools, standards, methodologies, and databases available.

ii. To evaluate the whole life embodied carbon of the building by manual computation and appraise the effectiveness of the One Click LCA digital tool.

## 2. Literature Review

In recent times, more specific standards and protocols have emerged to address carbon-related issues. CEN EN 15603 offers guidance on evaluating the energy efficiency of constructions, encompassing total energy usage and the determination of energy ratings (CEN EN 15603, 2008). The procedure for computing the environmental effectiveness of constructions is outlined in BS EN 15978 (BS EN 15978, 2012). Additionally, CEN EN 15804 functions as the benchmark for the Environmental Product Declaration (EPD) in the evaluation of sustainability in construction activities and services. This standard delineates the technical functionality of a construction product and delivers data on various indicators throughout distinct stages of its life cycle (CEN EN 15804, 2012). BS EN 15942 facilitates business-to-business communication, and ensures a consistent exchange of information to promote the sustainability of construction activities, with the aim of fostering a mutual comprehension among stakeholders (BS EN 15942, 2021). Moreover, an array of sustainability certifications have been established, including BREEAM (Building Research Establishment Environmental Assessment, UK), LEED (Leadership in Energy and Environmental Design, USA), and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen, German Sustainable Building Council), aimed at fostering sustainable practices.

These standards and sustainability criteria have played a critical role in the development of various digital tools utilized in the field. Apart from adhering to relevant standards and protocols, digital tools utilized in the construction industry must also comply with various building rating systems (Yan et al., 2022). Few of the authors have done a comprehensive review of the available digital tools for LCA assessment. The common tools reported by the authors include Athena Impact Estimator for Buildings, SimaPro, One Click LCA, Tally, Embodied Carbon in Construction Calculator (EC3), ECOSOFT, eToolLCD, IMPACT, EPiC Grasshopper, Totem, etc. These tools identified are categorized according to their country of origin (Lasvaux et al., 2013), specific purposes such as building design support, and certification (Prideaux et al., 2022), the scope of tools such as buildings, infrastructures, etc. (Yan et al., 2022). Some of the authors classified the tools depending on functionalities and aspects of the building's life cycle, specialized tools, integration with building design (BIM-LCA), web-based/cloud-based platforms, spreadsheets, and standalone assessment programs (Hollberg and Ruth, 2016; Giordano, Gallina and Quaglio, 2021).

However, LCA is data intensive methodology and requires a sufficient and reliable data set for embodied carbon assessment (Peereboom et al., 1998). Embodied carbon assessment databases have great significance in providing reliable, standardized, and up-to-date data to facilitate well-informed decision-making during the early design stages. These databases serve as repositories of information concerning the carbon emissions linked to construction materials, manufacturing processes, and transportation (Gelowitz and McArthur, 2017). Additionally, these databases establish a common platform that allows for consistent data comparison between different systems and promotes the harmonization of evaluation procedures. Some of the prominent databases used in the industry are:

- Inventory of Carbon and Energy (ICE)

It is a well-known, openly accessible database containing cradle–to–gate carbon factors pertinent to the UK. Originating in the late 1990s at the University of Bath, it compiles embodied carbon coefficients for commonly used construction materials (Jones et al., 2019).

- Environmental Product Declarations (EPDs)

Environmental Product Declarations (EPDs) are considered the most accurate data as they are developed following the EN 15804 standard (EN 15804:2012). They are the standardized documents that communicate the full lifecycle environmental performance of a specific product, considering factors such as material extraction, manufacturing, repair, disassembly, and disposal. Within the life cycle stages. EPDs are mandatory only for the A1-A3 boundary, while other stages can be voluntarily included (Gelowitz and McArthur, 2017).

- EcoInvent

EcoInvent is a widely recognized and extensively utilized database that offers comprehensive coverage of various environmental impact categories, including embodied carbon. This database takes a global perspective and provides users with valuable data on materials, energy systems, and processes.

Some of the other prominent databases include Athena Sustainable Materials Institute, GaBi, and SimaPro, which provide thousands of LCI datasets to perform life cycle assessments.

### *2.1 Challenges Associated with the Use of LCA Tools*

Even though the digital tools in the building sector are more advanced and provide more choices in targeting different application scenarios compared to the infrastructure scope (Yan et al., 2022), there are some underlying challenges associated with the tools limiting their ability and application in the global industry. The authors acknowledge the valuable insights of LCA tools but underscore their limited applicability in the industry due to various challenges, including data availability, complexity, and a lack of standardized protocols (Meex et al., 2018; Ekundayo et al., 2019; Budig et al., 2021).

- Lack of Design Flexibility

Cabeza et al. (2014) and Safari and AzariJafari (2021) highlight the challenges related to the LCA of buildings due to the high degree of uncertainty related to the long-life span of buildings, especially regarding the use phase (due to refurbishments, occupant behaviour, consumption patterns, etc.) and the end-of-life (EOL) treatment (Alotaibi et al., 2022). Moreover, the unique design of buildings makes standardization difficult and causes the need for the LCA of individual buildings (Verbeeck and Hens, 2010). Lasvaux et al. (2013) and Budig et al. (2021) report that existing tools have been tailored to a particular context with a predetermined objective and often lack the flexibility necessary to accommodate design variations in buildings.

- Lack of Standardized Methodologies

Chen et al. (2019), Pan and Teng (2021) and Akponeware et al. (2022) identified the methodological variables such as goals and scope, system boundaries, functional units, life cycle stages considered, data sources, calculation specifications, etc., which impact the accuracy of embodied carbon assessment. Furthermore, the authors highlight the importance of standardizing methodologies and establishing consistent practices to ensure reliable and comparable assessments of embodied carbon. Yan et al. (2022) underline the risk of the undetermined impact of the standards and protocol followed by the digital tools in carbon footprint assessment.

- Inconsistency in Databases used

Mohebbi et al. (2021) and Keyhani et al. (2023) studied the impact of the various databases on the whole life cycle embodied emissions of a building in the UK. The authors utilized the most commonly used databases such as Environmental product declarations (EPDs), Inventory of Carbon and Emission (ICE) database, the UK Department for Business, Energy, and Industrial Strategy (BEIS). The study concluded that the generic databases such as BEIS and ICE databases can overestimate the embodied carbon for the materials showing inconsistency in the datasets.

- Issues with Data Accessibility and Transparency

Yan et al. (2022) noted the need for transparency in the digital tools, i.e., calculation specifications, databases used, parameters considered, etc. The author highlights the challenges associated with the product manuals and calculation procedures in developed software tools and favours spreadsheet-based tools relating to the flexibility and transparency they offer in the calculation process. Prideaux et al. (2022) also suggest the need for improved data transparency and accessibility, the development of user-friendly interfaces, and standardized assessment frameworks. The authors also draw attention to the importance of clear communication of assumptions, limitations, and uncertainties associated with the results to ensure credibility and facilitate trust among stakeholders.

- Lack of Complete Embodied Emission Datasets

Blay-Armah et al. (2022) report the limited availability of databases especially for the end-of-life stage, while the available resources showed a high degree of inconsistency in the assessment results. Lasvaux et al. (2013) also highlight the need for consistent, complete, and validated datasets and

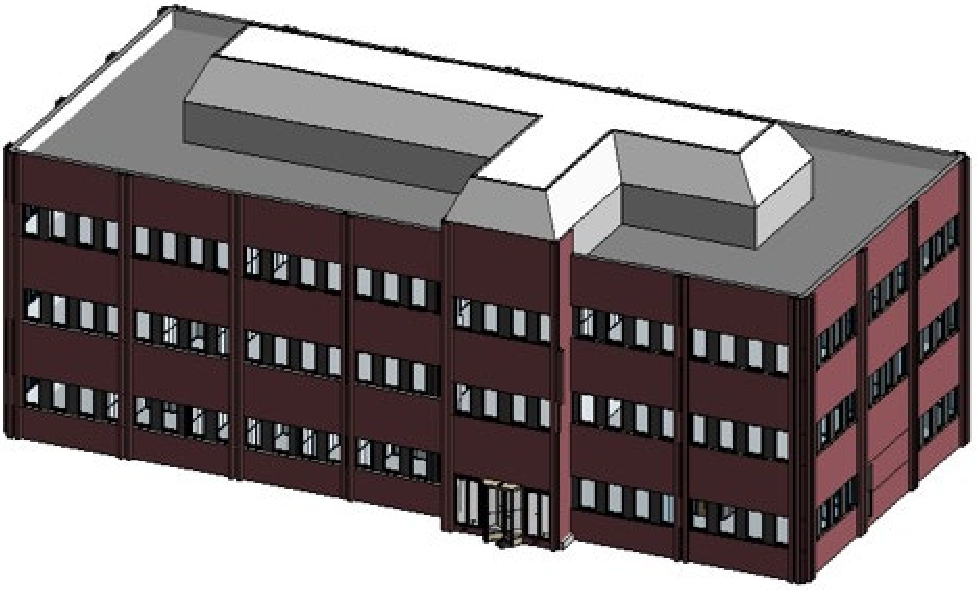

Figure 3: Case study building model in Revit

methodologies in digital tools.

- Accuracy and Reliability of Tools

Nair, Fransson and Olofsson (2021) performed an interview-based study to identify and understand the challenges and opportunities related to incorporating LCA tools in the industry. The study suggests that the lack of competency to perform LCA, its complex nature and the lack of transparency in LCA tools are hindering its application in the industry. Ekundayo et al. (2019) found inconsistency in the functionalities, data sources, and calculation methodologies of various open-source tools utilized in the study.

This research aims to bridge these identified gaps by evaluating the whole-life embodied carbon of a case study educational building. The study aims to offer empirical insights into the reliability and discrepancies inherent in current methodologies. This will be achieved through a comparative analysis of modern digital tools, such as One Click LCA, against traditional manual procedures. The research endeavors to highlight the distinctions between the two methodologies, shedding light on the potential impact of challenges on result reliability. It is worth noting, however, that certain challenges persist, specifically related to the absence of region-specific data and lack of regular updates in available EPDs within the utilized tool.

## 3. Methodology

This research will conduct a whole-life embodied carbon evaluation of an educational building. The Institute of Carbon and Energy (ICE) database, Institute of Structural Engineers (IStructE), and Royal Institute of Chartered Surveyors (RICS) guidelines are utilized to conduct the manual computation. One of the most popular digital tools, One Click LCA is utilized for assessing the embodied carbon of the same case study building to evaluate the reliability of the digital tool.

### *3.1 Case Study Building*

For this study, a 3-storeyed educational building located in the UK is considered. The Gross Internal Area (GIA) of the building is 2150 m². The case study building is modelled using Building Information Modelling (BIM) software, Autodesk® Revit® v2023, shown in Figure 3.

Adhering to the framework of LCA, it is crucial to establish the scope, system boundaries, and goals of the assessment. As outlined in the RICS 'Whole Life Carbon Assessment for the Built-environment' guideline, the minimum scope for assessing embodied carbon in buildings includes primary structural components within the substructure and superstructure. Thus, this embodied carbon assessment includes substructure components and superstructure components including walls and finishing works. Additional information regarding the scope of the case study building can be found in Table 1.

To accurately represent the building's carbon footprint, a comprehensive evaluation of its entire life cycle carbon

**Table 1: List of structural elements and component**

| Building Element | Structural element and component |
|---|---|
| Substructure | Structural foundation: Pad Foundation 3500x3500x800mm and 3500x5035x800mm |
| | Floor: Ground Floor Slab and Flat Slab |
| Frame | Structural Columns: Concrete Rectangular: 300 x 400mm |
| | Staircase: Stair: 150mm Waist Slab |
| Envelope | Ceiling: Acoustic Ceiling Tile 24 x 48 (Fiberglass), Rectangular Mullion: 30mm Square (Aluminium) |
| | Roof: Concrete Cast in-situ, Gravel, Rock Mineral Wool, Expanded Polystyrene (EPS) |
| | Walls: Basic Aerated Concrete Block, External Brick Wall with Cavity 300mm, Plasterboard, Rock Mineral Wool |
| | Windows and Doors: Windows Plain: 1350x900m, Aluminium Frame, Double Glazing, MDF |

impact is essential. However, this study primarily focuses on the embodied carbon aspect of the building, thus excluding the consideration of operational carbon (B6-B7). The system boundaries of study considered include Product Stage (A1-A3), Construction Stage (A4-A5), Use (B4), and End–of–Life (C1-C5). For the use phase (B1-B5), only the replacement stage (B4) is considered in the study because the embodied carbon for use (B1) is generally insignificant, the data available for the maintenance and repair phase (B2) is much less, and the embodied carbon for refurbishment (B5) is according to the planned change in usage of the building (IStructE).

For the impact assessment phase, the analysis considers the Global Warming Potential (GWP) as a measure of the carbon footprint. This relates to the quantity of carbon dioxide discharged into the atmosphere as a mixture of various greenhouse gases.

To conduct the Life Cycle Assessment (LCA) evaluation of the building, a compilation of the materials and products utilized in its construction is required. This involves simulating the case study building using Building Information Modelling (BIM) software, Autodesk® Revit® v2023, to gather information about material quantities. A comprehensive list of various materials and corresponding quantities can be found in Table 2.

**Table 2: List of material volume and weight in the case study building**

| Structural Component | Materials Name | Materials Volume (m³) | Materials Weight (tonnes) |
|---|---|---|---|
| **Structural foundation** | Concrete | 302.596 | 726.230 |
| | Rebar | 9.077 | 71.254 |
| **Floor** | Damp Proof Course | 787.848 m² | 0.425 |
| | Concrete | 583.639 | 1400.734 |
| | Rebar | 18.691 | 146.724 |
| | Cement/Sand Screed | 39.392 | 74.845 |
| **Structural Columns** | Concrete | 43.154 | 103.570 |
| | Rebar | 1.295 | 10.163 |
| **Staircase** | Concrete | 11.680 | 28.032 |
| | Rebar | 0.350 | 2.751 |
| **Ceiling** | Acoustic Ceiling Tile (Fiberglass) | 22.789 | 2.188 |
| | Rectangular Mullion (Aluminium) | 3.686 | 9.952 |
| **Roof** | Concrete | 194.250 | 466.200 |
| | Rebar | 3.302 | 25.923 |
| | Gravel | 77.990 | 155.980 |
| | Rock Mineral Wool | 38.995 | 3.510 |
| | Expanded Polystyrene (EPS) | 21.552 | 0.639 |
| **Walls** | Aerated Block work | 176.045 | 158.441 |
| | Aluminium | 4.886 | 13.192 |
| | Brick | 121.372 | 182.058 |
| | Door Frame | 0.198 | 0.535 |
| | Glass | 2.810 | 7.025 |
| | Paint | 2.725 | 2.998 |
| | Plaster (Plasterboard) | 55.539 | 47.652 |
| | Softwood(Lumber) | 27.127 | 10.037 |
| | Rock Mineral Wool | 28.571 | 2.571 |
| **Windows** | Aluminium Frame | 7.672 | 20.714 |
| | Double Glazing | 4.928 | 12.320 |
| **Doors** | MDF | 5.185 | 4.407 |
| | Double Glazing | 0.771 | 1.928 |
| | Stainless steel | 0.014 | 0.110 |
| | Aluminium | 0.056 | 0.151 |

This study is approached through the utilization of two prominent LCA methods: the traditional spreadsheet-based approach (using the ICE database) and the digital One Click LCA tool, which is explained in detail below.

### *3.2 Traditional Approach (ICE Database)*

The calculation of embodied carbon has become vital in the design process since the carbon reduction commitments. However, during the calculation of embodied carbon, there should be meaningful comparisons between the approaches. The traditional approach utilizes the spreadsheet method to calculate the embodied carbon. The basic principle for the calculation of embodied carbon is multiplying the quantity of each material by the carbon factor of that material for the life cycle stages considered, given by equation (1):

$$\boldsymbol{EC_i = \sum i(Qmat, i\ x\ ECFi)} \tag{1}$$

Where:

$EC_i$ = Embodied Carbon of $i^{th}$ material

$Qmat$ = Quantity of $i^{th}$ material

$ECFi$ = Embodied Carbon Factor of $i^{th}$ material

The Institute of Structural Engineers (IStructE) guideline named 'How to calculate embodied carbon' is employed in this study. This guideline provides a thorough assessment methodology of the embodied carbon of buildings considering various life cycle stages from cradle to grave (A-

C). The embodied carbon factors (ECF) (A1-A3) are taken from the ICE database v2.0 and v3.0 (Table 3). Since ICE database only covers embodied carbon emissions during A1-A3, the IStructE guideline is utilized to compute ECFs related to other life cycle stages.

For the construction process stage (A4-A5), ECF is calculated on the basis of transport distance and transport emission factor for considered transport mode (A4), site wastage, waste processing and disposal (A5w), and site activities (A5a) (IStructE). The material wastage at site data is considered from WRAP, Net Waste Tool reference guide.

For the use stage (B1-B5), in this study, only B4 is taken into account due to their significant impact on embodied carbon, outweighing other aspects of the use phase. Module B4 considers the embodied carbon related to the replacement of building elements during the life cycle of the structure, i.e. Reference Study Period (RSP). The RSP of the case study building is considered 60 years, equal to the service life of the building (RICS, 2017). The substructure and superstructure building components are not replaced during the life cycle of the building. Thus, the estimated component life span for these elements is considered equal to the service life/RSP of the building. However, certain elements like plasterboard, paint, and fiberglass are assumed to be replaced after their service life. The service life for fiberglass and plasterboard is considered 30 years whereas, for paint, the service life is taken as 10 years. The carbon factor for Module B4 is obtained by the product of the frequency of replacement of the component during the life cycle of the building with the sum of the carbon factors for life cycle modules A1-A5 and C2-C4.

Module (C1) is related to the demolition and deconstruction of the building, module (C2) is related to the transportation of waste materials, modules (C3-4) are linked to waste processing such as reuse, recovery, or recycling (C3) and disposal (C4).

### *3.3 One Click LCA*

For the digital tool, One Click LCA with a student license is employed for conducting embodied carbon assessment. This software is developed by Bionova Ltd, aligns with the ISO 14044 and EN 15978 standards, and stands as a widely used LCA tool specifically designed for buildings. Notably, One Click LCA boasts compatibility with more than 40 certifications including LEED, BREEAM, and ISO standards. One Click LCA operates in accordance with Environmental Product Declarations (EPDs) based on EN 15804 and ISO 14044 standards. These EPDs are associated with registered materials and reflect their environmental performance over their entire life cycle and thus, are considered the most reliable datasets to give the embodied carbon values. The EPDs in One Click LCA are based on EcoInvent and GaBi databases. Leveraging these datasets and incorporating input data on material volume and types, it conducts analyses and generates reports detailing the carbon emission levels attributed to different materials.

The EPDs for the construction materials used in the case study building are selected to closely represent the materials selected in the building. Primarily, the EPDs selected are from UK manufacturers, however, some of the unavailable materials are considered from EU manufacturers. The details of the materials considered in manual calculation and EPDs selected in One Click LCA are reported in Table 3.

**Table 3: List of selected ICE materials and EPDs in One Click LCA**

| Materials Name | ICE-ECF(kgCO2e/kg) | ICE database (v2.0 & v3.0) | One Click LCA (EPDs selected) |
|---|---|---|---|
| Concrete | 0.138 | In-Situ Concrete (32/40 MPa) | Ready-mix concrete, C32/40, C III A |
| Rebar | 1.99 | Steel, Rebar | Carbon steel reinforcing bar (rebar) (secondary production route – scrap (member of UK CARES) |
| Damp Proof Course | 4.2 | Damp Proof Course/Menbrane | EPDM waterproofing membrane |
| Cement/Sand Screed | 0.183 | Mortar (1:3 cement: sand mix) | Self-levelling mortar (SLM) |
| Acoustic Ceiling Tile (Fiberglass) | 1.35 | Fibreglass (Glasswool) | Suspended ceiling system with acoustic insert/pad |
| Aluminium | 6.67 | Aluminium General, European Mix, Inc Imports | Aluminium façade cladding panel |
| Gravel | 0.00747 | general UK, secondary and recycled, bulk, loose | Aggregate (crushed gravel), generic |
| Rock Mineral Wool | 1.28 | Insulation, Mineral Wool | Rock wool/mineral wool insulation |
| Expanded Polystyrene (EPS) | 3.29 | Expanded Polystyrene | EPS insulation panels, graphite |
| Aerated Block work | 0.28 | AAC concrete block | Autoclaved aerated concrete block |
| Brick | 0.45 | A Single Brick | Perforated dense facing bricks, strong coloured |
| Paint | 2.91 | Paint, General | Emulsion for interior use with recycled paint content |
| Plaster (Plasterboard) | 0.39 | Plasterboard | Gypsum plasterboard, fire and moisture resistant |
| Softwood(Lumber) | 0.263 | Timber, Softwood | Softwood timber from spruce and pine, planed |
| Aluminium Frame | 6.83 | Aluminium extruded profile, European Mix, Inc Imports | Extruded aluminium profiles for window and door frames, generic, |
| Double Glazing | 1.63 | Glass, Glazing, Double | Insulating Glass Unit (IGU), fire-resistant ,double glazed |
| MDF | 0.856 | Timber, MDF | Medium-density fibreboard (MDF) |
| Stainless steel | 6.15 | Steel, Stainless | Door handle set |

## 4. Results

First of all, the whole life embodied carbon of the case study building is evaluated utilizing the traditional manual calculation using the ICE database and the RICS guidelines.

The case study building considered substructure components, and superstructure components including envelope and roofing. The total embodied carbon value of 1738.306 tCO$_2$e is obtained for the case study building considering the A1-A5, B4, and C1-C5 life phases. The product stage has the highest embodied carbon value of 1426.234 tCO$_2$e. The contribution of each life cycle stage in tCO$_2$e is shown in Table 4 and Figure 4 (bar graph). Figure 5 shows the contribution of each life stage in %. A1-A3 constitutes the highest share of 82%, followed by A5 with 7% and the rest of the stages B4, C1-C5, and A4 have less contribution of 4%, 4%, and 3% respectively. This result suggests that to reduce the whole-life embodied emission of buildings, materials with low product stage embodied impact should be selected. Also, recycled products can be opted for construction rather than selecting products manufactured from virgin materials.

**Table 4: Embodied Carbon at various Life stages**

| **Life Cycle Stage** | **Embodied Carbon (tCO$_2$e)** |
|---|---|
| Product stage (A1-A3) | 1426.234 |
| Construction stage (A4) | 43.914 |
| Site activities (A5) | 118.752 |
| Use (Replacement) (B4) | 75.551 |
| End-of-Life stage (C1-C5) | 73.855 |
| **Total** | **1738.306** |

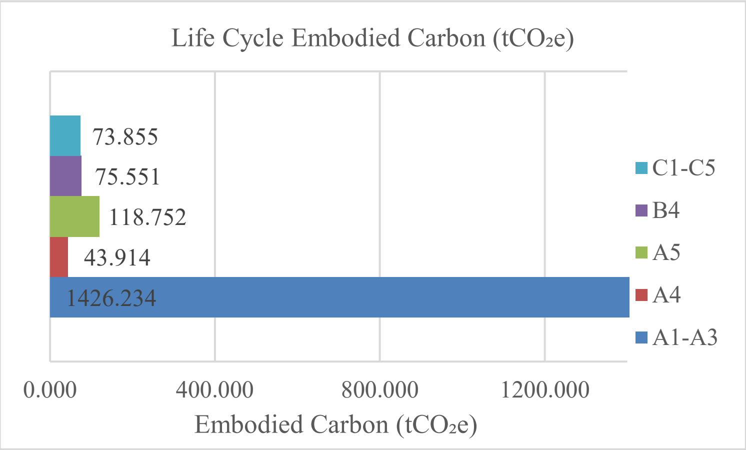

Figure 4: Embodied Carbon according to Life Cycle stage (tCO$_2$e)

Secondly, a digital tool, One Click LCA is employed to assess the embodied carbon of the same case study building. It's worth noting that while this tool has the capability to evaluate carbon emissions across the entire lifecycle, including operational emissions, in this study, only the life cycle stages from A1 to A3 are considered. This is for the purpose of better comparison between the methodologies adopted because the embodied carbon calculation in One Click LCA for life cycle stages like A4-5, C1-4, etc. require detailed information about construction and site activities, site wastage, and disposal scenarios which is unavailable in this case. For the manual calculation, the generic data are considered from RICS.

To ensure a reliable and meaningful comparison between the adopted assessment methodologies only embodied carbon emissions from A1-A3 are presented here (Table 5). The total embodied carbon of the building (A1-A3) for the manual computation using the ICE database and One Click LCA is obtained as 1426.234 tCO$_2$e and 984.48 tCO$_2$e respectively. This shows that the manual calculation utilizing the ICE database overestimated the A1-A3 embodied carbon of the case study building by 30.9% when compared to One Click LCA. Table 5 provide a side-by-side comparison of embodied carbon evaluation from both methodologies in terms of construction materials. Figure 6 provides graphical representation of embodied carbon (A1-A3) comparison of major contributing building materials for both the approaches. It is seen that a significant portion of the impacts arise from the utilization of concrete and steel in construction. Additionally, materials like aluminium, block work, brick, and glass also make substantial contributions to the overall embodied carbon. Most of the construction materials such as concrete, rebar, aluminium, brick, softwood are overestimated by ICE when compared to One Click LCA results. EPDs provide more accurate estimation of embodied carbon when the complete details of construction materials are available and used in accordance with the region of construction.

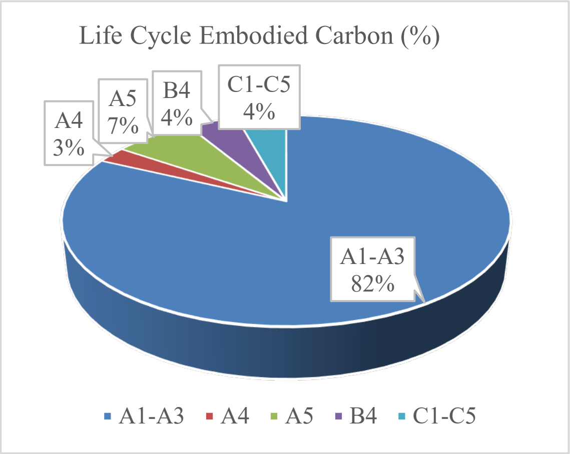

Figure 5: Embodied Carbon according to Life Cycle stage (%)

**Table 5: Embodied Carbon (A1-A3) for ICE and One Click LCA**

| **Materials** | **A1-A3 EC ICE (tCO$_2$e)** | **A1-A3 EC One Click LCA (tCO$_2$e)** |
|---|---|---|
| Concrete Cast in situ | 376.02 | 270 |

| | | |
|---|---|---|
| Rebar | 511.06 | 303 |
| Aluminium | 310.61 | 245 |
| Brick | 81.93 | 26 |
| Aerated Block work | 44.36 | 42 |
| Glazing | 34.67 | 47 |
| Plaster (Plasterboard) | 18.58 | 11 |
| Cement/sand screed | 13.70 | 25 |
| Rock Mineral Wool | 7.78 | 7.5 |
| Paint | 8.72 | 0.25 |
| Softwood | 6.31 | 0.49 |
| MDF | 3.77 | 1.7 |
| Acoustic Tile (Fiberglass) | 2.95 | 1.2 |
| Gravel | 1.17 | 0.37 |
| Expanded Polystyrene (EPS) | 2.13 | 2.1 |
| DPC | 1.79 | 1.4 |
| Door (Stainless steel) | 0.67 | 0.47 |
| **Total** | **1426.23** | **984.48** |

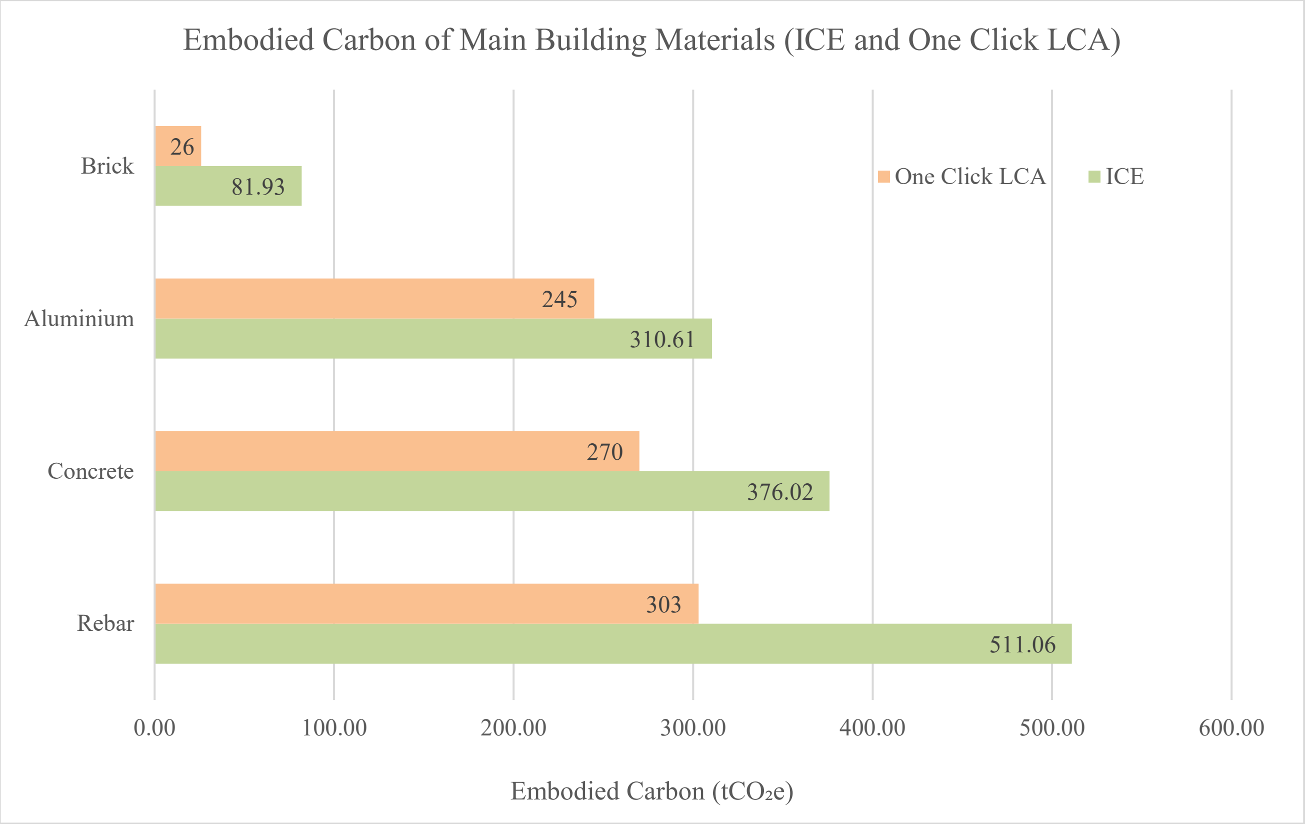

Figure 6: Embodied Carbon (A1-A3) comparison of main building materials (ICE and One Click LCA)

Even though both approaches follow the ISO 14044 principles and framework, the analysis results of the case study building in both manual (ICE) and One Click LCA show that both of the approaches can have a significant difference in embodied carbon estimation from the A1-A3 modules. This considerable difference in the embodied impact value is attributed to the fact that the ICE database gives generic carbon factors for materials specifically for the UK, while the available EPDs in One Click LCA are manufacturer-specific based on EcoInvent and GaBi databases. Some of the EPDs might not closely replicate the construction scenario of the UK, thus careful consideration should be made while choosing the available EPDs.

Furthermore, it is important to highlight several challenges encountered during the assessment of the case study building within the One Click LCA tool. Firstly, there is underlying challenge regarding data consistency and geographical coverage. Despite the extensive collection of generic data and EPDs within One Click LCA, certain materials remain unavailable for the UK region. This implies that even though this tool consists of numerous EPDs, reproducing the assessment process accurately for a specific location using solely One Click LCA is intricate. The selection of such alternative materials from another region can have a huge influence on the evaluation result and potentially lead to inaccurate prediction of carbon footprint of the building. Hence, further investigation is essential to gain a deeper comprehension of the impact of datasets on the analysis of environmental impacts related to buildings. Alongside this, there is a shortfall associated with the regular updating of data. Numerous EPDs accessible within the tool are identified as outdated, restricting the software's flexibility and reliability. Thus, it has become imperative to build an updated, complete, transparent, and region-specific database for accurate and reliable estimation of environmental impacts of buildings.

## 5. Conclusions

The aim of this research was to study the present development in the standards, guidelines, databases, and tools available for the LCA of buildings in the UK. It is observed that LCA in buildings is more developed than other scopes such as infrastructure. There has been significant progress in the reduction of operational carbon of buildings along with the advent of nearly zero buildings (nZEB). However, the embodied carbon assessment approaches need further development due to the underlying challenges associated with the LCA methodologies and digital tools. The standardization in LCA assessment methodology and transparency in methodologies adopted by the digital tools, and the inconsistent and incomplete databases regarding embodied carbon are the major challenges that are affecting the accuracy of the environmental impact evaluation of buildings.

The other aim of the study is to evaluate the whole-life embodied carbon impact of an educational building. This study considered the product stage (A1-A3), construction and site activities stage (A4-A5), use phase (B4), and end-of-life phase (C1-C5) using the popular manual approach adopting the ICE database. The total embodied carbon value of 1738.306 $tCO_2e$ is obtained for the case study building. The product stage has the highest embodied carbon share of 82% (1426.234 $tCO_2e$), while other stages A5, B4, C1-C5, and A4 consist of 7%, 4%, 4%, and 3% respectively of total embodied carbon. Given that a substantial number of studies have relied on the ICE database for their analysis, we opted to employ One Click LCA, a precise digital tool, to assess the reliability of the ICE database. Only the life cycle stages (A1-A3) are compared to ensure a meaningful comparison between the approaches as the site activities and wastage data are unavailable. The results from the manual approach utilizing ICE databases are 30.9% higher than One Click LCA, which utilizes EPDs based on EcoInvent and GaBi. Both approaches follow ISO 14044 standards for the evaluation of the environmental impacts of buildings. However, the difference in the results is due to the discrepancy in the ECF based on the respective database. Moreover, the underlying challenges in the One Click LCA tool such as the unavailability of region-specific data and lack of update of EPDs are explored.

## References

Akponeware, A. et al. (2022) ‘An integrated empirical analysis of UK rail industry’s carbon assessment: An industry perspective’, Case Studies on Transport Policy, 10(1), pp. 315–330. Available at: https://doi.org/10.1016/j.cstp.2021.12.012.

Alotaibi, B.S. et al. (2022) ‘Life Cycle Assessment of Embodied Carbon and Strategies for Decarbonization of a High-Rise Residential Building’, Buildings, 12(8). Available at: https://doi.org/10.3390/buildings12081203.

Blay-Armah, A. et al. (2022) ‘An Evaluation of the Impact of Databases on End-of-Life Embodied Carbon Estimation’, Sustainability (Switzerland), 14(4). Available at: https://doi.org/10.3390/su14042307.

Budig, M. et al. (2021) ‘Computational screening-LCA tools for early design stages’, International Journal of Architectural Computing, 19(1), pp. 6–22. Available at: https://doi.org/10.1177/1478077120947996.

BS EN 15804:2012+A2:2019; Sustainability of Construction Works-Environmental Product Declarations-Core Rules the Product Category of Construction Products. The British Standards Institution: London, UK.

BS EN 15942:2021; Sustainability of Construction Works. Environmental Product Declarations. Communication Format Business-to-Business. The British Standards Institution: London, UK, 2021.

BS EN 15978-2011. (2012) ‘Sustainability of construction works, assessment of environmental performance of buildings: calculation method’, English version. London, UK: British Standards Institution.

Cabeza, L.F. et al. (2014) ‘Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review’, Renewable and Sustainable Energy Reviews, 29, pp. 394–416. Available at: https://doi.org/10.1016/j.rser.2013.08.037.

Chen, G. et al. (2019) ‘Review on City-Level Carbon Accounting’, Environmental Science & Technology, 53(10), pp. 5545–5558. Available at: https://doi.org/10.1021/acs.est.8b07071.

Copiello, S. (2016) ‘Economic implications of the energy issue: Evidence for a positive non-linear relation between embodied energy and construction cost’, Energy and Buildings, 123, pp. 59–70. Available at: https://doi.org/10.1016/j.enbuild.2016.04.054.

Dean, B. et al. (2016) ‘Towards zero-emission efficient and resilient buildings.: Global Status Report’. Available at: https://api.semanticscholar.org/CorpusID:133588941.

Dixit, M.K. (2019) ‘Life cycle recurrent embodied energy calculation of buildings: A review’, Journal of Cleaner Production, 209, pp. 731–754. Available at: https://doi.org/10.1016/j.jclepro.2018.10.230.

Ekundayo, D. et al. (2012) ‘CARBON REVIEW AND QUALITATIVE COMPARISON OF SELECTED CARBON COUNTING TOOLS’.

Ekundayo, D. et al. (2019) ‘Life cycle carbon emissions and comparative evaluation of selected open source UK embodied carbon counting tools', Construction Economics and Building, 19(2), pp. 220–242. Available at: https://doi.org/10.5130/AJCEB.v19i2.6692.

EN 15603: 2008; Energy Performance of Buildings-Overall Energy Use and Definition of Energy Ratings. Comite Europeen de Normalisation: Brussels, Belgium, 2008.

Gelowitz, M.D.C. and McArthur, J.J. (2017) 'Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation', Journal of Cleaner Production, 157, pp. 125–133. Available at: https://doi.org/10.1016/j.jclepro.2017.04.133.

Gibbons, O.P. et al. (2022) 'How to Calculate Embodied Carbon, 2nd ed.', The Institution of Structural Engineers: London, UK.

Giordano, R., Gallina, F. and Quaglio, B. (2021) 'Analysis and assessment of the building life cycle. Indicators and tools for the early design stage', Sustainability (Switzerland), 13(11). Available at: https://doi.org/10.3390/su13116467.

Hollberg, A. and Ruth, J. (2016) 'LCA in architectural design—a parametric approach', The International Journal of Life Cycle Assessment, 21(7), pp. 943–960. Available at: https://doi.org/10.1007/s11367-016-1065-1.

Intergovernmental Panel on Climate Change (IPCC) (2021) 'Global Warming of 1.5 °C', Available at: https://www.ipcc.ch/2022/05/05/ipcc-wgi-final-report-materials-online/ (Accessed: 19 July 2023)

ISO (2006a) ISO 14025:2006, ISO. Available at: https://www.iso.org/standard/38131.html.

ISO (2006b) ISO 14040:2006, ISO. Available at: https://www.iso.org/standard/37456.html.

ISO - International Organization for Standardization (2014) ISO 14044:2006, ISO. Available at: https://www.iso.org/standard/38498.html.

Jones, G.H.C. (2019) Embodied Carbon — The ICE Database. Available at: https://circularecology.com/embodied-carbon-footprint-database.html

Keyhani, M. et al. (2023) 'Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources', Sustainability, 15(6), p. 5115. Available at: https://doi.org/10.3390/su15065115.

Khan, S.A. et al. (2022) 'Life Cycle Assessment of Embodied Carbon in Buildings: Background, Approaches and Advancements', Buildings, 12(11), p. 1944. Available at: https://doi.org/10.3390/buildings12111944.

Lasvaux, S. et al. (2013) 'Towards a new generation of building LCA tools adapted to the building design process and to the user needs', Conference: Proceedings of the International Conference on Sustainable Buildings, Construction products and Technologies (SB13), Graz [Preprint].

Life cycle assessment software for Infrastructure | One Click LCA (2023) One Click LCA® software. Available at: https://www.oneclicklca.com/construction/infrastructure-life-cycle-assessment/.

Luo, Z., Yang, L. and Liu, J. (2016) 'Embodied carbon emissions of office building: A case study of China's 78 office buildings', Building and Environment, 95, pp. 365–371. Available at: https://doi.org/10.1016/j.buildenv.2015.09.018.

Meex, E. et al. (2018) 'Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design', Building and Environment, 133, pp. 228–236. Available at: https://doi.org/10.1016/j.buildenv.2018.02.016.

Mohebbi, G. et al. (2021) 'The role of embodied carbon databases in the accuracy of life cycle assessment (LCA) calculations for the embodied carbon of buildings', Sustainability (Switzerland), 13(14). Available at: https://doi.org/10.3390/su13147988.

Müller, L.J. et al. (2020) 'A Guideline for Life Cycle Assessment of Carbon Capture and Utilization', Frontiers in Energy Research, 8. Available at: https://doi.org/10.3389/fenrg.2020.00015.

Nair, G., Fransson, Å. and Olofsson, T. (2021) 'Perspectives of building professionals on the use of LCA tools in Swedish climate declaration', in E3S Web of Conferences. EDP Sciences. Available at: https://doi.org/10.1051/e3sconf/202124613004.

Nawarathna, A. et al. (2018) 'ESTIMATING EMBODIED CARBON EMISSIONS OF BUILDINGS IN DEVELOPING COUNTRIES: A CASE STUDY FROM SRI LANKA', in International Sustainable Ecological Engineering Design for Society (SEEDS) Conference. Dublin Institute of Technology, Dublin, Ireland. Available at: https://www.researchgate.net/publication/327573267.

Net Zero Carbon Buildings: A Framework Definition (2019) UKGBC. Available at: https://ukgbc.org/resources/net-zero-carbon-buildings-a-framework-definition/.

Onat, N.C. and Kucukvar, M. (2020) 'Carbon footprint of construction industry: A global review and supply chain analysis', Renewable and Sustainable Energy Reviews, 124, p. 109783. Available at: https://doi.org/10.1016/j.rser.2020.109783.

Pan, W. and Teng, Y. (2021) 'A systematic investigation into the methodological variables of embodied carbon assessment of buildings', Renewable and Sustainable Energy Reviews. Elsevier Ltd. Available at: https://doi.org/10.1016/j.rser.2021.110840.

Papakosta, A. and Sturgis, S. (2017) 'Whole life carbon assessment for the built environment. In RICS Professional Standards and Guidance', Royal Institution of Chartered Surveyors: London, UK.

Peereboom, E.C. et al. (1998) 'Influence of Inventory Data Sets on Life-Cycle Assessment Results: A Case Study on PVC', Journal of Industrial Ecology, 2(3), pp. 109–130. Available at: https://doi.org/10.1162/jiec.1998.2.3.109.

Prideaux, F. et al. (2022) 'A review of embodied life cycle assessment tools used to support the building design process', in IOP Conference Series: Earth and Environmental Science. Institute of Physics. Available at: https://doi.org/10.1088/1755-1315/1122/1/012031.

Reference guide Net Waste Tool Guide to Reference Data, Version 1.0 (2008).

Röck, M. et al. (2018) 'LCA and BIM: Visualization of environmental potentials in building construction at early design stages', Building and Environment, 140, pp. 153–161. Available at: https://doi.org/10.1016/j.buildenv.2018.05.006.

Safari, K. and AzariJafari, H. (2021) 'Challenges and opportunities for integrating BIM and LCA: methodological choices and framework development', Sustainable Cities and Society, p. 102728. Available at: https://doi.org/10.1016/j.scs.2021.102728.

Verbeeck, G. and Hens, H. (2010) 'Life cycle inventory of buildings: A calculation method', Building and Environment, 45(4), pp. 1037–1041. Available at: https://doi.org/10.1016/j.buildenv.2009.10.012.

Webster, M. et al. (2020) 'Achieving Net Zero Embodied Carbon in Structural Materials by 2050'. Available at: https://doi.org/10.13140/RG.2.2.28440.14085.

Yan, J., Lu, Q., Tang, J., et al. (2022) 'Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes', Buildings. MDPI. Available at: https://doi.org/10.3390/buildings12081097.

Zhang, X. and Wang, F. (2017) 'Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China', Energy and Buildings, 155, pp. 404–413. Available at: https://doi.org/10.1016/j.enbuild.2017.09.049.