Whole life embodied carbon assessment and reduction in UK buildings

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Whole Life Embodied Carbon Assessment and Reduction in UK Buildings

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Abstract

The UK aims to reduce greenhouse gas (GHG) emissions by 68% by 2030 and achieve net zero by 2050, necessitating urgent reductions in carbon emissions from the building sector, which accounts for 39% of energy-related emissions. This research focuses on assessing and mitigating embodied carbon (EC) in residential, educational, and hotel buildings in the UK using Life Cycle Assessment (LCA) across the entire building lifecycle to support net-zero targets. The study evaluates EC from raw material extraction to end-of-life disposal (modules A1-A5, B2-B4, and C1-C4), addressing critical gaps in current EC assessment methodologies. This study also examines EC savings from current end-of-life strategies in existing UK buildings and their impact on new constructions. As Module A accounts for the highest EC in the case studies, the majority of reduction strategies should focus on this stage.

To enhance accuracy and efficiency, this research integrates Building Information Modelling (BIM) with LCA using Dynamo and Python scripting, enabling automated EC assessment. Dynamo was used to connect the LCA database with Autodesk Revit, creating a smooth link between them. Then, Python scripting was used to automate the EC assessment by organizing and processing the data from the LCA database, making the process faster and more efficient. The study identifies discrepancies between traditional manual assessments and automated approaches, refining methodologies to improve reliability. Additionally, the research explores EC reduction strategies, including the use of low-carbon materials and sustainable design interventions such as green roofing systems, to minimize carbon emissions across different buildings.

The findings demonstrated the accuracy and reliability of the automated method by comparing its results with the traditional manual approach. The automated approach was validated through two case studies: an educational building and a hotel, where the results demonstrated over 98%

alignment between the manual and automated methods, with discrepancies consistently below 2%, confirming the reliability of the automation approach. In the educational building, the largest discrepancies, though relatively small, were observed in the ceiling during A5w and C2 (0.77% and 0.74%, respectively), the column during A5w (1.72%), and the foundation during A5w (0.69%). For the hotel building, the most notable differences occurred in windows during B4 (0.78%), doors during B4 (0.75%), ceilings during A4, C2, and C3-C4 (0.72%, 0.67%, and 0.72%, respectively), and foundations during A5w (0.62%). Additionally, the automated method reduced EC assessment time from over 200 hours in manual calculations to just minutes, highlighting its practicality for industry adoption.

The most impactful strategy for reducing EC emissions involves incorporating Ground Granulated Blast Furnace Slag (GGBS) as a replacement for cement. This approach has the potential to achieve a substantial reduction in the EC of concrete within the buildings under investigation, ranging from 60% to 70%. The study reveals that specification strategy can lead to significant Whole Life Embodied Carbon (WLEC) reductions, with the residential building achieving a 22.53% reduction, the college building a 35.17% reduction and the hotel building a reduction of 17.72%.

Table of Contents

List of Figures

List of Tables

List of Acronyms

BEIS	Business, Energy, and Industrial Strategy
BIM	Building Information Modelling
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EC	Embodied Carbon
EPD	Environmental Product Declaration
EU	European Union
GABC	Global Alliance for Buildings and Construction
GBCT	Global Buildings Climate Tracker
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LETI	London Energy Transformation Initiative
OC	Operational Carbon
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors

SDG	Sustainable Development Goal
NDC	Nationally Determined Contribution
N_2O	Nitrous Oxide
nZEBs	nearly Zero Energy Buildings
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
WLC	Whole Life Carbon
WLEC	Whole Life Embodied Carbon

List of Published Papers

Keyhani, M., Abbaspour, A., Bahadori-Jahromi, A., Mylona, A., Janbey, A., Godfrey, P. and Zhang, H. (2023) 'Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources', Sustainability (Basel, Switzerland), 15(6), pp. 5115. Available at: doi: 10.3390/su15065115.

Keyhani, M., Bahadori-Jahromi, A., Mylona, A. and Godfrey, P. (2023) ‘Discrepancy in Embodied Carbon Calculations for Concrete Materials’, Springer Publishing Partner.

Keyhani, M. & Bahadori-Jahromi, A. & Mylona, A. & Janbey, A. & Godfrey, P. B. & Taşeli, B., (2023) ‘Measuring and mitigating embodied carbon in educational buildings: A case study in the UK’, Engineering Future Sustainability 1(2). doi: https://doi.org/10.36828/efs.220

Chaudhary, D. & Bahadori-Jahromi, A. & **Keyhani, M**., (2023) ‘Use of Digital Analysis Methods in Determination of Embodied Carbon of Buildings in the UK’, Engineering Future Sustainability 1(2). doi: https://doi.org/10.36828/efs.236

Keyhani, M., Bahadori-Jahromi, A., Godfrey, P., Keihani, R. and Amirkhani, S. (2024) 'Analysing carbon impacts of green roof at Hilton Watford: life-cycle assessment approach', Proceedings of the Institution of Civil Engineers. Waste and resource management, 177(4), pp. 183–195. Available at: doi: 10.1680/jwarm.23.00037.

Keyhani, M., Bahadori-Jahromi, A., Fu, C., Godfrey, P. & Zhang, H. (2024) ‘Whole-Life Embodied Carbon Reduction Strategies in UK Buildings: A Comprehensive Analysis’, Energy Science & Engineering, 12, pp. 5370–5384. Available at: https://doi.org/10.1002/ese3.1958

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List of Under review Papers

Keyhani, M., Bahadori-Jahromi, A., Fu, C. & Godfrey. (2025) ‘Automating Whole Life Embodied Carbon Assessments: Integrating BIM and LCA with Python’, Computing in Civil Engineering.

Chapter 1 : Introduction

1.1 Background

In recent years, there has been a considerable rise in worldwide awareness of global warming and climate change resulting from GHG emissions (Pachauri and Meyer, 2015).

GHG emissions are gases released into the atmosphere, like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases, and water vapour, contributing to the greenhouse effect. Mainly from human activities, these emissions impact climate by altering Earth's energy balance. Monitoring and reducing GHG emissions are crucial for addressing climate change and promoting environmental sustainability.

The United Nations in 2015 introduced The Sustainable Development Goals (SDGs) which are a set of 17 global goals as part of the 2030 Agenda for Sustainable Development. These goals are designed to address a wide range of global challenges and promote sustainable development across economic, social, and environmental dimensions. Among these goals, goal 13 specifically focuses on "Climate Action". The goal aims to take urgent action to combat climate change and reduce GHG emissions to limit global warming to 1.5°C (United Nations, 2015). This 1.5°C target refers to limiting the rise in global average temperature to no more than 1.5°C above pre-industrial levels (typically the 1850–1900 baseline), as set by the Intergovernmental Panel on Climate Change (IPCC). This goal is to be achieved by the end of the century (2100) to reduce the risk of severe climate impacts.

In 2016, with a commitment toward achieving Goal 13, a synthesis report was conducted to evaluate the impact of 161 intended nationally determined contributions (INDCs). This report provides estimates of GHG emission levels anticipated in 2025 and 2030 as a result of the implementation of these INDCs. Figure 1.1 shows a comparison between the NDCs scenario and two other scenarios: (1) the actions communicated by Parties before the NDS scenario and (2) the scenario aiming to keep the average global temperature rise below 1.5 ºC. The graph highlights a significant discrepancy between the NDC scenario and the 1.5°C scenario for both 2025 and 2030. This underscores the necessity for heightened efforts to align with the goal of limiting global warming (United Nations, 2016).

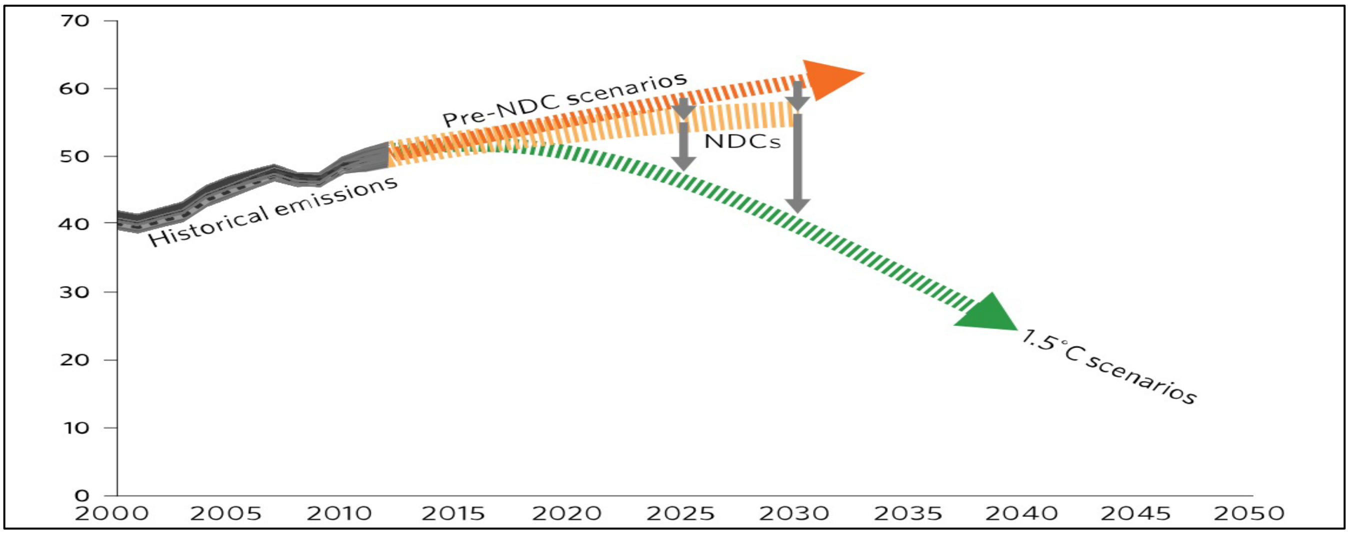


Figure 1.1: GHG emission levels resulting from the implementation of current NDCs and under other scenarios (gigatons of equivalent CO_2 per year)

Addressing climate change and its environmental consequences has emerged as one of the most pressing challenges of contemporary society (Fenner et al., 2018). This issue not only threatens ecosystems and biodiversity but also poses significant risks to human health, economic stability, and global security. As a result, most modern sustainable strategies are deeply tied to the overarching goal of reducing GHG emissions, recognizing their central role in driving global warming and climate disruption. According to the report of the IPCC, global GHG emissions should be reduced by 45% by 2030 compared to 2010 (Chen et al., 2020; Xu et al., 2021). This target is crucial to limit global warming to no more than 1.5°C, as outlined in the Paris Agreement. Adopted at COP21, the Paris Agreement is a legally binding international treaty in which nearly 200 countries pledged to keep global temperature rise well below 2°C and ideally to 1.5°C, above pre-industrial levels.

The UK's Sixth Carbon Budget necessitates an ambitious 78% reduction in GHG emissions by the year 2035, compared to the baseline 1990 levels (Committee on Climate Change, 2020), in order to achieve the goal of reaching net zero emissions by 2050. Additionally, at COP26, which was held in Glasgow in 2021, the UK Government pledged to reduce greenhouse gas emissions by 68% by 2030 compared to 1990 levels (United Nations, 2022). COP26 marked a critical milestone in global climate negotiations, where countries strengthened their climate targets, committed to phasing down coal, and increased climate finance to support the implementation of the Paris Agreement.

The 2023 Global Sustainable Development Report highlights that progress towards the majority of the SDGs remains either moderately close to or significantly behind the targets set for 2030. Among the goals, Goal 13, which emphasizes Climate Action, stands out as one of the most lagging areas. The report underscores a considerable gap in achieving the 2030 ambitions for this goal, reflecting insufficient advancements in reducing GHG emissions, enhancing climate resilience, and implementing effective adaptation strategies. This shortfall signals an urgent need for accelerated global efforts, stronger policy measures, and enhanced international collaboration to address the challenges of climate change and fulfil the commitments outlined in the SDG framework (United Nations, 2023).

The most recent synthesis report on nationally determined contributions (NDC) by the United Nations Framework Convention on Climate Change (UNFCCC) reveals that the collective climate commitments from 193 Parties under the Paris Agreement will result in a reduction of 0.3 per cent in GHG emissions by 2030, in comparison to 2019 levels. However, this falls well short of the 45 per cent emissions reduction called for by the IPCC to be on the 1.5°C pathway and would propel the world to an unsustainable potential warming of around 2.5°C by the end of the century (United Nations, 2023).

GHG emissions are quantified in million tonnes of carbon dioxide equivalent (Mt CO_2e), a standardized unit that accounts for the seven main GHGs. This metric considers each gas's global warming potential (GWP), allowing for a comparison of their relative impact on global warming over a specific timeframe. For instance, methane (CH4) and nitrous oxide (N_2O) are assigned higher GWPs than CO_2 due to their greater heat-trapping ability, even in smaller quantities.

Figure 1.2 presents the GHG emissions in the UK from 1990 to 2021, highlighting trends and changes over time. CO_2 dominates GHG emissions, comprising an average of 80% of total emissions during the years 2017 to 2021. As such, fluctuations in CO_2 emissions are often mirrored in overall GHG emission trends. This underscores the importance of accurately measuring and mitigating CO_2 emissions to ensure effective climate action and compliance with reduction targets. These insights are particularly relevant for developing and implementing policies aimed at achieving the UK’s net-zero goals. (Climate Change, 2023).

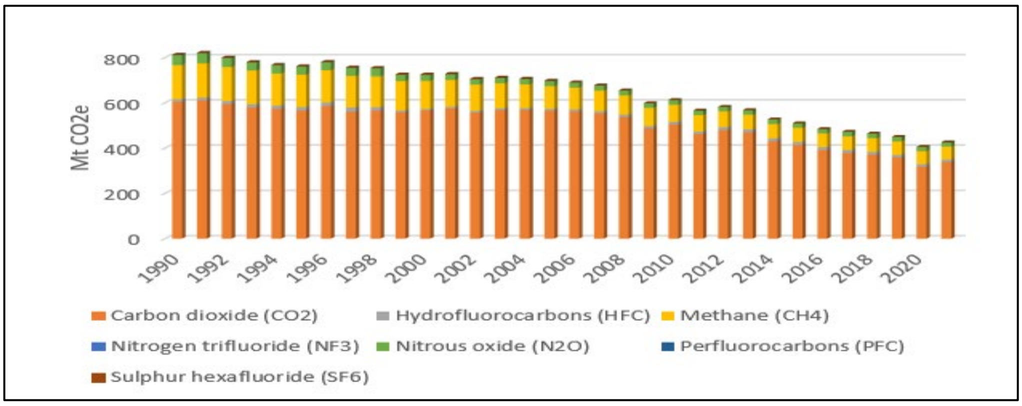


Figure 1.2: UK greenhouse gas emissions national statistics: 1990 to 2021 reproduced from the Department for Business, Energy & Industrial Strategy (Climate change, 2023)

The Paris Agreement (COP21), which was adopted by all the parties in December 2015, aims to limit the harmful effects of global warming by reducing GHG emissions (Papakosta and Sturgis, 2017). Therefore, lowering carbon emissions, as one of the most essential and significant parts of GHG from buildings, is a crucial and necessary goal of government climate policy (Moussavi Nadoushani and Akbarnezhad, 2015).

After the Paris Agreement in 2015, the European Union (EU) established its own comprehensive plan and released the European Green Deal in December 2019, which outlines a thorough and far-reaching transformation for both EU member states and nations that engage in trade with the EU. The EU has set ambitious goals, including lowering carbon emissions in Europe by 55%

from 1990 levels by the year 2030. The ultimate objective of the EU is to become the world's first carbon-neutral continent by the year 2050. This commitment is further demonstrated by the "Fit for 55" program, which was introduced in July 2021 in alignment with this overarching objective. In the long run, the EU’s target is to achieve net zero GHG emissions by the year 2050, as highlighted by the European Commission in 2023.

United Nations Environment Program (UNEP), International Energy Agency (IEA), and Global Alliance for Buildings and Construction (GABC) reports indicate that building construction and operations account for 39% of energy-related GHG emissions (Dean et al., 2016). According to UNEP, the building industry should cut GHG emissions in both developing and developed nations (Asensio and Delmas, 2017). Given the potential negative effects of climate change (Li et al., 2017), the building sector should provide environmentally friendly structures to reduce GHG emissions (Zhang and Li, 2022). Since carbon emissions are an important factor in GHG emissions, it is imperative that prompt action be taken to reduce these emissions (Keyhani et al., 2023). It can be achieved by providing environmentally friendly structures to reduce these emissions (Zhang and Li, 2022).

The IPCC has firmly concluded that achieving net-zero carbon emissions by the year 2050 is absolutely essential to limit global warming to 1.5°C (Webster et al., 2020). The Global Buildings Climate Tracker (GBCT), which monitors decarbonisation progress in the buildings sector, has been tracking changes and advancements in this area starting from 2015 (Figure 1.3). For this purpose, the decarbonisation status was set at 0 for the base year of 2015, serving as a reference point for all subsequent measurements and evaluations. The target value for the year 2050 has been defined as 100, representing the maximum level of decarbonisation that is deemed necessary to be achieved in the buildings sector to align with climate goals (United Nations Environment Programme, 2022).

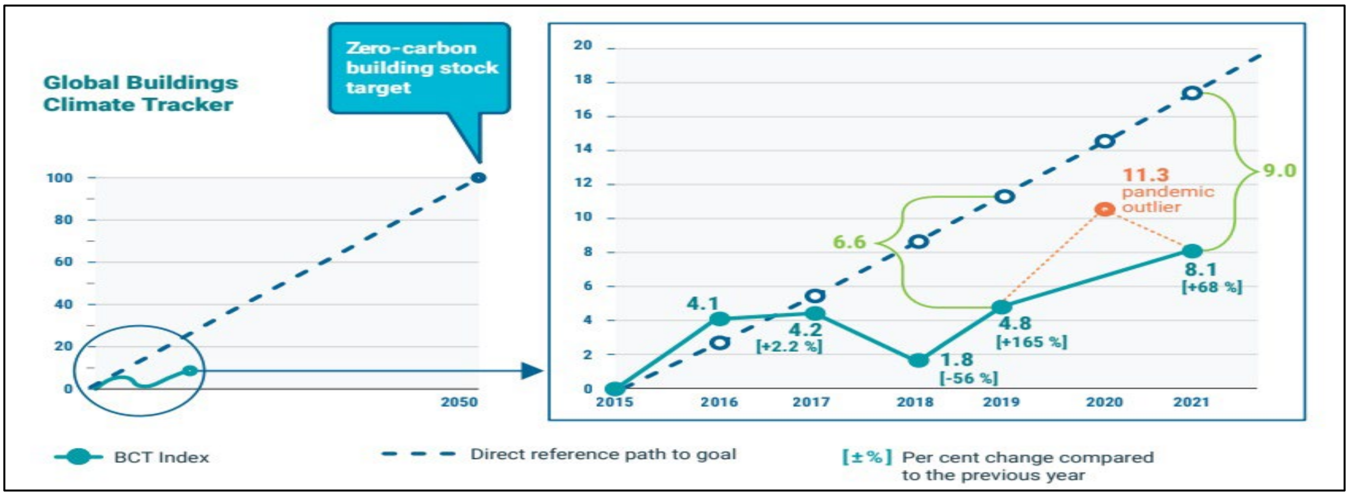


Figure 1.3: Decarbonisation progress in the buildings sector (United Nations Environment Programme, 2022)

In 2020, the GBCT index moved closer to the reference path, as indicated by the orange dashed line that appears to approach the blue line. This shift primarily stems from a notable economic slowdown, particularly affecting sectors like construction, along with the restricted utilization of non-residential spaces, such as offices, due to the challenges and disruptions posed by the COVID-19 pandemic. However, as this situation could give a misleading or false positive impression of decarbonisation being “on track,” the 2020 observation is treated as an outlier in the overall analysis. In reality, the progress of buildings’ decarbonisation is slowing down significantly, and the decarbonisation gap continues to grow, indicating an increasing departure from the required path. Even though the GBCT index improved by 68% from 2019 to 2021, it's now farther from the goal of a zero-carbon building stock. In 2019, the gap between the two lines was 6.6, but by 2021, it increased to 9.0. This means we're moving away from the target of having buildings with zero carbon emissions (United Nations Environment Programme, 2022). Therefore, further actions are required to get back on track and reach zero-carbon buildings by 2050.

Carbon emissions are incurred in all stages of a building's life cycle and are generally categorised into operational carbon (OC) and embodied carbon (EC) (Akbarnezhad and Xiao, 2017).

For the first time, the United Nations Framework Convention on Climate Change (UNFCCC) negotiations officially acknowledged the critical role of embodied carbon. The Sharm el-Sheikh Mitigation Ambition and Implementation Work Programme emphasized strategies such as reducing OC emissions, designing energy-efficient building envelopes, and notably, minimizing EC emissions (World Green Building Council, 2025).

With enhanced energy efficiency, the decarbonization of grid electricity, and the increased use of materials in buildings (such as thicker insulation, double-glazing, and additional technologies) to improve thermal performance and reduce operational energy demands (Salem et al., 2020), EC has emerged as a significant contributor to the ongoing environmental impacts of the built environment (Vickers et al., 2021; Teng and Pan, 2020; Schmidt, Crawford, and Warren-Myers, 2020). This shift means that EC can now represent a higher proportion of Whole Life Carbon (WLC) than it did in the past, highlighting its growing importance in sustainability assessments and climate mitigation strategies (Keyhani et al., 2023).

According to current building regulations, for a typical residential building, OC contributes as much as 67% of emissions, while 33% of emissions are attributed to EC. However, in the case of ultra-low-energy buildings, the contribution of OC can be reduced to as low as 23%, with 77% of emissions resulting from EC (London Energy Transformation Initiative, 2020).

Nowadays, the challenge for the profession is to expand excellent practice to all future work, as highlighted by the WorldGBC’s report on net zero EC (Adams, Burrows and Richardson, 2019).

The Royal Institute of British Architects (RIBA) joined the global ‘declare’ movement in June 2019 and has set RIBA Chartered Practices to achieve EC reduction of < 540 $kgCO_2e/m^2$ for non-domestic buildings and < 625 $kgCO_2e/m^2$ for domestic buildings by 2030 (minimum 40% reduction in EC compared to the current business as usual benchmarks) (Royal Institute of British Architects, 2021).

EC encompasses emissions that are generated throughout the entire life cycle of a building, including emissions arising from the production, construction, use, and end-of-life stages of buildings. A significant portion of the structural EC is concentrated in the production phase, which occurs before the building is occupied. Since these emissions will be released prior to 2050, the target year for achieving net-zero emissions, it is imperative to focus on reducing them as quickly as possible. EC assessment in buildings is commonly conducted manually; however, the challenges and limitations associated with manual data handling, such as time constraints and potential errors, underscore the increasing appeal of automated solutions (Tam et al., 2023; Guignone et al., 2023). Automated methods play a crucial role in facilitating EC assessment during the design stage by drastically reducing the time, effort, and resources required for accurate evaluations.

Studies have consistently shown that the end-of-life stage contributes relatively little to carbon emissions compared to other phases of the life cycle (Pan and Teng, 2021), making it of less importance.

Nonetheless, it is crucial to highlight that adopting different strategies, such as reusing and recycling materials instead of disposing of them in landfills, can substantially reduce EC during the production stage, particularly for materials with high carbon intensity, such as steel (Santero, Loijos, and Ochsendorf, 2013). These strategies not only mitigate the environmental impact but also contribute to the sustainable use of resources. Therefore, the end-of-life stage also holds significant importance, as it plays a vital role in determining the overall carbon footprint of materials, and more research is required for accurately calculating the EC during this phase to develop more effective and sustainable practices.

One of the particularly challenging parts of EC assessment is the calculation of carbon emissions during the use stage of a building. This stage involves the carbon emitted throughout the building's lifecycle and is associated with activities such as repair, replacement, refurbishment, and maintenance of various components within the structure. There is not much existing research specifically addressing this stage, primarily because of its inherent complexity. Predictions related to repair and replacement cycles are especially difficult and can often be very subjective. Within a building, each individual component has its own unique lifespan. For instance, roofing materials and window units possess significantly different lifespans and repair cycles (Hu and Esram, 2021). Consequently, this variability makes it particularly hard to calculate the EC in this stage with accuracy.

Module D covers the potential loads and benefits that arise from reusing or recycling materials and components at their end of life, or from any energy that can be recovered from them at the end of their lifecycle (e.g., energy derived from waste, incineration processes, or the utilization of captured landfill gas). What is modelled within Module D is therefore directly connected to the specific end-of-life routes accounted for in Module C and must be aligned with them to maintain consistency (Sturgis et al., 2023). Consequently, the inclusion of Module D is essential as it provides a more comprehensive and holistic perspective on EC within building materials.

The aim of this research is to critically examine the Whole-Life Embodied Carbon (WLEC) emissions of both domestic and non-domestic buildings, thoroughly identifying the stages and materials with the highest EC potential. Furthermore, this study aims to enable a more efficient and swift assessment of WLEC emissions by introducing an innovative and practical approach for automating WLEC calculations in buildings. Through the effective automation of WLEC assessments, elements with the highest EC can be accurately detected early in the design phase, thereby facilitating the evaluation and promotion of practices and strategies that reduce EC and ultimately support the broader and essential goal of achieving net-zero carbon emissions in the built environment.

1.2 Identified Knowledge Gap

In the context of this research, a comprehensive literature review was undertaken to recognize the gaps in the literature, which are described in the following:

- No extensive studies have been performed on the WLEC emissions of buildings in the UK. Typically, analyses focus on EC during module A or C.
- No research study has been conducted to investigate the discrepancy in EC between treating building materials as singular entities and examining them in terms of their component parts.
- There is no comprehensive life cycle carbon assessment that analyses the carbon savings resulting from the implementation of green roofs in buildings.
- There is currently no research on automating WLEC assessments for UK buildings using Python.

1.3 Aims and Objectives

The primary goal of this research is to accurately assess the WLEC in buildings and to streamline and accelerate the process by automating the integration of LCA with BIM. This integration helps identify the primary sources of high EC early in the design stage. In addition, this research aims to develop effective strategies to reduce the EC of buildings early in design stage. The goal is to identify and propose mitigation approaches applicable to both new construction and existing buildings. In order to achieve these goals, the following objectives are employed:

I. Establishing a precise and comprehensive database for accurately assessing the EC of buildings in the UK.
II. To generate accurate material quantity data for Hotel, Educational, and Residential buildings as a basis for EC assessment.
III. Assess and understand the operational carbon (OC) performance of the case study buildings through energy performance analysis.
IV. EC assessment of the buildings during Product (A1-A3), Construction (A4-A5), Use (B2-B4) and end-of-life (C1-C4) and module D of the buildings.

V. Develop an automated workflow for EC assessment in UK buildings, improving efficiency and accuracy through digital solutions.
VI. Identifying high EC components in UK buildings by applying a color-coding system that highlights components based on their EC potential.
VII. Developing diverse strategies to reduce EC for different building types contributes to achieving the goal of constructing net-zero carbon buildings.

The findings of this research can be applied to other cases across the UK, enabling automated EC assessments, identifying building components with high EC, and supporting reductions in EC within the building industry early in the design stage.

1.4 Motivation and Research Questions

The urgent global challenge of climate change necessitates a focused investigation into the building sector's role in contributing to EC emissions. With the escalating awareness of global warming and the significant impact of GHG emissions, particularly from the building sector, there is a critical need to deepen the understanding and develop effective strategies for achieving net-zero carbon emissions in the built environment. This research is motivated by the critical need to comprehensively understand emissions at every stage of a building's life during the design stage of buildings. While numerous studies have thoroughly evaluated carbon emissions in buildings, there still remains a gap in research that systematically and holistically automates the EC assessment at all stages of the building lifecycle in order to make EC assessment at the early design stage both feasible and practical. By effectively addressing these research gaps, this study seeks to provide valuable insights into reducing carbon emissions across various life stages, thereby contributing to the broader and essential goal of constructing net-zero carbon buildings. This aligns with global and local climate objectives and emphasizes the potential for significant reductions in the carbon emissions associated with building practices.

The research questions are as follows:

I. What is the discrepancy in EC between treating building materials as singular entities and analysing them based on their individual component parts?

II. Which element and life cycle stage of buildings have the greatest impact on reducing EC?

III. What effect will building's maintenance, repair and replacement have on EC?

IV. What is the variation in results between traditional and automated EC assessments?

V. How much can automating the EC assessment speed up the analysis?

1.5 Delimitations and Selection of case-studies

This research is centred on the assessment and mitigation of EC emissions in the building sector, particularly emphasising three key building types: residential, commercial, and educational buildings. In this manner, comprehension of EC across a diverse range of buildings in the UK is enhanced.

Some assumptions that should be considered within the project are as follows:

- In the absence of specific information regarding scenarios on the end-of-life phase of the building materials, the default assumption as outlined in the RICS guideline should be carefully considered (Papakosta and Sturgis, 2017).
- In the absence of carbon factor data for a material or procedure, a default value will be used.
- In the absence of project-specific information, default distances for transportation will be used.

The study is specifically delimited to include detached residential buildings, hotel buildings, and college buildings. The choice to limit the scope to these particular categories is primarily driven by two key reasons. One important reason is the recognition of their significant and measurable contributions to EC emissions. The other reason is the availability and accessibility of the necessary data required for conducting the assessment. This essential data includes, but is not limited to, detailed architectural plans, construction material specifications, and energy usage records, which are vital for ensuring the accuracy and reliability of the analysis.

Studies have shown that EC can contribute 9–80% of a residential building's total lifecycle emissions (Chastas *et al.,* 2018). In highly efficient buildings, such as nearly zero energy buildings (nZEBs), that range is much higher, from 74% to 100% (Robati *et al.,* 2021).

In addition, research conducted by (Drewniok *et al.,* 2023) revealed that within the residential building category, detached buildings stand out as significant contributors to EC emissions.

Additionally, around 18% of the UK's total carbon emissions come from commercial buildings (Roche, 2024). Within this sector, hospitality contributes significantly to global emissions, amounting to 15 percent of the total. The imperative to mitigate carbon emissions in hotel buildings is underscored by the findings in the report titled "The Business Case for Sustainable Hotels" (Dickinson, 2023). The report presents compelling evidence, revealing that hotels specifically account for approximately 21 percent of the industry's total emissions. These statistics emphasize the substantial environmental impact of hotel on carbon emissions. Therefore, the mitigation of carbon emissions in hotel buildings becomes crucial as part of a broader effort to address and reduce the overall carbon emissions associated with the hospitality industry.

A major analysis of the carbon emissions of universities and further education colleges has revealed that they emitted more than 18 million tonnes of carbon dioxide equivalent (CO_2e) into the environment in 2020/21, which represents around 2.3% of the UK's overall carbon footprint (Priestley Centre for Climate Futures, 2023). To justify the selection of the mentioned buildings as the case study for the research, it is also important to note that the buildings were chosen due to the availability of comprehensive data necessary for the study. This data includes, but is not limited to, detailed architectural plans and energy usage records. Unfortunately, obtaining necessary data for the assessments is typically challenging due to confidentiality concerns.

However, since it is collaborative research with Hilton and The London College, access to all essential data has been granted.

The three cases examined in this research serve as representative examples of typical UK building stock and are as follows:

Case Study 1- A typical detached residential building in the UK

One of the case studies is a double story detached structure featuring a timber truss roof, concrete block walls, and air-filled double-glazed windows, with a total area of 145.86 m². It represents a typical residential building design commonly found in the UK, characterized by a pitched roof. This type of roofing provides effective rainwater drainage, ensuring durability and functionality in the region's climate.

Case Study 2- A typical educational building in the UK

As a case study, this research also used The London College, which is a large, detached educational building. This particular building is coated in distinctive red bricks and features double-glazed windows of a dark brown colour, adding to its aesthetic appeal. The total floor area of the building is approximately 2500 m², and it is constructed across three levels. The ground floor level accommodates various functional areas such as the kitchen, café, library, offices, and reception. The first floor is designed to accommodate staff rooms and classrooms, providing a suitable environment for teaching and administrative purposes. Finally, the second floor includes specialized spaces such as labs, along with additional classrooms and offices, catering to the diverse educational and operational needs of the institution.

Case Study 3- A typical hotel building in the UK

Within the scope of the research, the Hilton Watford, originally constructed during the 1970s, was chosen as the focus. The total floor area of this building is approximately 11,843 m², and it is designed with four levels in total. The lower ground floor level houses key functional spaces such as the kitchen, restaurant, and bar, along with meeting rooms and a spacious function room. The upper ground floor level serves as the main entrance area and accommodates spaces like the reception and lounge area, several conference rooms, and a portion of the guest rooms. The hotel comprises a total of 202 guest rooms, which are distributed across the upper ground floor, first floor, and second floor. The external walls of the building are constructed using cavity brickwork, and in some sections, asbestos has been used as a facade material, reflecting construction practices of the time.

1.5.1 Thesis outline and chapter layout

Chapter 1. Introduction

This chapter elaborates on the growing awareness of climate change, which is predominantly driven by GHG emissions, particularly those originating from buildings, and emphasizes the pressing need to reduce carbon emissions throughout the entire building lifecycle. It further outlines the research objectives aimed at comprehensively assessing and mitigating EC in residential, educational, and hotel buildings across the UK. By addressing existing gaps in understanding, the chapter proposes actionable strategies for achieving net-zero carbon buildings, providing a pathway toward sustainability and climate resilience.

Chapter 2. Literature Review

This chapter reviews existing literature to address the study's research questions and objectives, focusing on LCA as a tool for evaluating environmental impacts in the construction sector. It highlights the shift from OC to EC due to advancements in energy efficiency and renewable energy adoption. EC assessment methods, discrepancies in databases, and the impact of materials such as concrete are examined. Additionally, the importance of integrating BIM and LCA for EC evaluations during the design stage is highlighted. It categorizes BIM-LCA integration approaches based on data exchange and automation, analysing their advantages and limitations. The chapter also explores strategies for reducing EC across residential, educational, and hotel buildings, emphasizing the importance of the end-of-life phase in overall EC impacts. By addressing gaps in understanding and proposing innovative EC reduction methods, the chapter supports sustainable practices and net-zero carbon goals in the construction industry.

Chapter 3. Methodology

The Methodology chapter outlines the research paradigm, research design, strategy and specific means of data collection and analysis used in this research. Revit is utilised to initially create the baseline models and gives us the quantity of materials used in the building. EC analysis of all stages of the building’s life (A-C) as well as EC emissions outside the scope of buildings’ life (D) using LCA are explained. Whenever feasible, OC assessments are conducted using insights from the case studies to enhance comprehension of how carbon reduction strategies affect the overall carbon emissions of the buildings. In addition, the methodology employs traditional (Type I) and automated (Type IV) BIM-LCA approaches to assess EC across key life cycle phases (A1-A5, B4, C2-C4) using databases like Environmental Product Declarations (EPDs), Inventory of Carbon and Energy (ICE), and Royal Institution of Chartered Surveyors (RICS). Additionally, the chapter employs the London Energy Transformation Initiative (LETI) rating system for evaluating buildings, facilitating benchmarking.

Chapter 4. An In-Depth Analysis of the EC in case studies

Chapter 4 provides a thorough examination of EC in case studies. It starts by comparing the accuracy of databases for different stages, including product and end-of-life databases, and addresses discrepancies between them. The chapter also explores specific variations in EC within concrete databases. Following this, it presents detailed analyses of three case studies: a residential building, a college building, and a hotel building, including descriptions of each and assessments of their WLEC. Additionally, it discusses Module D outside the LCA for each case study.

Chapter 5. BIM-LCA integration for automated embodied carbon assessment

This chapter explores the integration of BIM and LCA to automate EC assessments for buildings, focusing on two case studies: the college and hotel buildings. The study compares traditional manual methods (Type I) with an automated approach (Type IV), highlighting significant improvements in accuracy, efficiency, and consistency. Automated methods achieve alignment with traditional approaches across various life cycle stages (A1-A3, A4, A5w, C2, C3-C4, and B4), demonstrating minimal deviations (typically within ±2%) across building components and materials. In addition, a color-coded visualization system provides clear insights into EC hotspots, identifying high-impact materials and components, such as roofs and floors, for targeted carbon reduction strategies.

Chapter 6. EC reduction strategies

Chapter 6 of the thesis thoroughly examines strategies to reduce EC in buildings. It starts by discussing the implementation of green roofing systems in hotel buildings, detailing their features, analysing their carbon emissions, and assessing associated costs. Furthermore, the chapter explores the use of low-carbon-intensity materials in residential, college, and hotel buildings. Lastly, it addresses EC benchmarking, particularly LETI's targets, providing a comprehensive framework for evaluating and comparing EC performance across buildings. This chapter offers valuable insights into effective methods for mitigating EC in the built environment.

Chapter 7. Conclusion and Future Work

Chapter 7 concludes the research by emphasizing the importance of reducing EC in buildings to meet climate targets. The study assessed WLEC in residential, educational, and hotel buildings and introduced an automated BIM-LCA system using Dynamo and Python, which achieved over 98% accuracy and significantly reduced assessment time. Key findings include the high impact of materials like concrete and the effectiveness of strategies such as using GGBS. While the study faced some limitations related to data and assumptions, it offers clear recommendations for expanding automation and integrating EC assessment into early design and policy frameworks.

Chapter 2 : Literature Review

In this chapter, a literature review is conducted to explore the research questions and objectives outlined above. The review is organized into the following sections:

Life Cycle Assessment:

- Highlighting the importance of LCA in assessing environmental impacts in the construction sector, underlining its role in addressing sustainability challenges.
- Exploring the shift in focus from OC to EC, driven by advances in building energy efficiency and the adoption of renewable energy, making EC a more significant contributor to the building's overall carbon footprint.
- Describing EC assessment methods that quantify total EC emissions from material production to end-of-life, providing insight into the environmental impact of construction materials.
- Identifying challenges in using EC databases, noting discrepancies that can impact the reliability of carbon assessments due to different data sources, assumptions, and calculation methods.
- Focusing on the significant role of concrete in EC calculations, emphasizing that database choice is crucial due to variations in data quality and assumptions for this high-impact material.
- Discussing LCA software tools used for EC assessment, outlining their unique characteristics and limitations, and underlining the importance of tool selection in achieving reliable and consistent results.

Building Information Modelling (BIM):

- Highlighting BIM's role as a transformative tool in the AEC industry, focusing on its integration of comprehensive building data into 3D models and its impact on project efficiency and management.
- Exploring BIM's application in conducting LCA at the design stage, showcasing its potential for comprehensive environmental impact evaluations of buildings.
- Recognizing Autodesk Revit as a widely adopted BIM platform, underscoring its effectiveness in various applications, including LCA integration and environmental analysis.

Integration of BIM and LCA:

- Providing an overview of four methods for integrating BIM and LCA, discussing their challenges and limitations, and highlighting the most advanced and efficient approach for sustainable construction practices.

Embodied carbon mitigation in buildings:

- Analysing literature on the elements that have the highest influence on EC in different stages of a building's life
- Reviewing literature on diverse strategies employed to reduce EC at various life stages, with a focus on different building types like hotel, educational, and residential structures.

The importance of the end-of-life scenario:

- Highlighting the importance of end-of-life strategies and its effect on the overall EC of materials.

2.1 Life Cycle Assessment

LCA is a systematic and comprehensive method for evaluating the environmental impact (such as CO_2 emission) of a product throughout its entire life cycle, starting from raw material extraction and continuing through production, use, and eventual disposal.

The evaluation of environmental impacts through LCA should be fully incorporated into building design practices due to the significant and far-reaching impact of the building industry on the environment and, consequently, the overall sustainability of the society (Bozicek, Kunic and Kosir, 2021). The application of LCA allows for the consideration of several possible alternatives for the same activity, which is particularly useful for effectively comparing their respective impacts (Hamidi and Bulbul, 2014). Despite LCA advancements, few new construction projects incorporate it due to limited familiarity among building professionals (Pai and Elzarka, 2021).

LCA is a widely recognised and standardised tool for carbon assessment and has been implemented in numerous climate mitigation action plans, such as RIBA 2030, LETI, and the Architecture 2030 Challenge (Dong and He, 2023). The methodology was widely standardised during the 1990s (Hellweg and Milà i Canals, 2014). This method provides a solid and comprehensive methodological base for accurately calculating CO_2 emissions and other environmental indicators across the entire life cycle of buildings (Basbagill et al., 2013; Lasvaux et al., 2016; Buyle, Braet and Audenaert, 2013). Furthermore, LCA is increasingly becoming more widely accepted and integrated within the context of both national and international environmental standards.

To help describe the environmental impact of an asset, its life cycle is carefully split into specific stages and modules, as clearly defined by BS EN 159785 for buildings and PAS 208010 for infrastructure (Gibbons et al., 2022). The EN 15978 standard defines the life cycle stages of a building. These include A1–A3 (‘Cradle to Gate’), which covers raw material extraction, transport, and manufacturing; A1–A5 (‘Upfront Carbon’ or ‘Cradle to Site’), which also includes construction activities; B1–B5 (‘Use Stage’), which accounts for maintenance, repair, and replacement; and C1–C4 (‘End of Life’), covering demolition, transport, waste processing, and disposal. These stages are classified as Embodied Carbon (EC). Stages B6–B7, relating to the building’s energy and water use during operation, are referred to as Operational Carbon (OC) (Schmidt, Crawford, and Warren-Myers, 2020). The division of life cycle stages into modules provides essential transparency and flexibility in environmental impact assessment. These modules also offer a standardized and structured approach for comprehensive and coherent reporting, with distinct clusters that can be examined individually or in conjunction with one another, facilitating detailed and meaningful analysis (Hammond and Jones, 2008).

2.1.1 Embodied carbon VS Operational carbon

Operational carbon is the carbon emissions generated from building energy use during its operation phase, including heating, cooling, lighting, and ventilation over its lifetime and embodied carbon is the carbon emissions associated with materials and construction, including raw material extraction, manufacturing, transportation, installation, maintenance, and disposal over the building’s life cycle. Unlike OC which only relates to energy used to keep the building running when in-use, EC is associated with different phases of the building’s life cycle (Ekundayo et al., 2019).

The focus of carbon reduction is increasingly shifting from OC to EC as a direct result of the improved operational energy efficiency in buildings (Victoria and Perera, 2018). During a building’s full life cycle, OC plays a critically role in total carbon emissions due to the extended duration of the use stage, whereas EC generated during construction has been increasingly emphasised as a consequence of the promotion of low/zero carbon building design (Pan and Pan, 2018; Ansah, Chen and Yang, 2022) and ongoing advances in renewable energy technologies (Liu and Rodriguez, 2021; Zhang et al., 2022).

This means that EC can represent a higher proportion of WLC than it used to in the past. Thus, EC has become increasingly significant and, in some cases, can account for as much as 40-70% of the WLC in a new building. Figure 2.1 illustrates the magnitude and detailed breakdown of WLC, highlighting the role of EC within the overall carbon footprint of buildings (London Energy Transformation Initiative, 2020).

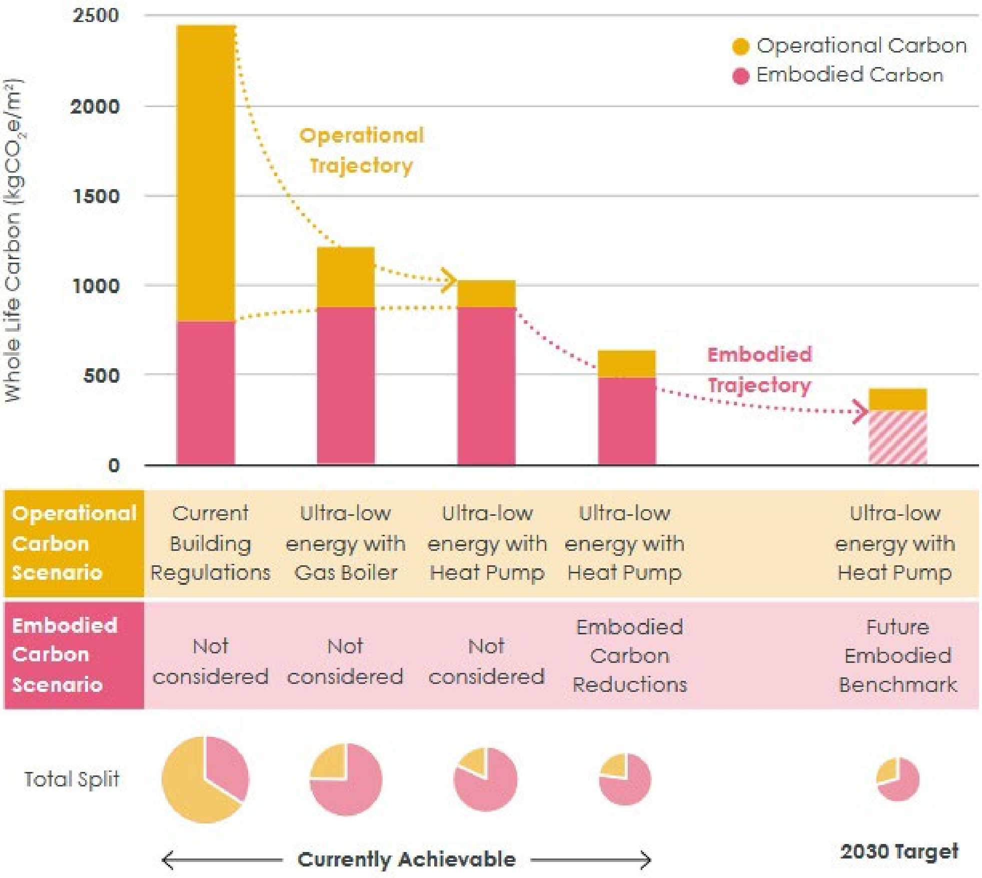


Figure 2.1: The magnitude and breakdown of WLC emissions (London Energy Transformation Initiative, 2020)

As the significance of EC becomes increasingly evident, the UK government published the Net Zero Strategy in 2021, outlining its commitment to improving EC reporting. The strategy aims to assess the feasibility of establishing maximum emission limits for new buildings in the future. Additionally, it highlights the potential for reducing EC through different strategies like material substitution (UK Government, 2021).

WLC assessment have the potential to significantly contribute to reducing emissions across the building sector. However, there is currently no government policy mandating the assessment or regulation of EC in buildings. As a result, progress in addressing these emissions has been limited. Establishing a requirement for WLCAs is a critical first step, enabling the industry to systematically measure EC and implement strategies for its reduction (House of Commons Environmental Audit Committee, 2022).

2.1.2 Embodied Carbon Assessment

EC assessment is a systematic method used to quantify the total EC emissions associated with the entire life cycle of a building, comprehensively considering all stages from the production of building materials (A1-A3) through to the end-of-life of the building (C1-C4). This process serves as the initial and fundamental stage in understanding the environmental impact of building materials, representing a pivotal step towards identifying critical hot spots in buildings and exploring various strategies for reducing EC in construction.

EC can be measured using different boundary conditions, such as cradle-to-grave, which is considered the most complete and inclusive boundary condition. This boundary encompasses all processes, starting from the extraction of raw materials from the ground, their transport, refinement, and processing, through to the assembly of components, the in-use phase of the product, and ultimately its end-of-life profile, including disposal, recycling, or reusing (Jones, 2023).

Demonstrating commitment to reducing EC emissions is quickly becoming a key consideration in obtaining planning permission. Several local authorities - including Westminster City Council, Brighton, Oxford, Hammersmith and Fulham, Camden and City of London - have started to enquire about the EC emissions of developments. Having an EC assessment may soon make all the difference in the planning process.

Numerous studies have limited their analysis to specific phases of a building's life, such as focusing solely on the product or end-of-life stage. However, a more comprehensive understanding of the EC of buildings emerges when all life stages are taken into account, revealing the interplay and impact of each stage on the others. Examples of conducted research analysing the EC of buildings include:

A product stage EC assessment of a UK educational building was undertaken using two distinct scenarios: 1) considering the full building scope and 2) focusing solely on the substructure and superstructure. The results demonstrated that Scenario one (which accounted for the full building scope) resulted in an EC value of 526 $kgCO_2e/m^2$, while Scenario two (considering only the substructure and superstructure) resulted in a significantly lower EC value of 312 $kgCO_2e/m^2$. The ICE database, which was utilized in this study, provides EC coefficients exclusively for the product stage (Marsh, Orr and Ibell, 2021).

(Hart, D'Amico, and Pomponi, 2021) conducted an analysis of EC in multistorey buildings, focusing on steel, reinforced concrete, and engineered timber frames. In their research, carbon coefficients associated with the embodied emissions during the product stage, construction process stage, and end-of-life stages were derived from sources including the Ecoinvent 3.5 database, UK Government emission factors, and established literature benchmarks. The findings revealed that the EC values for the timber frame, concrete frame, and steel frame were 119, 185, and 228 $kgCO_2e/m^2$, respectively, highlighting significant variations in EC depending on the structural material used.

A research study conducted by Pan and Teng (2021) revealed that concrete residential buildings are identified as the most widely studied building type for EC assessment. The cradle-to-gate EC of these sample cases has been determined to range between 120 and 931 $kgCO_2e/m^2$, with the average value being calculated as approximately 420 $kgCO_2e/m^2$.

Some studies focus solely on evaluating the primary building materials to simplify the EC assessment process. For instance, Zhu et al. (2020) estimated the annual EC emissions from China’s building sector. This study specifically considered only steel, timber, cement, brick, glass, and aluminium in its estimation of the EC emissions from the transportation stage. The results indicated that the EC emissions in the building sector were 1421.70 Mt and 1599.62 Mt in 2015, respectively. When analysing emissions by building types, it was found that the EC in the residential building sector is approximately 1.5-2.2 times higher than that in the non-residential building sector.

(Cang et al., 2020) Proposed quick prediction calculation models of EC emissions based on carbon emissions of main building materials during scheme design phase by conducting case studies on 129 residential buildings of different structures in Jiangsu, China. Embodied Carbon Factors (ECFs) come from other literatures. It is proved that the proposed models simplify EC emissions calculation, guide low-carbon building design and facilitate policy making on sustainable development of buildings and cities.

End-of-life refers to the final stages of a product or material's phase of use, marking the point at which it is no longer functional or needed in its original form (Circular Economy, 2021). End-of-life considerations are frequently omitted from assessments or plans due to the scarcity of reliable data, uncertainty surrounding the eventual treatment methods (such as whether a product will be landfilled, recycled, or reused), or other unknown variables and limitations (Walters, 2022).

32% of landfill waste originates from the construction and demolition of buildings in the UK. Therefore, it is crucial to pay more attention to how buildings are managed at the end of their lifespan. The treatment and disposal of construction materials, once they have reached the end of their useful life, is becoming an increasingly important issue as significant steps are being taken to try and handle these materials in the most efficient way possible. This approach aims to minimise waste, reduce EC emissions, and limit the reliance on landfill sites, ensuring that these processes align with sustainable practices (Circular Economy, 2021).

For timber, the majority of LCA studies utilize a cradle-to-site system boundary, focusing on the stages up to construction and neglecting the end-of-life phase (Liang et al., 2020; Robertson, Lam, and Cole, 2012; Robertson, Lam, and Cole, 2012). Creating an effective end-of-life strategy for timber is crucial because it significantly affects the amount of EC produced during this final stage. The optimal approach for managing timber at the end of its life involves reusing it in new projects, as this practice retains the biogenic carbon within the timber and avoids additional EC production associated with common end-of-life scenarios. However, current data from (Gibbons et al., 2022) reveal that none of the timber used in construction undergoes reuse, highlighting a critical area for improvement. Instead, 55% is recycled, 1% is sent directly to landfill, and 44% is incinerated, as reported by KLH Sustainability (2020).

In cases where timber ends up in landfills, it decomposes, releasing carbon and methane into the atmosphere. This poses a more significant environmental impact than the original carbon storage potential of the timber, particularly due to methane's GWP, which is 28 times greater than that of CO_2 (KLH Sustainability, 2020).

The assessment of EC in many other materials is significantly influenced by how they are treated at the end of their life. Consider the end-of-life scenario for cast in situ concrete: the most effective approach involves crushing it after demolition and repurposing the material as aggregates for producing new concrete. This not only minimizes the EC in crafting new concrete but also prevents the need for landfill disposal (Christensen, 2022).

Therefore, considering the end-of-life scenario is crucial as it can influence the overall EC of buildings, either increasing or decreasing it significantly.

2.1.3 Embodied Carbon Factor

ECF has 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, transportation, construction and end of life (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:

EPDs, which are the inaugural database. They are regarded as the most reliable source of information about a product's environmental impact. However, manufacturers in the United Kingdom only produce a limited number of EPDs, so it is not possible to get EPDs for all the project's materials (Keyhani et al., 2023).

EPDs are a growing source of environmental data in the construction products market and are increasingly being used for (1) environmental performance assessment of buildings and (2) product comparison for procurement decisions during the later stages of building design (Waldman, Huang and Simonen, 2020). Additionally, CEN EN 15804 functions as the benchmark for the EPD in the evaluation of sustainability in construction activities and services. This standard defines the technical functionality of a construction product and delivers data on various indicators throughout distinct stages of its life cycle (EN 15804, 2012).

The second most commonly used database is the ICE database (Alwan and Ilhan Jones, 2022), which provides an extensive database for a variety of construction materials. The ICE database, initially created by Hammond and Jones in 2008, is widely recognized for its comprehensive information. This database contains the cradle-to-gate carbon factor for more than 500 of the most prevalent construction materials, making it an essential resource for assessing EC. However, it is important to note that it does not cover the end-of-life phase of materials (Gibbons et al., 2022).

Another widely used database is the UK Department for Business, Energy, and Industrial Strategy (BEIS). Within this database, the ECFs are organized into forty distinct categories, while construction materials are classified into twelve specific categories. The materials included in these categories are Aggregates, Asbestos, Asphalt, Bricks, Concrete, Insulation, Metals, Soils, Mineral Oil, Plasterboard, Tires, and Wood, all of which are commonly utilized in various aspects of building construction.

There are databases with global applicability as well. For instance, EcoInvent is a widely recognized and extensively utilized database that offers comprehensive coverage of various environmental impact categories, including EC. 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 datasets to perform LCAs (Chaudhary, Jahromi and Keyhani, 2023). Although various databases have been adopted for assessing buildings' EC, the results displayed inconsistencies and the reasons behind the differences were not well revealed (Teng et al. 2023).

It has been emphasized in European and UK reports that environmental impact data are crucial factors, however, no clear EC legislation exists to address these issues. Even while awareness of EC's importance has increased and the UK Government has recognised that EC must be included in the appraisal system for new projects, there is still no clear guidance outlining the system that will allow EC to be included in new projects (Alvi, Kumar and Khan, 2023).

- **Discrepancy in Embodied Carbon Databases**

A lot of research has shown the inconsistency of various EC databases of building materials, highlighting the challenges in ensuring accurate and reliable data. For instance, (Kayaçetin and Tanyer, 2020) found that there is a substantial difference between the Gabi database and the ICE database, indicating a lack of consistency in the values provided. Therefore, using an unsuitable database or relying on an incorrect dataset may result in significant errors and inaccuracies, ultimately leading to a failure of carbon assessment processes.

Another study conducted by (Brogaard et al., 2014) indicated that the differences between the estimated highest and lowest carbon emissions from the primary production of steel could be as high as 1761% when using different datasets. Similarly, (Takano et al., 2014) compared the carbon emissions of three case buildings by utilizing the GaBi and ecoinvent 3.0 databases. The findings revealed that differences of up to 183% could result from using different databases when evaluating the carbon emissions of materials such as wood fiber board.

Research by (Ekundayo et al. 2019) revealed that the disparities between databases were due to different boundary definitions, varying underlying assumptions, and methodological differences in calculations. It was also revealed that common sources of uncertainty are variability, data gaps, measurement error, and epistemic uncertainty (Marsh et al. 2021). Despite investigation involving the comparison of diverse databases, there is still an opportunity to enhance the assessment of EC in buildings. A more accurate estimation of EC can be achieved by incorporating EPD and other databases into the comparison, contributing to a comprehensive understanding of environmental impact in construction.

In this research, the developed database, which combines EPDs and the ICE database as the most reliable sources, are compared with commonly used database in the UK. This comparison aims to demonstrate the significant impact that databases can have on the total EC of buildings.

2.1.3.1 Discrepancy in Concrete Materials

Choosing the right databases is crucial, especially for materials with a high potential for EC, such as concrete. Some databases offer only a single dataset for generic concrete, lacking information on its strength. It would be impossible to be used in calculating the carbon emissions of concrete buildings as different concrete strengths are used to guarantee the structure stability (Teng et al. 2023).

(MPA UK Concrete, 2020) report represent that cement account for approximately 1.5% of UK CO_2 emissions. The majority of cement is used in concrete, which is globally recognized as the most common material in buildings (Anderson and Moncaster, 2020). A research study revealed that cast in situ concrete and precast concrete are the top two contributors among the diverse materials, accounting for 39% and 20.1% of emissions, respectively (Xu et al. 2022).

Furthermore, research conducted by (Alwan and Ilhan Jones, 2022) also demonstrated that concrete exhibits the highest EC emissions when compared to other construction materials.

One of the key challenges for accurately calculating EC from buildings lies in the choice of database for materials during the early design stage, a phase when material specifications have not yet been fully detailed or finalized (Moncaster et al., 2018). For materials like concrete, the potential variations in composition are almost infinite, as they depend on factors such as the type and proportions of cement and aggregates used, as well as the addition of admixtures and plasticizers, each of which influences the final material properties. Each database available for this purpose differs in its specific features, including functionality, underlying assumptions, covered life cycle stages, data quality, and the principles of modelling applied (Steubing et al., 2022; Sacchi et al., 2022).

For the product stage of concrete, the differences observed when using various databases tend to be less significant. This is likely due to the widespread use of concrete and the extensive amount of data available for this material, which allows for greater consistency across databases. The ICE database, for instance, provides multiple ECFs for a range of concrete mixtures, offering the essential data required to conduct an EC assessment with a reasonable degree of accuracy (Mohebbi et al., 2021).

Despite studies investigating the factors contributing to discrepancies among various databases for concrete materials, a significant research gap exists in exploring the variations in the EC of concrete materials, whether analysed within the context of databases as a unified entity or as distinct individual components.

2.1.4 LCA software

The process of selecting an appropriate software tool for use in LCA is extremely crucial, as there are numerous commercial software programs readily available in the market. Each software program comes with its own unique characteristics and features, which might vary significantly in terms of functionality, the availability of databases, the design of the user interface, the management of data quality, and the concepts for creating product systems modeling (Herrmann and Moltesen, 2015).

Few research studies have conducted comprehensive reviews of the available digital tools for LCA. Using Simapro and Gabi, Emami et al. (2019) carried out a comparison of the LCAs of two residential buildings. The results clearly demonstrate that the choice of tool has a substantial effect on the outcome of the assessment. Specifically, the comparison revealed that, for the entire building, the difference in results is approximately 15%, which highlights that major work is still required to enhance the reliability of LCA tools in the building sector. This improvement is essential in order to provide trustworthy and accurate information for effective policymaking.

The common tools mentioned in these reviews include Athena Impact Estimator for Buildings, One Click LCA, Tally, and EC in Construction Calculator (EC3), as well as ECOSOFT, eToolLCD, IMPACT, Beacon, and more. These tools have been categorized and grouped based on various factors, such as their country of origin (Lasvaux et al., 2013), their specific purposes, like building design support and certification (Prideaux et al., 2022), and their scope of applications, which includes both buildings and infrastructures (Yan et al., 2022).

Among the tools listed, "One Click LCA" is a widely recognized cloud-based software tool that is known to provide free access to its users, and it includes a specific module designed for the UK market. The tool is specifically customized for use within the construction and building industry, enabling users to efficiently assess the environmental impacts associated with building materials and various construction processes. It utilizes EPDs as its primary EC database. However, when an EPD is unavailable, the software relies on generic databases that provide industry-average values, which may not accurately represent specific products.

2.2 Building Information Modelling (BIM)

BIM, as an emerging technology, has recently attracted much attention worldwide (Carvalho, Bragança, & Mateus, 2019).

BIM is increasingly being recognized as a transformative and innovative tool in the architecture, engineering, and construction industry. As a comprehensive, three-dimensional virtual model that seamlessly integrates extensive and detailed building data (Cheng et al., 2022), BIM serves as a highly structured digital representation of project-related information, significantly streamlining processes and reducing the time and labour required to manage such complex data (Zhao, Deng, and Lai, 2021; Lu et al., 2021). Due to its structured and organized nature, BIM data has been effectively utilized to enhance various critical aspects of construction performance, including improving construction safety and minimizing risks during project execution (Li, 2018).

BIM is particularly effective in addressing the significant challenges of obtaining essential building data for LCA, presenting substantial potential for conducting complete building LCAs at the design stage (Azhar et al., 2011). The use of BIM in assessing the environmental impacts of buildings provides crucial and valuable insights into the life cycle inventory, including detailed information such as material specifications, quantity take-offs, and other important data related to building components and materials (Lee et al., 2015; Soust-Verdaguer, Llatas and García-Martínez, 2017).

Moreover, BIM supports decision-making throughout a project's life cycle by enabling rapid, data-driven decisions that enhance project results. For instance, during the design phase, BIM assists architects and designers in selecting sustainable materials, encouraging the use of options with low energy content (Raza, Kumar, and Nawab, 2018).

The use of BIM is also identified as a key tool for waste reduction and deconstruction in the context of sustainable design. (Rajendran and Pathrose, 2012) confirmed the increasing interest in and the numerous benefits associated with the use of BIM for this specific purpose, highlighting its potential through the detailed revision of various waste reduction strategies that have been successfully applied across different BIM implementations.

In other words, BIM serves as a digital, intelligent representation of data-rich objects created collaboratively by project stakeholders to enable early feedback, enhance decision-making, and boost project efficiency at all stages. Utilizing BIM and its tools leads to improved performance and quality, while minimizing waste, errors, costs, and resource use (Ghaffarianhoseini et al., 2017). Additionally, it helps bridge gaps in the building industry and mitigates environmental impacts through its distinctive capabilities.

Currently, the use of BIM in Architecture, Engineering, and Construction industry is growing globally. According to Directive European 2014/24/EU (Official Journal of the European Union, 2014) the use of BIM for public building will be compulsory in the EU from October 2018. Countries such as the UK have already adopted BIM for public procurements from 2016 (H.M. Government, 2015).

Among the various BIM platforms available, Autodesk Revit has increasingly emerged as the industry’s preferred choice due to its comprehensive features and capabilities (Teng et al., 2022). Numerous studies have documented Revit as the most widely used tool in the field, with its adoption rate in BIM-LCA research reaching an impressive 78% in 2020, up from 73% in 2017, highlighting its growing prominence and acceptance within the industry (Carvalho, Bragança, and Mateus, 2020; Eleftheriadis et al., 2017). Another significant study demonstrated how the quantity of materials derived from Autodesk Revit could be effectively linked to the Microsoft Access database to establish the EC of prefabricated buildings during the materialization phase (Ding et al., 2020). In other words, these studies show that utilizing Revit can significantly enhance the efficiency and accuracy of calculating and managing EC. This widespread and growing adoption further underscores BIM’s integral and transformative role in advancing data-driven, sustainable practices across the Architecture, Engineering, and Construction industry.

2.3 Integration of BIM and LCA

To effectively reduce carbon emissions and energy consumption, extensive international research is currently being carried out with the aim of developing a BIM-based detection system that facilitates the easy estimation of carbon emissions and energy consumption. By utilizing such a system, these emissions can be analyzed promptly, accurately, and objectively, which allows for the timely implementation of the necessary changes to support and promote energy-efficient design practices (Alvi, Kumar, and Khan, 2023).

Currently, OC and EC calculation methods based on specific commercial BIM software are relatively mature (Lu et al., 2021). For the operational stage, the existing researchers calculated OC by energy simulation software, such as Ecotect (Peng, 2016), Green building studio (Lu et al., 2019), Design Builder (Cheng et al., 2020; Yang et al., 2018) and Insight.

Using BIM for EC assessment has the potential to enable a more comprehensive and rapid evaluation of the environmental impact of a structure (Hunt and Osorio-Sandoval, 2023). The integration of BIM and LCA has increasingly become a crucial and innovative strategy for evaluating EC in buildings, highlighting the construction industry's growing focus on advancing sustainable construction practices. Despite the widely recognized potential of these methods, the actual adoption and implementation remain limited across the sector. A recent national survey conducted among architects, engineers, developers, contractors, consultants, and suppliers (Ruchit Parekh and Dario Trabucco, 2024) revealed that while 72% of participants acknowledged LCA’s ability to enhance environmental assessments beyond traditional green building rating systems, the actual integration of LCA into BIM workflows is still uncommon. In fact, only 12% of the respondents reported having used both tools together in green building projects, underscoring the pressing need for greater implementation efforts and enhanced industry-wide collaboration to overcome existing challenges.

The integration of BIM and LCA tools enables a more rapid and efficient assessment of various design solutions, thereby significantly aiding decision-making processes during the crucial design phase (Najjar et al., 2017; Ajayi et al., 2015). Over the past few years, a considerable number of literature reviews focusing on the integration of BIM and LCA have been published. These prominent review articles have primarily concentrated on thoroughly examining the advantages and challenges associated with merging BIM and LCA tools to evaluate and address the environmental impacts of buildings in a comprehensive manner (Seyis, 2020).

Several studies have attempted to classify BIM and LCA. (Nizam, Zhang and Tian, 2018) categorized the studies into four main types. The first type focuses on project-specific outcomes without detailing an integration process that could be replicated in other projects. The second type involves studies where BIM is solely used for quantity take-off, with data exported to other tools. The third type is limited to the cradle-to-site phase. The fourth type is considered impractical for broader application.

(Antón and Díaz, 2014) proposed two methods for integrating BIM and LCA. The first involves using the IFC data format to extract BIM model information for real-time environmental performance assessment, reducing manual data entry, though it is not yet fully established. The second method involves embedding environmental properties in BIM objects, which must evolve with the project. Challenges remain in including data for aspects like transportation and maintenance. (Soust-Verdaguer, Llatas and García-Martínez, 2017) identified three types of BIM and LCA integration: the first uses BIM for generating the bill of quantities (BoQ) during the LCA stage, the second involves using BIM to supply material data and calculate energy demand, and the third combines BIM and LCA tools in an automated process.

Taking all research in this field into account, BIM-integrated LCA approaches can be categorized into four primary types based on the data exchange flow (Figure 2.2).

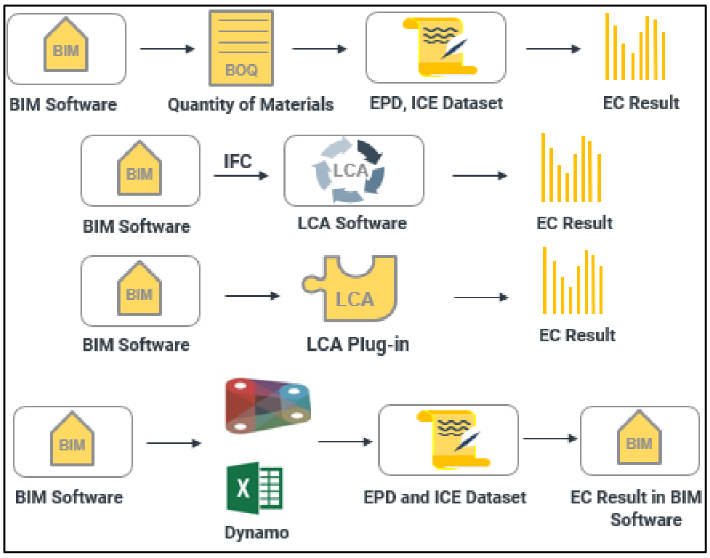


Figure 2.2: Integration of BIM and LCA methods for EC assessment

2.3.1 Type I BIM-LCA approach

Type I (traditional) approach involves exporting BIM data and combining it with ECF sourced from various databases, which are typically available in spreadsheet format (Hunt and Osorio-Sandoval, 2023). In this particular approach, after the creation of the basic model in Revit, the software can calculate the quantity of work by taking into account the input of materials and components used in the model (Cheng et al., 2020; Dzambazova, Krygiel and Demchak, 2009).

Material quantities can also be calculated in a number of different ways, depending on the stage of design and the tools available, including:

- Actual data from the real case project
- Manual calculations
- Structural analysis models
- Previous project experience
- A quantity surveyor’s cost plan (Gibbons et al., 2022)

Then, the quantity of materials created by Revit (Dzambazova, Krygiel and Demchak, 2009) are multiplied by the ECF to carry out EC assessment.

Therefore, Revit (BIM tool) is linked with an ECF for calculating the amount of carbon produced during the complete lifecycle of the building; these factors come from various sources like EPDs, SimaPro, GABI, VJK, JEMAILCA, etc (Alvi, Kumar and Khan, 2023). This method requires a significant time investment, thereby reducing their overall efficiency and potentially delaying critical decision-making processes during the early stages of design. The Type I method often necessitates the use of external data management systems, as the analysis is typically conducted outside the BIM environment, which creates additional layers of complexity in data handling and integration. While this method remains prevalent in the industry, the inherent limitations associated with manual data management make automated and streamlined solutions increasingly attractive (Tam et al., 2023; Guignone et al., 2023). Additionally, this method is highly labor-intensive, requires detailed and precise data inputs, and is generally performed later in the design process, at a stage where implementing changes becomes significantly more complex and costly (Ayman Mohamed et al., 2023).

2.3.2 Type II BIM-LCA approach

The Type II approach involves importing BIM data into dedicated LCA software tools and performing the assessment directly within these LCA-specific tools. In this approach, the BIM data are carefully utilised as input for the LCA software, ensuring that the necessary information is effectively transferred and accurately applied to the assessment process (Hunt and Osorio-Sandoval, 2023).

Research conducted by (Xu et al., 2022) utilized an Industry Foundation Classes (IFC)-enabled data transfer tool to effectively integrate BIM data with LCA software SimaPro for evaluating a prefabricated residential building located in Hong Kong. This seamless integration resulted in a minimal 1% discrepancy when compared to traditional LCA methods, demonstrating its high level of accuracy. Moreover, the approach significantly reduced the time required for LCA modelling, decreasing it from a lengthy 729 minutes to just 62 minutes, thereby achieving an impressive 91.5% improvement in efficiency. Another study conducted by (Resch *et al.,* 2020), introduces a method for evaluating and visualizing buildings' EC emissions by linking material inventory data with LCAs. Utilizing the building LCA database tool (bLCAd-tool) for organizing and analysing LCA data, the study demonstrates the method's effectiveness through a case study, highlighting its ability to identify key emission drivers and support low-carbon building design.

Although Type II automated BIM-LCA approaches streamline workflows and save considerable time, the dependence on pre-existing databases can limit the accuracy of EC assessments. This reliance can lead to a generalized carbon profile, which may fail to fully account for the unique characteristics of a project’s materials and environmental context.

2.3.3 Type III BIM-LCA approach

In the Type III approach, LCA plug-ins are installed directly within Revit software, enabling comprehensive calculations to be performed seamlessly within the software environment. After completing the process of modelling the building in Revit, these plug-ins can then be run to accurately calculate the building’s EC.

An example of this integration is Tally (KT Innovations, Autodesk, & Tally-Autodesk, 2014), a software plug-in specifically designed for Autodesk Revit that helps quantify the environmental impacts of building materials based on the LCA method. In addition to this, it provides functionality for conducting comparative analyses of different design options. Currently, the application is customized and geographically adapted to suit the US region.

Most studies employing the plug-in approach have utilized the Tally tool (Najjar et al., 2017; Najjar et al., 2019; Raposo, Rodrigues, and Rodrigues, 2019; Bueno and Fabricio, 2018), which is a Revit plug-in specifically designed to conduct LCA analysis using the Gabi database.

However, some researchers have taken a different approach by developing their own customized plug-ins to extend the capabilities of BIM. For example, (Lee, Kim, and Yu, 2014) created a specialized Revit plug-in capable of generating results for six impact categories. Similarly, (Jalaei, Zoghi, and Khoshand, 2021) developed an innovative plug-in that integrates BIM with LCA to assess EC, perform energy analysis, and conduct lighting simulations. Another significant study by (Parece, Resende, and Rato, 2024) aimed to assess EC in buildings by integrating BIM and LCA with a Construction Classification System (CCS) and a custom plug-in for Autodesk Revit. This research utilized the plug-in to extract material quantities from BIM models, link these quantities to environmental data within LCA databases, and calculate EC. Through case studies, the tool was shown to be effective in accurately assessing EC and optimizing design choices to align with sustainability goals.

This method is highly time efficient. However, specialized LCA tools often come with high costs, making them inaccessible to many stakeholders, particularly during the critical early design stages. This limitation hinders widespread adoption and prevents many professionals from using these tools for real-time EC assessments.

2.3.4 Type IV BIM-LCA approach

(Dalla Mora *et al.,* 2020) found that most studies integrating BIM with LCA have so far utilized tools like MS Excel, Athena, or Simapro to conduct their LCA analyses. This suggests a common approach in which environmental assessments are not fully automated to simplify the process and reduce the risk of human error in calculating impacts.

Researchers widely recognize BIM's potential to automate modeling tasks and serve as a primary information source for LCA (Llatas, Soust-Verdaguer and Passer, 2020). Although some studies have been conducted, the integration of BIM with LCA is still in its early stages. Establishing a workflow and gaining a clearer insight into the processes of input and output insertion are essential areas that require additional research (Tam *et al.,* 2022).

Case studies clearly highlight the significant potential for automated methods to drastically lower the EC of buildings by enabling precise and efficient carbon accounting and facilitating material optimization during the design phase (Alzara et al., 2023; Giaveno et al., 2021; Heydari and Heravi, 2023). Type IV is recognized as an automated method for EC assessment that effectively integrates LCA and BIM within Dynamo to streamline and simplify EC calculations. This innovative approach efficiently identifies carbon "hot spots" within the structure and actively supports informed and sustainable material selection (Hunt and Osorio-Sandoval, 2023). Research has shown that using visual programming languages like Dynamo for automating EC assessments is particularly effective throughout the design process, allowing for dynamic updates and real-time decision-making (Tam et al., 2023; Alzara et al., 2023; Giaveno et al., 2021). This flexibility provides designers with the ability to explore a wide range of design scenarios and ultimately select the most sustainable options available. Another study conducted by Alzara et al. (2023) presents an efficient and innovative method that utilizes Autodesk Revit, Dynamo, and BIM360 to automate EC calculations during the design phase. This automated approach empowers designers by providing them with the tools needed to make more informed, data-driven, and sustainable material choices. A detailed case study carried out in Cairo illustrates the reliability and effectiveness of the method, with the results demonstrating minimal variance when compared to traditional and more manual carbon calculation methods.

The main differences between these integration processes and calculation approaches are based on how the data were collected and used, as well as the process of data exchange and type of computation (Vandervaeren et al., 2022). This research addresses a key research question identified by the IEA Annex 57: " How can new calculation methods and 3D models better account for embodied impacts from the early stages of construction?".

As the construction industry continues to move toward achieving more sustainable outcomes, the automation of EC assessments through the integration of BIM and LCA represents an increasingly critical tool for effectively reducing the carbon footprint of buildings. By utilizing these advanced digital innovations, the industry can facilitate a seamless transition to a more efficient, low-carbon future, thereby making automated EC assessments an essential part of the modern design and construction process (Ruchit Parekh and Dario Trabucco, 2024; Ghorbany and Hu, 2024; Xu et al., 2022).

However, despite the growing interest in BIM-LCA integration, challenges persist. While current methods efficiently cover the cradle-to-gate phases of a building’s lifecycle (A1–A3), such as material extraction and manufacturing, extending the automation to include the construction (A4–A5) and end-of-life phases (C1–C4) remains complex (Ayman Mohamed et al., 2023; Parece, Resende and Rato, 2024). Furthermore, the interoperability between BIM software and LCA databases, such as the UK LCI or the ICE database, can be difficult, limiting the full automation potential (Alwan and Ilhan Jones, 2022; Xu et al., 2022). To address these significant challenges, this research introduces an advanced level of automation for EC assessment, effectively utilizing Revit software, Dynamo visual programming, and Python scripting techniques. The scope of the study comprehensively encompasses the entire life cycle of buildings, ranging from material extraction and production to construction, operation, and end-of-life disposal or recycling. A dedicated database for EC assessment specific to UK buildings was developed and integrated into Dynamo, enabling automated and streamlined EC calculations throughout the building's lifecycle.

2.4 Embodied Carbon mitigation in buildings

Increasing building constructions have become one of the fastest-growing drivers of carbon emissions. Proportionally more construction occurred among high-income countries, which reflected strong investment through 2021 (Figure 2.3). Across Europe, construction sector expenditure, which directly drives the increase in floor space, has varied due to differences in the economic recovery processes following the pandemic. Notably, the UK experienced a substantial 12% increase in construction sector activities compared to 2020, effectively highlighting a considerable upswing in the sector's activities and contributions (United Nations Environment Programme, 2022).

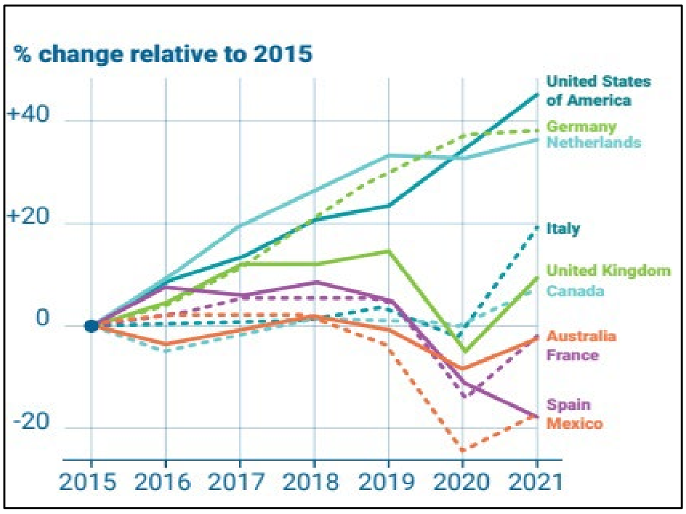


Figure 2.3: Global Construction Investment Proportions: 2015-2021 Analysis (United Nations Environment Programme, 2022)

Energy conservation and carbon reduction in buildings have become crucial in the context of global carbon neutrality (Chen *et al.,* 2022). According to the World Green Building Council (World GBC), EC is expected to account for 50% of all carbon emissions from new construction projects. A new vision released in 2019 called for a reduction in EC of at least 40% by 2030 and a goal of net-zero EC by 2050 for all new structures, infrastructure, and renovations (United Nations, 2015).

Organisations such as the RIBA, the LETI, and UK Green Building Council (UKGBC) have also introduced LCA guidelines for lowering EC emissions by 2050. LETI also provides benchmark figures and labelling system for different types of buildings to help the comparability of the projects in the building sector (Figure 2.4).

Upfront Carbon, A1-5 (exc. sequestration)

	Band	Office	Residential	Education	Retail
	A++	<100	<100	<100	<100
	A+	<225	<200	<200	<200
LETI 2030 Design Target	A	<350	<300	<300	<300
	B	<475	<400	<400	<425
LETI 2020 Design Target	C	<600	<500	<500	<550
	D	<775	<675	<625	<700
	E	<950	<850	<750	<850
	F	<1100	<1000	<875	<1000
	G	<1300	<1200	<1100	<1200

Figure 2.4: the EC letter bandings for four typologies (Hannah, 2022)

The British building research institute developed Building Research establishment environmental evaluation, the world's first green structure appraisal method, in 1990 (BREEAM). In 2000, the Leadership in Energy and Environmental Design (LEED) grading system was developed and promoted by the US Green Building Committee (Lin and Su, 2014; Tang, 2022).

BREEAM and LEED are all building rating systems that recognise EC assessment and mitigation as part of minimising the impact of a building's life cycle (RPS, 2023).

2.4.1 Key Factors Affecting Embodied Carbon

The majority of structural EC is emitted during the construction phase, which takes place before the building is occupied and becomes operational. Since this carbon will be released into the atmosphere well before 2050, which is the critical deadline for achieving net-zero emissions, it is essential for these emissions to be reduced as quickly and effectively as possible.

Recently, researchers have shown increased interest in assessing the environmental impacts at all stages of a building's life using LCA (Keyhani et al., 2023). Numerous studies have been conducted to identify the building hotspot in terms of EC. Significant reductions in the overall amount of EC in buildings can be accomplished by identifying and substituting items that have a high level of EC.

According to (Pacheco Torgal and Jalali, 2011), around half of the raw materials extracted from the earth's surface were turned into building materials. It shows that sand, gravel, brick, and cement respectively accounted for 35%, 24.4%, 19.9%, and 12.3% of the total building material consumption in 2018. It is noticeable that steel accounted for a small share in the total building material consumption but was the top carbon emitter.

Studies have shown that structural materials can be responsible for up to 50% of initial EC, and up to 20% of WLC (Robati et al., 2021; Robati, McCarthy and Kokogiannakis, 2018; Robati, Kokogiannakis and McCarthy, 2017; De Wolf, Pomponi and Moncaster, 2017; Akbarnezhad and Xiao, 2017). (Chen, 2022) showed that cement, steel, brick, lime, and linoleum were five major materials with high EC. Approximately 95.7% of the total EC were associated with the five materials.

(Khan et al., 2019) used Building Information Modeling to assess the environmental implications of a three-storey commercial building in Pakistan. The top contributing materials to the overall carbon emission were steel (33.51%), concrete (19.98%), brick (14.75%), aluminum (12.10%), and paint (3.22%), accounting for a combined contribution of over 80%.

A recent output from the IEA project Annex 57 reviewed and analysed the data from over 80 individual life-cycle assessments of buildings (Moncaster et al. 2019). In most of the case studies analysed, the product stage was found to have the highest impact. Cements and metals were shown to be the highest impact materials, and the sub- and super-structure found to be the highest impact building elements.

(Agung Wibowo, Uda and Zhabrinna, 2018) noted that steel, concrete, and aluminium are amongst the highest emitters of carbon within the sector. Similarly, in the review of literature done by (Teng and Pan, 2019) on the assessment of EC ('cradle-to-end of construction') of high-rise buildings, the authors discovered that most of the reviewed articles stated that steel and concrete are responsible for the highest carbon emitted when it comes to consumption of materials.

Other studies also showed that metal and concrete materials contribute significantly to EC, though for different reasons. Concrete is a significant contributor due to its high quantity, while metal stands out for its high intensity. It is noted that ready-mixed concrete has relatively low carbon intensity because it accounts for over 80% of the total material mass of the reference building but contributes only 18% of the total EC. In contrast, although steel rebar and structural steel account for only 18% of total material mass, their contributions to the total EC of the reference building are more than 80% (Gan *et al.,* 2017).

There is also research that compares the EC on a broader scale, specifically within the context of building frames. In research, a comparative analysis was conducted on the mass and EC emissions of building superstructures. The findings revealed distinct variations, where the concrete frame exhibited a mass approximately five times that of the timber frame and 50% higher than the steel frame. Median values for EC were recorded as 119 $kgCO_2e/m^2$ for the timber frame, 185 $kgCO_2e/m^2$ for the concrete frame, and 228 $kgCO_2e/m^2$ for the steel frame (Hart, D'Amico and Pomponi, 2021).

(Ruttenborg, 2020) compared the environmental impact of two different buildings (wood and concrete) using LCA. The study concluded with a reduction in the environmental impact of a building when choosing a wooden structure instead of concrete. (Petrovic et al., 2018) analysed the LCA of single-family home building materials. The results indicated that the concrete building slabs contribute the most to CO_2e emissions, whilst the wood frame and cellulose insulation have minimal environmental impact. Having a high proportion of wood-based products keeps Co_2e emissions low.

In another study, (Lenzen and Treloar, 2002) concluded that concrete-framed buildings caused higher carbon emissions than wood-framed buildings. In addition, a study indicated that while the timber apartment had the lowest carbon footprint in several life-cycle analysis modules, the hybrid (timber and concrete) apartment building demonstrated significant environmental performance, particularly when compared to the reinforced concrete apartment building (Rinne, Ilgın and Karjalainen, 2022). In this sense, modifications in design configurations that can use thinner massive wood panels, smaller foundations, and less concrete for flooring should further reduce the overall environmental impact for hybrid construction (Rinne, Ilgın and Karjalainen, 2022).

By identifying the elements with high EC in a particular building, the most effective strategies for reducing EC can be determined and implemented.

2.4.2 Strategies for Reducing EC in Diverse Building Types

The demand for future building materials and the associated emissions can be reduced through several strategies. These include using buildings more intensively (reducing floor area per capita), extending the lifespan of buildings, adopting lighter construction methods, and utilizing less carbon-intensive materials, such as wood-based construction instead of steel and cement. Additional measures involve minimizing construction waste, for instance, through prefabrication (Jaillon, Poon, and Chiang, 2009; Mao et al., 2013), reusing structural elements, and recycling building materials (Allwood et al., 2012). The effectiveness of these strategies varies depending on a region’s stage of development, local building material resources, and existing building stock. For developing countries, efforts should focus on strategies for new buildings, while in regions with a significant existing building stock, priorities should include extending building lifetimes, reusing materials, and improving recycling practices.

There are currently three primary strategies of low-embodied-carbon solutions for buildings: whole-building design, one-for-one material substitution, and specification. In general, whole-building design solutions can result in the highest reductions in EC. Yet, material substitution and specification can also result in significant reductions in EC, particularly when applied to carbon-intensive materials such as concrete and steel (Esau *et al.,* 2021).

2.4.2.1 Whole-building design

Initial decisions that affect the fundamental design of a building to reduce EC while meeting the functional requirements of the project. These strategies include adaptive reuse of an existing building, reducing the overall square footage of a project, using more efficient structural systems or alternative building techniques, using prefabricated systems or components, and designing to minimize waste (Esau *et al.,* 2021).

Minimizing the built area holds significant potential for reducing EC, as it effectively avoids carbon emissions throughout all life cycle stages. Achieving this goal involves strategies such as maximizing multifunctional spaces and optimizing the use of existing space (Hu, 2022). In addition, minimizing the overall quantity of material used in a building, especially high-embodied-carbon materials such as concrete, steel, and petrochemical-based insulation products, can significantly reduce the overall EC of a project (Esau *et al.,* 2021).

The methods mentioned can be utilised in brand new buildings. However, to achieve remarkable emission mitigation benefits, it is not only necessary to pay attention to new buildings but also to diagnose the status of existing buildings and take maintenance or renovation measures as soon as possible to increase the reasonable service life of buildings (Chen et al., 2023). In this context, implementing sustainable features such as green roofs become vital.

2.4.2.1.1 Green roofing system

A green roof is an environmentally friendly feature that involves planting vegetation on the roof of a building. Green roofs, or vegetated roofs, have been considered an effective nature-based solution and have been adopted worldwide to improve urban sustainability and resilience (Mihalakakou et al., 2023). A typical green roof consists of several layers, namely:

plant/vegetation layer, growing medium/substrate, filter layer, drainage layer, protection layer, and waterproofing layer (Nadeeshani et al., 2021).

Due to these additional components, green roofs can be constructed as an addition to conventional roofing, making it possible for existing roofs to be effectively reconstructed with green roofs (Petrović et al., 2017). Several researchers have identified that green roofs can be divided into two main categories, i.e., intensive and extensive green roofs (Voelz et al., 2006; Kamarulzaman et al., 2014; United States General Services Administration, 2011). Among the types of green roofs, extensive green roofs dominate market share; in fact, this segment accounted for the largest share of the green roof market in 2020 and is expected to account for more than half of the total market share by 2027, specifically estimated to reach USD 3.6 billion in 2027 (Voelz, 2019). Green roofs are expected to be a solution to the limited urban spaces for ground EC reduction strategies (Dong and He, 2023). Studies have shown that green roof construction provides environmental, economic, and social benefits in terms of heat island mitigation, air pollution alleviation, energy demand reduction, storm water runoff control, noise attenuation, and roofing material life extension (Liu et al., 2021; Shafique, Luo and Zuo, 2020; Shafique, Kim and Rafiq, 2018; Yousefi et al., 2021).

Application of green roofs could reduce CO_2 emissions through direct and indirect impacts (Shafique, Xue and Luo, 2020). By incorporating green roofs into building designs, there is a potential to reduce carbon emissions, sequester CO_2, and mitigate the effects of climate change.

It can also reduce building energy demand by optimising envelope thermal insulation (Permpituck and Namprakai, 2012). For instance, (Berardi, 2016) revealed that a green roof has the potential to reduce the annual energy use by 4.15 KWh/m^2 in Toronto, Canada. It is important to note that the performance of green roofs depends on different design variables such as growing media, composition and thickness, slope of the roof, and type of vegetation (Akther et al., 2018). An experimental study by NRCC analysed two different green roofs with a reference roof in Toronto. The differences between green roofs were in the thickness and colour of the growing media. The analysis illustrated that the green roofs reduced the heat gain during the summer by 70–90% and heat losses during the winter by 10–30% (Mahmoodzadeh, Mukhopadhyaya and Valeo, 2020). One of the key advantages of green roofs is their ability to sequester CO_2 from the atmosphere. It was found that designers can greatly enhance carbon sequestration by adopting optimal plants for green roofs (Shafique, Kim and Rafiq, 2018). In this regard, (Agra et al., 2017) quantified the effect of the green roof plant layer on carbon sequestration. They performed the experimental research using three different roofs, with each having a different vegetation—sedum, annuals, and sedum + annuals. They found that CO_2 concentrations were reduced most in annuals, and for capturing higher carbon content in a green roof, the optimal choice was the combination of sedum and annual. Another study revealed the beneficial capacity of Buddha grass to effectively sequester CO_2, demonstrating its ability to absorb 1.79 kilogrammes of CO_2 per square metre annually (Cai et al., 2019). Green roofs provide a range of benefits, from improving energy efficiency to enhancing urban biodiversity. However, green roofs also come with some challenges, such as their end-of-life carbon analysis. The research to date has tended to focus on the general advantages of green roofs, while less attention has been paid to the environmental impacts of the layers used in green roofs (Bozorg Chenani, Lehvävirta and Häkkinen, 2015). Based on the results of a review study, it can be stated that the end-of-life phase of green roofs is a phase in their life cycle that is still an open issue not only from the regulatory point of view (absence of specific technical standards) but also from the point of view of methods for their analysis (Rizzo et al., 2023).

Due to green roofs' broad development and increasing adoption, waste generation in this area is expected to grow significantly in the future, necessitating careful attention to how the waste derived from these coverings will be managed, particularly when considering the potential environmental impact of their disposal in municipal settings (Cirrincione et al., 2022). A variety of possible end-of-life scenarios can be considered, such as recycling, reusing, or landfilling. However, researchers have emphasized the critical need to identify the most optimal end-of-life process to minimize the environmental impact associated with the disposal stage (Shafique et al., 2020). Most studies focusing on the environmental evaluation of green roofs have primarily concentrated on the operation phase, often overlooking the disposal phases during the LCA (Shafique et al., 2020). Assessing the environmental impact of green roof disposal, particularly for a stratigraphic roofing system, clearly requires detailed knowledge—layer by layer—of the end-of-life treatments to which individual green roof components are or will be subjected.

2.4.2.2 One-for-one material substitution

Direct replacement of one material with another that will meet the functional requirements of the original design while having a lower GWP (Esau et al., 2021).

A lot of research has been done to identify carbon reduction strategies, and one such approach is utilising environmentally friendly materials to lower EC.

A study by (Robati et al., 2021) determined that the structural system is the primary source of EC. The reference building, in this case, is an 18-story mid-rise concrete structure. As an alternative, using a post-tensioned concrete structure resulted in an 8% reduction in EC, while a fully timber structure achieved savings ranging from 13% to 26% (Robati et al., 2021).

Another study showed that replacing in situ construction with prefabrication has been recognised as an efficient way to reduce EC (Chen et al., 2023; Dodoo, Gustavsson and Sathre, 2009; Hu, 2022).

In (Robati *et al.,* 2021) study, the biggest decrease in EC was achieved by replacing a concrete structure with a mass timber construction. They reached the conclusion that the use of a whole-timber structure (ST.5S) and a high-performance facade (ST.6c) would cut lifecycle carbon emissions by 446 $kgCO_2e/m^2$.

A study determined the significant reduction in the cradle-to-grave net embodied emissions of a four-story office building achieved when utilizing mass timber construction as an alternative to traditional construction methods involving concrete and structural steel. The results indicate that the building constructed with steel produced a total of 3999 tons of CO_2e, whereas the mass timber design demonstrates an impressive 80–99% reduction in EC, resulting in a total of 50–795 tons of CO_2e, depending on the specific end-of-life treatment applied to the mass timber products (Greene et al., 2022). The strategy of reusing materials has been recognized as a strategy to minimize carbon emissions in construction activities (Sattary and Thorpe, 2016; Fernández-Sánchez et al., 2015). As highlighted by (Kumari et al., 2022), incorporating reused construction materials into building projects could lead to a reduction of almost 6.2% in EC. Similarly, in a study conducted by (Chau et al., 2012) that explored the emission reduction potential of various material use options over a 60-year lifespan for high-rise concrete office buildings, it was found that substantial EC emission savings, approximately 17%, could be realized by reusing between 15% and 30% of existing non-structural and structural components in the building construction process. Furthermore, the study also identified that a 3% reduction in emissions could be achieved by reusing between 5% and 10% of the existing material resources, emphasizing the importance of reusing materials to reduce the environmental impact of construction activities.

2.4.2.3 Specification

Specification means establishing a value or limit for a material characteristic that will dramatically reduce EC content (Esau et al., 2021).

Depending on the building type, strategies for reducing EC can vary. According to (Robati and Oldfield, 2022) the EC profile of concrete and timber buildings requires different strategies to minimize their environmental impact. In concrete structures, the majority of EC emissions occur initially, or in stage A of the lifecycle. This indicates that initiatives to dematerialize concrete in structural design, reduce emissions through cement replacement materials would be the most effective at reducing EC. In contrast, timber structures would benefit from end-of-life emission reduction techniques.

(United Nations, 2015) concluded the use of cement replacements such as pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) can have a very significant effect in reducing the EC for concrete.

Concerning the GGBS, the proportion of replacement by GGBS can climb to 75% (Gan, Cheng and Lo, 2019). As characterized by the cementitious behaviour similar to Portland cement, cement replaced by GGBS brought less adverse impacts on the overall compressive strength, despite the high replacement ratio (Lee et al., 2021; Teh et al., 2017). Based on the results of prior studies, incorporating GGBS in main components in concrete buildings potentially could achieve a 10% to 30% EC reduction, while having no substantial impact on the structural performance of the components or the building in this range (Teng and Pan, 2019; Zhang et al., 2018).

Crossin (2015) also reported that a maximum reduction of 47.5% CO_2 emissions could be achieved by replacing 70% of OPC with GGBS in concretes. Gan et al. (2017) identified that using 75% GGBS in major building components such as walls and slabs could achieve around 10%-20% EC reduction for a 60-story office building. Similar study in a 40-story concrete residential building concluded that 13% - 28% EC reduction was found when employing 35% - 75% GGBS for replacement (Gan et al., 2018).

By incorporating Fly Ash (FA), research indicates that the physical and structural performance of concrete is minimally impacted even when replacing 30% to 40% of ordinary cement (Chen et al., 2023).

Zhao et al. (2022) determined that substituting 50% of OPC with FA in concrete could lead to a substantial reduction of approximately 41.4% in CO_2 emissions. It's worth noting that the recommended proportion typically falls within the range of 15% to 25%. (Nath and Sarker, 2011; Tushar et al., 2022).

It's important to highlight that substituting 75% of the cement with GGBS in concrete has a significantly more substantial potential impact on reducing EC in buildings when compared to a 35% replacement with FA (Gan et al., 2017). The utilization of ready-mixed concrete incorporating 75% GGBS can lead to a 20% reduction in the EC of buildings, which underscores its effectiveness as a strategy for achieving lower-carbon construction (Gan et al., 2017).

Additionally, it was noted that while steel accounted for only a minor portion of the total consumption of building materials, it was, in fact, the largest user of energy and the most significant carbon emitter among construction materials (Chen et al., 2022).

The most straightforward and practical approach to reducing EC for structural steel today is to specify and prioritize the use of steel that is produced in facilities operating with relatively low-emissions (or even zero-emissions) energy sources, such as hydroelectric power, renewable hydrogen, solar energy, or wind energy (Luo et al., 2015).

For energy-intensive building materials like steel, improving steel recycling and using low carbon energy sources and technologies in manufacturing are effective strategies. By transforming the currently dominated Basic Oxygen Furnace (BOF) to Electric Arc Furnace (EAF), significant carbon reductions in steel production can be achieved (Chen et al., 2022).

Certain design factors like the type and quantity of recycled materials can significantly influence EC. A study compared the EC of three building types: steel, composite (RC and steel buildings), and RC buildings. The steel building had the highest EC at 759 $kgCO_2e/m^2$ GFA, surpassing the composite and RC buildings by 25% and 30%, respectively. The research demonstrated that increasing the recycled steel content reduces the EC in all three buildings. When recycled steel makes up 28%, the EC of the RC building exceeds that of the composite building. Interestingly, with 70% recycled steel, the RC building has more EC than the steel building. However, at nearly 80% recycled steel, the steel building exhibits the lowest EC among the three buildings (Gan et al., 2017).

This research will examine various strategies for reducing EC to identify the elements that most significantly affect EC reduction and measure their potential to lower total EC emissions in buildings.

Chapter 3 : Methodology

Research Methodology is about how a researcher intends to carry out their research to ensure valid and reliable results that address the research aim and objectives.

Research methodology refers to the research technique, especially the numerous sorts of activities to systematically handle the research problem, which is founded on assumptions and justification of choices made (Wohlin and Runeson, 2021).

3.1 Research Paradigm

A research paradigm is a fundamental framework that guides the research process, shaping how research is conducted and interpreted. It encompasses a set of assumptions, beliefs, and principles that influence the researcher's worldview and approach to inquiry (Ulz, 2024).

Research paradigms help researchers understand how to approach their study, form their research questions, select appropriate methodologies, and interpret results within a specific worldview or theoretical perspective (Alele and Malau-Aduli, 2023). There are various research paradigms, including positivism, interpretivism, pragmatism, critical theory, and more, each with its own assumptions and methodologies (Rehman and Alharthi, 2016).

In order to provide the research questions with a firm theoretical and practical background, this research will follow a positivist approach, which relies on a quantitative approach and statistical analysis of collected data. Positivism research philosophy believes that there is a single reality which can be measured and known. In positivism-based research, a hypothesis is proposed which is proved using statistical analysis of data.

The method that will be used to carry out this research follows a quantitative approach, and the data is collected through existing data sources. Compared to qualitative research, quantitative analysis uses statistical data from computer models that save time and money (Bryman, 2012).

The quantitative data that positivist researchers use to answer research questions and formulate theories can be collected through true experiments or less rigorous quasi-experiments, standardized tests and large or small scale surveys using closed ended questionnaires. The numeric data that are generated through these methods are subjected to descriptive or inferential statistical analysis (Rehman and Alharthi, 2016).

According to the positivist approach, research is deemed to be of good quality if it has a) internal validity b) external validity c) reliability d) objectivity (Guba & Lincoln, 1994). If the researcher proves that it is the independent variable (and not other variables) that had an effect on the dependent variable, the study is considered to have internal validity. If the results thus arrived at are generalizable, it has external validity. If different researchers conduct the study in different times, places and contexts and arrive at the same results, it has reliability. If researchers study phenomena without contaminating their apprehension, they are considered to be objective (Rehman and Alharthi, 2016).

3.2 Research Design

A research design should tackle the research problem adequately and indicate that the chosen methodology is appropriate for the topic. It should be directly relevant to the study's clear aim. It will help the researcher to gain the most accurate result.

In this PhD research, the research design assesses the EC reduction potential for residential, college and hotel buildings. In this regard, it is important to analyse the EC emissions in the mentioned buildings to identify materials and life cycle stages with highest EC potential.

The research will focus on investigating various EC reduction strategies and propose the ideal strategy in terms of CO_2 emissions and also establish a set of recommendations for sustainable CO_2 reduction.

The first step will be exploring previous literature related to EC in buildings and different reduction EC methodologies in the building sector. This stage is very important because it will give us a better understanding of the current situation and different approaches to reach an ideal structural system. The scope of this study is cradle to cradle.

Thanks to a growing consensus around an LCA technique based on EN 15978, structural engineers are increasingly becoming more familiar with the detailed calculation of EC. Indeed, the most recent guidance from the Institution of Structural Engineers (ISE) provides a simple, clear, and comprehensive interpretation that makes this process easier and more accessible than ever before, and it adds to a chorus of similar, industry-focused guidance from the RICS. This research will be systematically carried out using both the ISE and RICS guidelines to calculate EC during various stages of the buildings' life.

The standard design model will be simulated using BIM software, Autodesk® Revit®, for the case studies which provides accurate quantity of materials within the project.

The fundamental principle of an EC calculation is to find and utilize the most reliable and accurate databases available. In the UK, the construction industry has developed a number of comprehensive and specialized databases that can be used to figure out and assess how much carbon is in building materials.

The first two preferred carbon factors will be EPD and ICE database. If neither an EPD nor data from the ICE database is available, alternative acceptable and credible data sources will be identified and utilized to generate an ECF for each material or component. Initially, various EC databases will be evaluated and compared in the first stage to assess their reliability and accuracy. Following this, the EC at various stages of the building's life cycle will be calculated in the next phase using the traditional method.

Then, a BIM and LCA integration system will be designed using Dynamo in Revit, utilizing Python coding to automate the EC assessment process. This system will subsequently be applied to the case studies to calculate the EC emissions at various stages of the building's life cycle. Once the calculations are complete, the results of the automated assessment method will be compared with the results obtained through traditional methods, and the accuracy and efficiency of the automated method will be evaluated and assessed.

After that, a color-coded visualization system will be implemented, allowing the components of the building to be visually distinguished based on their respective EC emissions. Opportunities for reducing EC will then be presented using strategies focused on incorporating less carbon-intensive building materials. Finally, the maximum achievable EC reduction will be calculated based on the application of these lower-carbon material strategies.

In addition to exploring EC reduction strategies, the hotel building will also involve the analysis of OC to gain a deeper understanding of the broader environmental benefits associated with carbon reduction measures. If an analysis of OC is required, the three-dimensional model will be transmitted to Insight, a cloud-based tool designed for performance analysis and simulation, where an energy analysis of the building will be conducted. To ensure the validity and reliability of the models created in Insight, the energy consumption results obtained from the simulation will be compared, wherever possible, to the actual energy consumption data from the buildings.

3.3 Modelling Strategy

3.3.1 Modelling Process

This research initially employs the Type I (traditional) BIM-LCA integration approach for assessing the EC of case studies and then introduces Type IV (Automated) BIM-LCA integration approach which is a novel method for integrating BIM with LCA. Subsequently, the results of this new approach are compared with the initial method for validation. Details of the modelling processes for both approaches are explained below.

3.3.1.1 Type I BIM-LCA integration approach

This research initially utilizes the Type I approach to perform the EC assessment on the selected case studies. In order to gather essential data for the simulation process, the initial step involves conducting a comprehensive site visit, marking the preliminary phase of the simulation. During this phase, a thorough survey of the actual buildings is carried out to collect crucial information required for accurate analysis. This includes obtaining AutoCAD plans and detailed information on the building's construction, such as the year it was built and the materials used in its structure. AutoCAD drawings are employed to extract precise measurements of elements like doors and windows, including their dimensions and quantities, as well as to determine critical structural details such as floor height. These drawings also include the necessary zones, clearly identifying spaces such as bedrooms, bathrooms, offices, kitchens, laundry areas, and other functional areas, ensuring comprehensive data collection for the assessment process.

To ensure precise material quantity calculations for the research, the standard design will be simulated in Autodesk® Revit®. The modelling process relies on the design plan data provided by the constructor to precisely determine the quantity of materials used in the construction of the building. Subsequently, a diverse set of ECFs, including EPD, ICE database, RICS guidelines and relevant research sources applied. These factors are multiplied by the respective quantities of materials, showing comprehensive insights into the EC emissions associated with various building materials across their life stages (Figure 3.1).

If an analysis of OC was required, the 3D dimensional model was transmitted to Insight, a cloud-based tool for performance analysis and simulation, where energy analysis of the building was performed. Insight serves as an invaluable adjunct to BIM software, particularly Revit, for comprehensive performance analysis and simulation of building designs. Insight is designed to provide data-driven and evidence-based insights into various aspects of a building's performance.

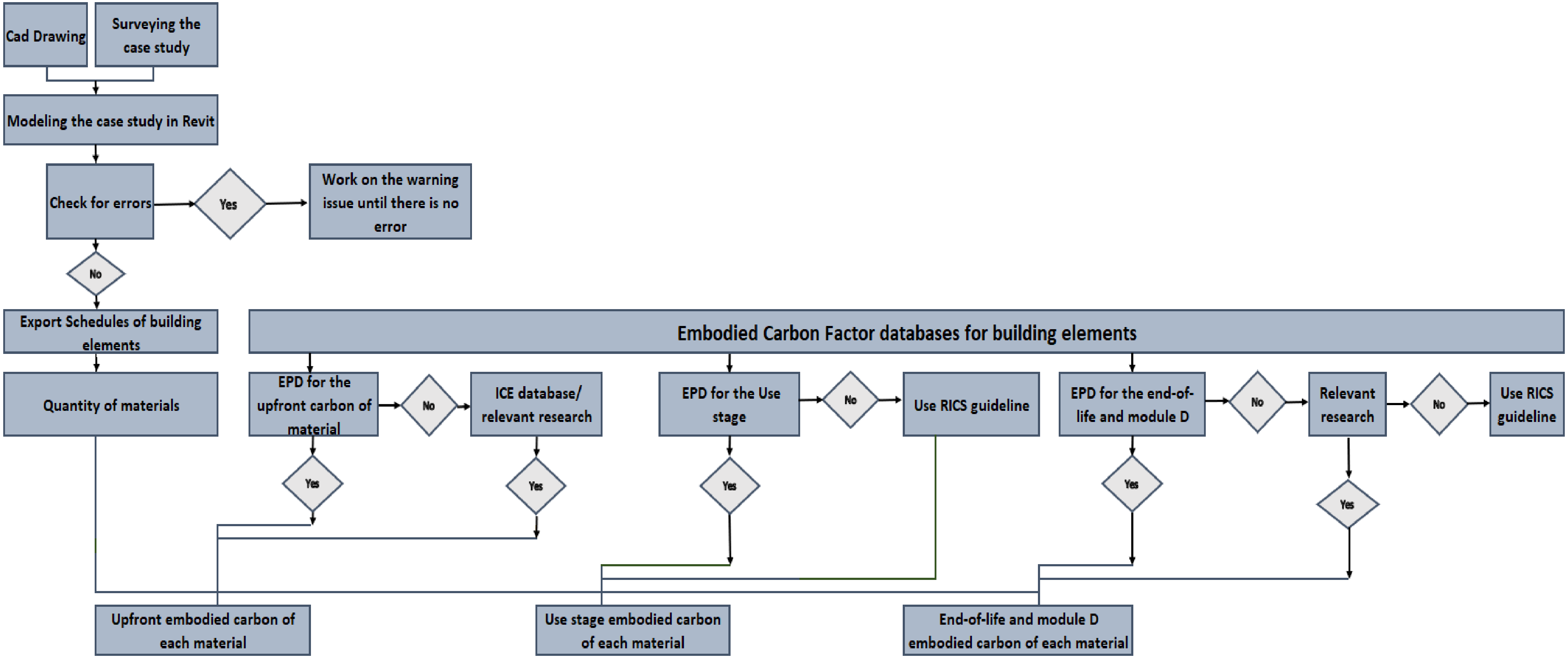


Figure 3.1: Modelling and calculation process for ECA for building materials

3.3.1.2 Type IV BIM-LCA integration approach

In the Type IV approach, as in Type I, the building is initially modelled in Revit after carefully collecting all the essential data required for the modelling process. A dedicated and comprehensive database has been specifically developed to gather all the necessary information needed for conducting WLEC assessments of UK buildings. This database is primarily based on EPD, ICE database, RICS guideline, and relevant research sources. The database is seamlessly integrated into the Dynamo environment within Revit, creating a streamlined and efficient platform for conducting these assessments. By utilizing Dynamo, the developed database can be seamlessly imported into the Revit environment, where EC calculations are performed efficiently through Python scripting. This scripting process has been carefully refined and saved as a reusable script, making it highly adaptable and facilitating its use across multiple projects, thereby significantly reducing the time required to complete EC assessments. Finally, a color-coding system is applied to visualize the EC potential of individual building components, enabling a clear representation of the results through effective colour differentiation (Figure 3.2).

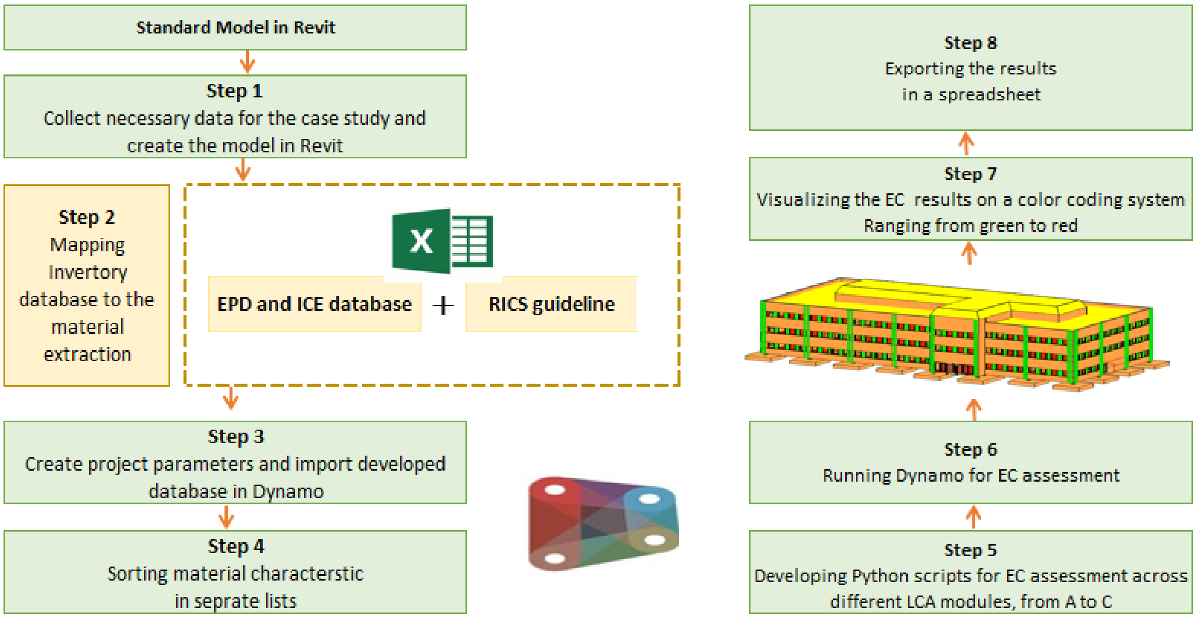


Figure 3.2: Methodology for Automating EC Assessment in Revit

3.3.2 Modelling Validation

3.3.2.1 Validation of Type IV Integration Between BIM and LCA

To validate the models developed through Type IV integration of BIM and LCA, the percentage difference or error between the two methods is calculated as follows: the EC calculated with the Type IV approach at each life stage of the building, from material extraction to end-of-life ($EC_i^{Type\ IV}$) is subtracted from the EC calculated using the Type I approach ($EC_i^{Type\ I}$). This result is then divided by the EC calculate using Type I approach ($EC_i^{Type\ I}$) and multiplied by 100, providing the percentage difference or error between the two methods, as outlined in Equation 3.1.

$$\text{Percentage error} = \frac{EC_i^{Type\ I} - EC_i^{Type\ IV}}{EC_i^{Type\ I}} \times 100 \qquad (3.1)$$

3.3.2.2 Validation of Energy Consumption Model

In order to validate the models created on Insight the actual annual energy consumption of the building (A^{ec}) is subtracted from the modelled energy consumption (M^{ec}); divided by the actual annual energy consumption of the building (A^{ec}) and multiplied by a 100 to provide the percentage difference or error between actual and modelled energy consumption (Equation 3.2).

$$\text{Percentage error} = \frac{M^{ec} - A^{ec}}{A^{ec}} \times 100 \qquad (3.2)$$

3.3.3 GIA Calculation

This section estimates the Gross Internal Area (GIA) of the model, which contributes to the overall structural score. The process involves identifying individual floor elements, calculating their areas, and summing them up. Specifically, the calculation excludes certain factors, such as perimeter wall thickness and external projections, which are typically omitted in standard GIA calculations. It is noted that in the detailed design stage, adjustments can be made to the GIA calculations to incorporate these exclusions more accurately, thereby improving the precision of the evaluation.

3.4 Calculation Model

3.4.1 Life Cycle Assessment Methodology

LCA is a systematic method for evaluating the environmental impact of products and procedures throughout their entire life cycle. It aims to identify and assess environmental impacts at all stages of a product's life cycle, from raw material extraction to disposal, and generates comprehensive data representing the overall environmental burden of the product (Kumanayake, Luo, and Paulusz, 2018). BS EN 15978, a recognized standard, categorizes the life cycle of a building into the following distinct modules: product (A1-A3), construction (A4-A5), use (B), end-of-life (C), and re-use/recovery potential (D), with the latter accounting for any advantages or benefits outside the system boundary. Including more of these steps allows for a more detailed and holistic understanding of the environmental effect to emerge (Papakosta and Sturgis, 2017). Figure 3.3 illustrates the life cycle stages of an asset, providing a visual representation of these phases (Gibbons et al., 2022).

According to the International Organization for Standardization (ISO), the LCA procedure consists of the following key steps:

1. **Goal and Scope:** This step determines which processes of the unit's life cycle will be included in the assessment and establishes the primary purpose of the analysis (Mohebbi et al., 2021). In this phase, critical elements such as the boundary, functional unit, assumptions, and intended purpose of the study are clearly defined (Ortiz, Castells, and Sonnemann, 2009).

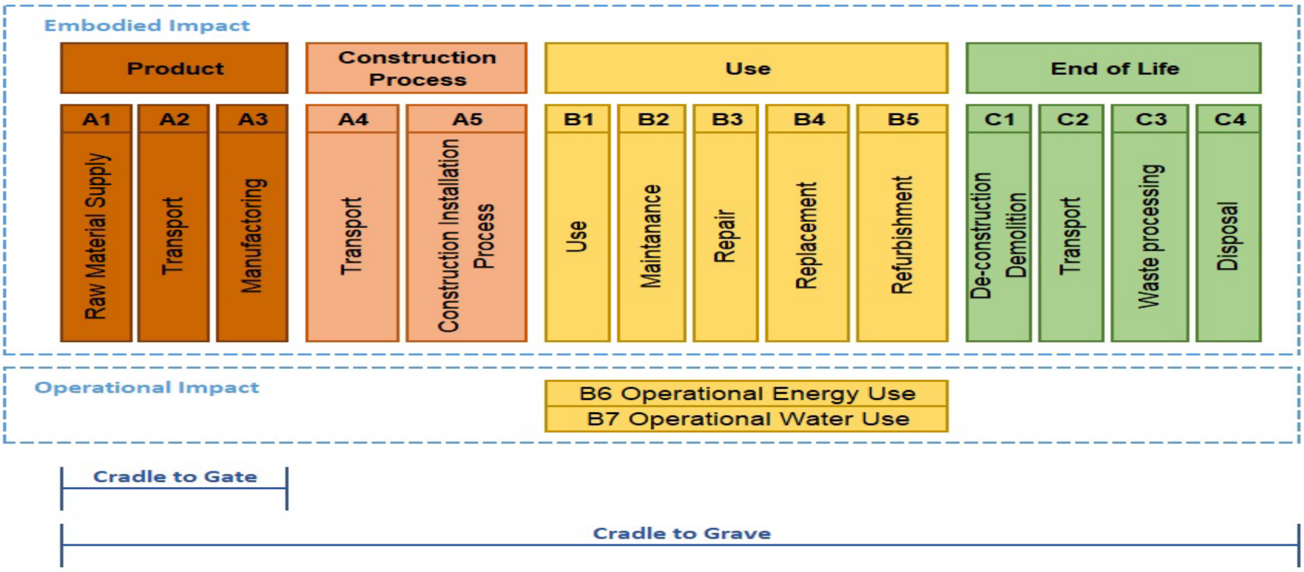


Figure 3.3: WLC emissions of a building reproduced from IStructE 'How to Calculate Embodied Carbon' (Gibbons et al., 2022)

2. **Life cycle inventory (LCI):** This step involves the systematic collection of input data that is required for the assessment process.
3. **Life cycle impact assessment (LCIA):** It includes the evaluation of both the size and the significance of the environmental impacts associated with a product throughout its entire life cycle.

4. **Life cycle Interpretation:** This stage focuses on the detailed analysis of the results obtained from the LCI and LCIA, ensuring they align with the defined goal and scope (Mohebbi et al., 2021).

Figure 3.4 provides a detailed description of the LCA methodology as outlined in the ISO standards (ISO, 2006).

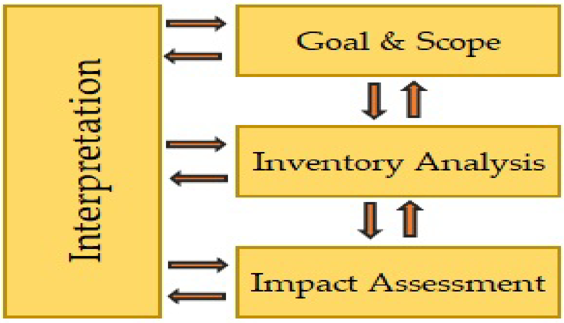


Figure 3.4: Description of LCA methodology in the ISO standard

3.4.2 Embodied Carbon Definition

Cradle-to-Cradle carbon refers to the carbon emissions that are released during various stages of a material's lifecycle, including its extraction, processing, manufacturing, demolition, transportation, waste processing, and eventual final disposal. The fundamental principle underlying an EC calculation involves multiplying the quantity of each material used by its corresponding carbon factor for the specific life cycle modules that are being considered (Equation 3.3) (Gibbons et al., 2022).

$$\mathrm{EC_i} = \sum \mathrm{i}\left(\mathrm{Q_{mat,i}} \times \mathrm{ECF_i}\right) \tag{3.3}$$

3.4.2.1 Product stage Embodied Carbon (A1-A3)

This stage involves the processing of raw materials and the manufacturing of building materials, which are essential steps in the construction process. The emissions generated during this stage are primarily caused by chemical reactions and the consumption of energy sources, such as diesel, gasoline, and electricity, during the manufacturing of a product from raw materials. These activities contribute significantly to the environmental impact of the product stage. The total amount of carbon emissions associated with the product stage (A1-A3) is determined using the calculations outlined in equations 3.4 (Gibbons et al., 2022).

$$\mathrm{EC_{A13}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \left[\mathrm{Q_i}\left(\mathrm{ECF_{A13,i}}\right)\right] \tag{3.4}$$

Where Q_i is the weight of $\mathrm{i^{th}}$ material, $\mathrm{ECF_{A13,i}}$ is the ECF associated with $\mathrm{i^{th}}$ material.

3.4.2.2 Transportation (A4)

The carbon factors for the transportation of each material to the site and the transportation of waste materials from the site to either landfills or recycling plants are calculated by multiplying the transportation distances provided in Table 3.1 by the respective emissions factors associated with the transportation modes, as outlined in Table 3.2. The detailed formula used for the ECF calculation is presented below (Gibbons et al., 2022).

$$\mathrm{ECF_{A4}} = \sum_{j} (\mathrm{TD_{mode}} \times \mathrm{TEF_{mode}}) \tag{3.5}$$

Where $\mathrm{ECF_{A4}}$ is ECF of transport to/from site for j^{th} material, $\mathrm{TD_{mode}}$ is transport distance for each transport mode and $\mathrm{TEF_{mode}}$ is transport emission factor for each transport mode considered.

Table 3.1: Transport emissions factors for the UK reproduced from IStructE 'How to Calculate Embodied Carbon' (Gibbons et al., 2022)

Mode	**$\mathrm{TEF_{mode}}$ ($\mathrm{gCO_2e/kg/km}$)**
Road transport emissions, average laden	0.10749
Road transport emissions, fully laden	0.07375
Sea transport emissions	0.01614
Freight flight emissions	0.53867
Rail transport emission	0.02782

Table 3.2: ECF for Module A4 for the UK reproduced from IStructE 'How to Calculate Embodied Carbon' (Gibbons et al., 2022)

A4/C2 transport scenario	**km by road**	**km by sea**	**$\mathrm{ECF_{A4,i}}$ ($\mathrm{kgCO_2e/kg}$)**
Locally manufactured	50	-	0.005
Nationally manufactured	300	-	0.032
European manufactured	1500	-	0.161
Globally manufactured	200	10000	0.183

3.4.2.3 Construction Installation Process (A5)

Module A5 emissions are divided into two distinct subsets for better categorization and analysis. The emissions associated specifically with the volume of each material wasted on-site are identified as A5w emissions, while the emissions resulting from general construction activities, such as energy consumption from machinery operations and the use of temporary site offices, are categorized separately as A5a emissions (Equation 3.6).

The carbon factor for material wastage on-site (A5w) is calculated by multiplying a specific waste factor by the sum of the carbon factors associated with the product's production phases (A1–A3), the transportation of the product to the site for construction activities (A4), the transportation of waste materials away from the site for processing or disposal (C2), and the waste processing or disposal phases (C3–C4) (Equation 3.7) (Gibbons et al., 2022).

$$\mathrm{EC_{A5} = EC_{A5w} + EC_{A5a}} \tag{3.6}$$

$$\mathrm{ECF_{A5w,k} = WF_k \times (ECF_{A13,k} + ECF_{A4,k} + ECF_{C2,k} + ECF_{C34,k})} \tag{3.7}$$

Where $\mathrm{ECF_{A5w,k}}$ is construction waste ECF for k^{th} material, $\mathrm{WF_k}$ is waste factor for k^{th} material, $\mathrm{ECF_{A13,k}}$ is ECF for A1–A3 for k^{th} material, $\mathrm{ECF_{A4,k}}$ is ECF for transport to site for k^{th} material, $\mathrm{ECF_{C2,k}}$ is transportation away from site carbon factor, $\mathrm{ECF_{C34,k}}$ is waste processing and disposal ECF (Gibbons et al., 2022).

$$\mathrm{EC_{A5a} = CAEF \times PC/100{,}000} \tag{3.8}$$

Where $\mathrm{EC_{A5a}}$ is EC from construction site activities (A5a), CAEF is construction activities emission factor of 700kgCO_2e/£100,000 for superstructure and substructure only, or 1,400kgCO_2e/£100,000 for whole building, and PC is project cost (Equation 3.7) (Gibbons et al., 2022).

3.4.2.4 Maintenance impacts (B2)

For all built assets, regular maintenance activities, including cleaning, play a crucial role in extending their lifespan and are important for avoiding the deterioration of critical building elements such as facades and internal spaces. Regular maintenance also ensures continued operational efficiency, maintains a good and appealing appearance, and preserves the validity of any warranties associated with the building. Module B2 must comprehensively account for the carbon impacts resulting from any activities associated with maintenance processes, including cleaning tasks, as well as any products or materials used, and the waste generated over the reference study period (RSP) (Sturgis et al., 2023).

The RSP that must be used for compliant WLCAs, as outlined based on the principles in EN 15978 and EN 17472, are set at 60 years for both domestic and non-domestic buildings. These RSPs are fixed and do not impose a limit on the actual life expectancy of a project; rather, they are designed to ensure consistent and comparable assessments between different projects. The RSPs are not meant to reflect the actual desired lifespan or the expected service life of an asset, as their purpose is purely for standardizing the comparison process (Sturgis et al., 2023).

Due to the limited availability of data regarding carbon factors specifically for maintenance activities (B2) (Gibbons et al., 2022), the London Plan Guidance for WLC Assessments (2022) emphasizes the importance of adopting a comprehensive and standardized approach. For the assessment of module B2 impacts within the UK context, the guidance recommends using a standardized figure of 10 $kgCO_2e/m^2$ GIA. This figure is intended to provide a consistent and inclusive estimate that covers all relevant building element categories.

3.4.2.5 Repair impacts (B3)

Module B3 is specifically intended to provide a reasonable allowance for repairing unpredictable damage that occurs over and above the routine maintenance regime, where repairing a product or system involves returning it to an acceptable or functional condition through the renewal, replacement, or mending of individual worn, damaged, or degraded parts. Module B3 must comprehensively take into account all carbon impacts arising from activities related to the repair processes, including any products used in the repair and any waste materials produced throughout the process over the Reference Study Period (RSP). All impacts from the production of repair materials, their transportation to and from the site, and the installation of the repaired items must be fully included in the calculation. This obligation extends to covering any material losses or inefficiencies occurring during these processes, such as the disposal of failed or irreparable parts (Sturgis et al., 2023). Due to the scarcity of robust data informing carbon factors specifically for repair activities (B3) within the UK context, it is advisable to adopt an estimated approach. Repair impacts may be considered as approximately 25% of the impacts associated with B2 maintenance activities, as suggested by Sturgis et al. (2023).

3.4.2.6 Replacement impacts (B4)

Module B4 relates to the EC associated with replacing building elements during the RSP e.g. replacement of the facade during RSP (Gibbons et al., 2022).

Module B4 must comprehensively take into account any carbon impacts associated with the anticipated replacement of built asset components, including any potential impacts arising from the replacement process, throughout the RSP. All relevant impacts from the production, transportation to the site, and installation of the replacement items must be thoroughly included, as well as any material losses incurred during these processes, along with any impacts related to the removal and end-of-life treatment of replaced items (Sturgis et al., 2023). In the UK, the specified lifespans provided in Table 3.3 should be used as the standard for building components.

Table 3.3: Indicative component lifespans (Sturgis et al., 2023)

Building part	Building elements/components	Expected life span
Substructure	Foundation	60 years
Superstructure frame, upper floor and roof structure	Structural elements, e.g. columns, walls, beams, upper floor and roof structure	60 years
Facade	Brick, stone, block and precast concrete panels	60 years
	Hardwood/steel/aluminium windows	30 years
	Doors	20 years
Roof	Roof covering:	
	Standing seam metal	30 years
	Tiles, clay and concrete	60 years
Superstructure	Internal partitioning:	
	Studwork	30 years
	Blockwork	60 years

Ceiling	Suspended grid (ceiling system)	25 years

The carbon factor for Module B4 is the number of times a component is replaced in the built asset's RSP multiplied by the sum of the carbon factors for life cycle modules A1–A4, A5w and C2–C4 (Equation 3.9).

$$\mathrm{ECF_{B4,i}} = \left[\frac{\mathrm{RSP}}{\mathrm{CL_i}} - 1\right] \times \left(\mathrm{ECF_{A13,i}} + \mathrm{ECF_{A4,i}} + \mathrm{ECF_{A5w,i}} + \mathrm{ECF_{C2,i}} + \mathrm{ECF_{C34,i}}\right) \tag{3.9}$$

$\mathrm{ECF_{B4,i}} =$ Replacement emissions for ith material

$\mathrm{RSP} =$ Asset reference study period. The suggested default RSP is 60 years for buildings (Sturgis et al., 2023).

$\mathrm{CL_i} =$ Estimated component lifespan for ith material.

3.4.2.7 Demolition stage Embodied Carbon (C1)

The demolition of the building structure is carried out using excavators. Excavators must deal with the interior and the building structure at the same time. Mixed waste is mainly obtained at the end of demolition, as sorting is less precise. Equation 3.10 shows the formula for calculating demolition EC.

$$\mathrm{EC_{C1}} = \sum\nolimits_{\mathrm{j}} \left(\mathrm{Q_{mac,j}} \times \mathrm{ECF_{mac,j}}\right) + \left(\mathrm{Q_{energy,e}} \times \mathrm{ECF_{energy,e}}\right) \tag{3.10}$$

$\mathrm{EC_{C1}}$ represents the carbon emissions concern with on-site machinery operation and energy consumption for demolition where $\boldsymbol{Q_{mac,j}}$ Refers to time of type j machinery operation and $\boldsymbol{Q_{energy,e}}$ is the quantity of type 'e' energy.

3.4.2.8 Waste transport stage Embodied Carbon (C2)

Any carbon emissions related to the transportation of deconstruction and demolition waste to the proper disposal site, including landfills, reuse, and recycle plants, must be captured in module C2 (Equations 3.11 and 3.12) (Gibbons et al., 2022).

$$\mathrm{EC_{C2}} = \sum_{\mathrm{k}} \left(\mathrm{Q_{tran,k}} \times \mathrm{ECF_{C2,k}}\right) \tag{3.11}$$

$$\mathrm{ECF_{C2,k}} = \sum_{\mathrm{k}} \left(\mathrm{TD_{mode}} \times \mathrm{TEF_{mode}}\right) \tag{3.12}$$

Where $\mathrm{Q_{tran,k}}$ is the quantity of type 'k' transport material from site, $\mathrm{TD_{mode}}$ is the transport distance for each transport mode considered and also $\mathrm{TEF_{mode}}$ is the transport emission factor for each transport mode considered.

3.4.2.9 Waste processing stage Embodied Carbon (C3, C4)

When materials and/or parts are meant to be recovered, reused, or recycled at the end of a built asset's life, all carbon emissions related to their treatment and processing before reaching the end-of-waste state must be included in module C3 (Equation 3.13) (Gibbons et al., 2022).

$$\mathrm{EC_{C3}} = \sum_{\mathrm{l}} \left(\mathrm{Q_{wap,l}} \times \mathrm{ECF_{C3,l}}\right) \tag{3.13}$$

Where $Q_{wap,l}$ is the quantity of type 'l' material for waste processing.

For elements that are not expected to be recovered and recycled but are intended for final disposal in a landfill or incineration, the parameter C4 must account for the emissions resulting from their disposal (Equation 3.14). Table 3.4 represents site waste disposal scenarios in detail. It shows three different scenarios for the EC produced from the product stage to the end-of-life (Gibbons et al., 2022). The waste management practices for end-of-life materials in the UK are outlined in Table 3.5. These values are collected from Standards, EPDs, and relevant research papers to ensure accurate and reliable data is presented.

$$\mathrm{EC_{C4}} = \sum_{1} (\mathrm{Q_{dis,m}} \times \mathrm{ECF_{C4,m}}) \tag{3.14}$$

Where $\mathrm{Q_{dis,m}}$ is the quantity of type ‘m’ material for disposal.

Table 3.4: Site waste disposal scenarios (Papakosta and Sturgis, 2017)

Disposal to landfill/incineration	Reuse or recycling on-site	Reuse or recycling off-site
(A1-A3) +(A4) +(C2)+(C4)	(A1-A3) +(A4) +(C3)	(A1-A3) +(A4) +(C2)+(C3)

Table 3.5: The waste management practices for end-of-life materials in the UK

Material	Reuse	Recycle	Incineration	Landfill	Source
Plasterboard	0	4%	0	96%	EPD Number: S-P-04921
Steel	0	85%	0	15%	Gibbons et al., 2022
Aluminium	0	95%	0	5%	Gibbons et al., 2022
Glass	0	50%	0	50%	Blay-Armah A, 2022
Timber	0	55%	44%	1%	Gibbons et al., 2022
Concrete	0	90%	0	10%	Gibbons et al., 2022
Rebar	0	92%	0	8%	Gibbons et al., 2022
Plastic	0	33%	38%	29%	Cullen, Drewniok & Cabrera Serrenho, 2020
Brick	0	90%	0	10%	Gibbons et al., 2022
Polyethylene (membranes, pipes)	0	5%	85%	10%	Delem and Wastiels, 2019

Table 3.5 highlights that, at present in the UK, reusing materials is not a widespread practice. The predominant approaches involve either recycling the materials or directing them to landfills.

3.4.2.10 Module D carbon factor

Module D estimates the benefits and burdens of materials and components beyond the buildin g's end-of-life date. According to (Sturgis et al., 2023), to calculate Module D emissions, compare the difference between carbon emissions of recovered materials (reuse, recycling, or incineration) and carbon emissions of the primary material (Equation 3.15).

$$\mathrm{Module\ D} = (\mathrm{M_{MR\ out}} - \mathrm{M_{MR\ in}}) \times ([\mathrm{E_{MR\ after\ EoW\ out}}] - \left([\mathrm{E_{VMSub\ out}}] \times \left[\frac{\mathrm{Q_{R\ out}}}{\mathrm{Q_{R\ in}}}\right]\right)) \tag{3.15}$$

$\mathrm{M_{MR\ out}}$ = Amount of material that will be recovered (recycled and reused) in a subsequent system

$\mathrm{M_{MR\ in}}$ =Amount of material that has been recovered (recycled or reused) from a previous system

$\mathrm{E_{MR\ after\ EoW\ out}}$ = Specific emissions and resources consumed, per unit of analysis, arising from the material recovery (recycling and reusing) processes of a subsequent system after the end-of-waste state.

$\mathrm{E_{VMSub\ out}}$ = Specific emissions and resources consumed, per unit of analysis, arising from acquisition and pre-processing of the primary material

$\frac{\mathrm{Q_{R\ out}}}{\mathrm{Q_{R\ in}}}$ = Quality ratio between outgoing recovered material (recycled and reused) and the substituted material

Module D comprehensively covers the potential loads and benefits that can be derived from reusing or recycling materials and components at the end of their life, or from any energy that may be recovered from them at the end of life (e.g., energy obtained from waste, incineration processes, or the use of captured landfill gas). Module D is particularly relevant to any end-of-life output that arises from the asset during the construction phase (module A5); as well as during maintenance, repair, replacement, and refurbishment activities (modules B2–B5); and from processes related to waste treatment and disposal (modules C3 and C4) (Sturgis et al., 2023) (Figure 3.5).

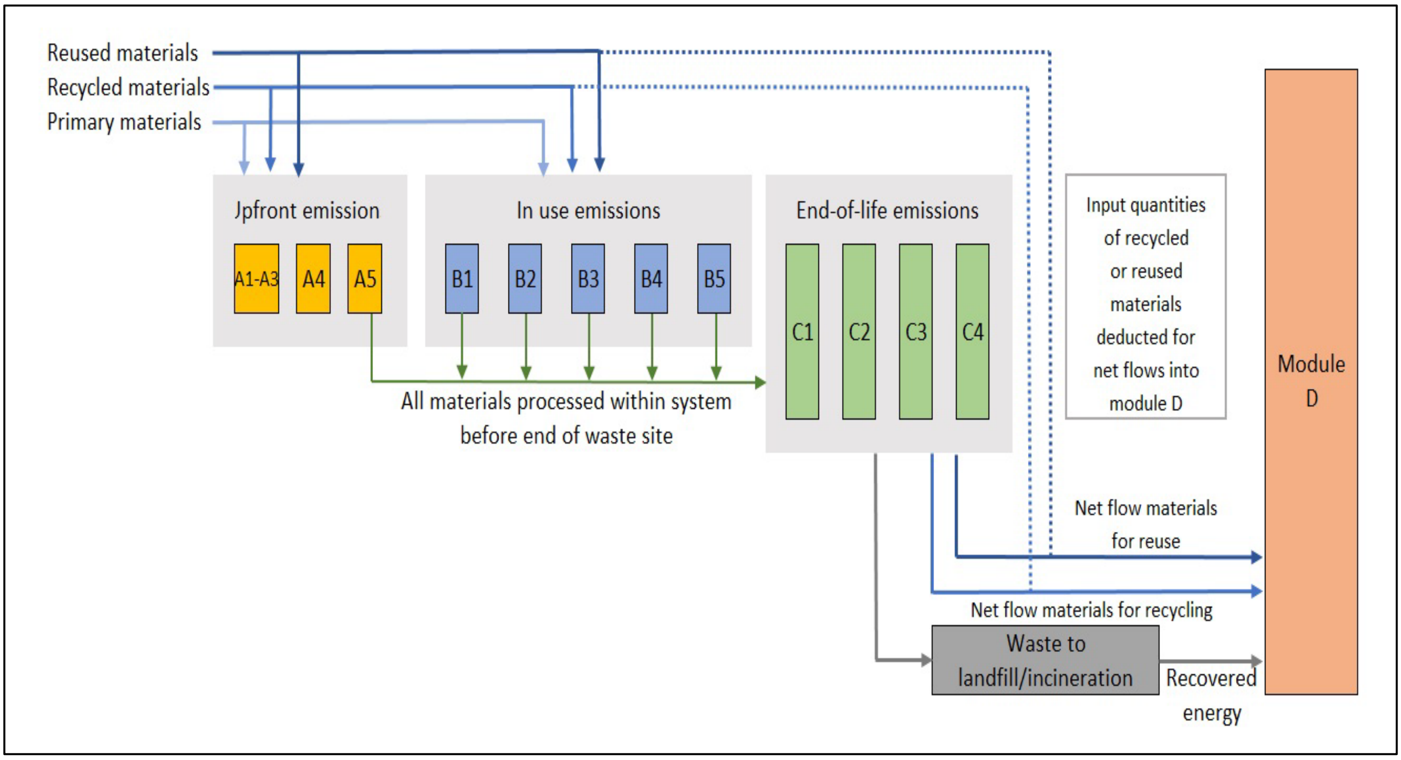


Figure 3.5: Flow of materials and emissions between modules

Carbon emission data originates from various reputable sources including the ICE database, IStructE guideline, EPDs, and other validated resources.

Module D is intended to provide a broader picture of the environmental impacts of a project by accounting for the future potential of its components when these are repurposed i.e. recovered and reused and/or recycled. Module D includes the potential environmental benefits or burdens of materials and components beyond the life of the project (Papakosta and Sturgis, 2017).

3.4.3 Biogenic Carbon

Biogenic carbon is the carbon absorbed and stored in trees during growth through photosynthesis. Trees capture CO_2 from the atmosphere, storing it in their wood. While storing biogenic carbon in timber structures offers climatic benefits, it doesn't offset the immediate effects of fossil carbon emissions. The table 3.6 shows the ECF of biogenic carbon in timber materials across three buildings, sourced from the ICE database. Timber materials are assumed to originate from a sustainably managed forest with FSC certification.

Table 3.6: The biogenic carbon for timber materials

Material	**ECF (Biogenic Carbon) ($kgCO_2e/kg$)**
Timber, MDF	-1.5
Timber, Softwood	-1.55
Timber, Hardwood	-1.59
Timber, I Joist Beam	-1.53
Timber, Glulam	-1.41
Timber, Chipboard	-1.52

3.4.4 System Boundary

The system boundary of the case studies in this research follows the modular approach defined by the EN 15804:2012+A2:2019. The system boundary is cradle-to-cradle. This comprehensive boundary includes all associated processes and activities, from the sourcing of building materials to the use stage, waste generation, and environmental impact outside the service life of a building.

3.4.5 Assumptions

In EC calculations, transport distances should be estimated based on project-specific scenarios. A default road transport distance of 50 km on average laden was assumed in this research (Gibbons et al., 2022).

All the various factors included in the ICE database account for cradle-to-gate emissions, as highlighted by Gibbons et al. (2022).

Module B1 (use) is generally considered insignificant for structural materials due to its minimal contribution to the overall environmental impact (Gibbons et al., 2022). Therefore, it is excluded and not taken into account in this study.

Motivation for refurbishment in buildings can arise from a variety of factors, such as the need for increased space in a residential building or the desire to attract more customers in a hotel setting, reflecting the unique requirements of each building. This motivation is highly specific to each individual building and cannot be easily generalized across different contexts. Therefore, this research does not take into account the specific impacts that may result from refurbishment changes (B5).

According to the RICS guideline, carbon factors for waste processing for reuse, recovery, or recycling (C3) and disposal (C4) are often grouped together in EC assessments, as the two scenarios are considered mutually exclusive in practice. If an available database for calculating the EC of a specific material does not exist within the scope of the project, a combined value of 0.013 $kgCO_2e/kg$ for materials in both C3 and C4 calculations has been assumed in accordance with RICS guidance (Gibbons et al., 2022).

Due to the lack of information from the contractor, Equation (3.16) can be assumed about the average rate:

$$\mathrm{ECC1} = 3.4\ \mathrm{kgCO_{2e}/m^2GIA} \tag{3.16}$$

Where ECC1 is EC due to demolition and deconstruction and GIA is gross internal area (i.e., the area of a building measured to the internal face of the perimeter walls at each floor level) (Gibbons et al., 2022).

At the end-of-life of the green roof, it is assumed that the sedum-blanket and the green roll are composted (100%), and the drainage layer in polypropylene is recycled (20%) and incinerated (80%) (Knauf Insulation, 2022). According to the EPD, the quantity of carbon sequestered by vegetation of the green roof over its entire lifecycle is 61.5 $kgCO_2e/m^2$ (Knauf Insulation, 2022).

3.4.6 Total Embodied Carbon and Score Calculation

This section first calculates the total EC of the structure. This is achieved by summing the EC contribution of each element within the model. Subsequently, it calculates a score expressed in $kgCO_2e/m^2$ by dividing the total EC by the gross internal area, as shown in Equation (3.17).

$$\mathrm{ECRating}_{\mathrm{structure}} = \frac{\sum \mathrm{EC}_{\mathrm{element}}}{\mathrm{GIA}} \tag{3.17}$$

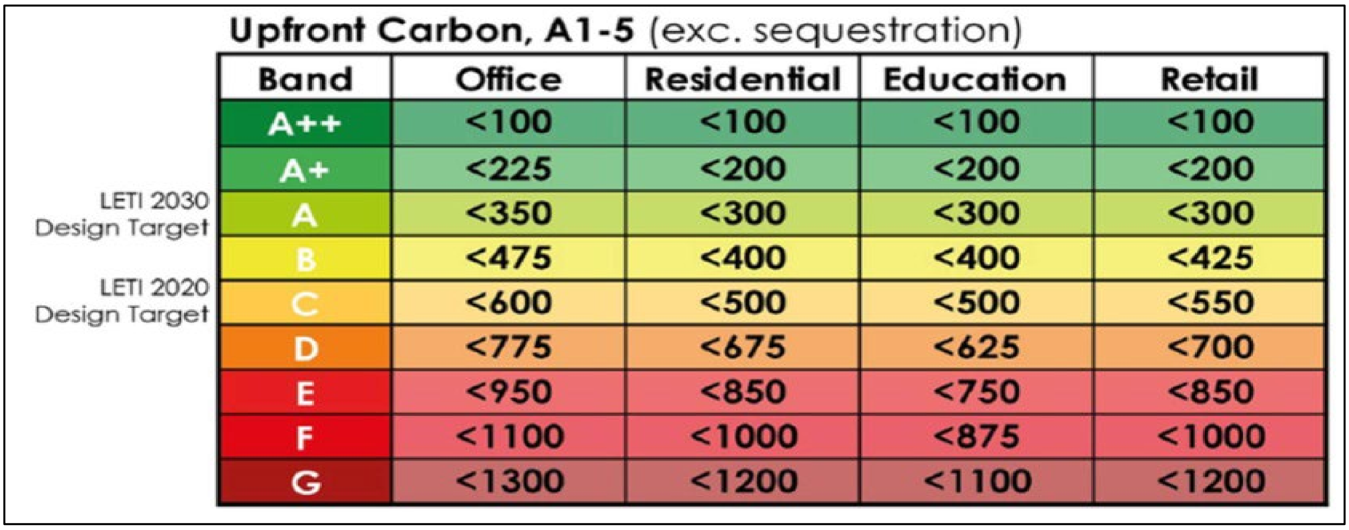
This section additionally calculates the project's EC emissions corresponding to various activities, offering stakeholders, who may not possess a familiarity with EC values with a clear way to understand the environmental impact of their project (Table 3.7).

Table 3.7: EC emissions of relatable activities (Hunt and Osorio-Sandoval, 2023)

Activity	EC Emissions ($kgCO_2e$)
A passenger vehicle running for 1 year	4600
A one-way ticket from London to Perth	1577
A person washing for 1 year	440
A mature tree absorbing CO2 for 1 year	25

3.4.7 Score Assignment

This section facilitates the evaluation of the structure through the application of an established rating system, LETI, thereby enabling benchmarking (Figure 3.6). This is achieved by comparing the score calculated in the previous section to the targets of each of these rating schemes.



Upfront Carbon, A1-5 (exc. sequestration)

	Band	Office	Residential	Education	Retail
	A++	<100	<100	<100	<100
	A+	<225	<200	<200	<200
LETI 2030 Design Target	A	<350	<300	<300	<300
	B	<475	<400	<400	<425
LETI 2020 Design Target	C	<600	<500	<500	<550
	D	<775	<675	<625	<700
	E	<950	<850	<750	<850
	F	<1100	<1000	<875	<1000
	G	<1300	<1200	<1100	<1200

Figure 3.6: LETI rating system for EC comparison (Hannah, 2022)

3.5 Type IV BIM-LCA integration to automate ECA

Type IV BIM-integrated LCA is a solution to accelerate EC assessment and minimize potential errors. Dynamo was used to connect the LCA database with Autodesk Revit, creating a smooth link between them. Then, Python scripting was used to automate the EC assessment by organizing and processing the data from the LCA database, making the process faster and more efficient. Figure 3.7 presents a workflow that automates EC assessment within Autodesk Revit using this integrated approach. This integration allows Revit to perform assessments internally, thereby enhancing both efficiency and accuracy.

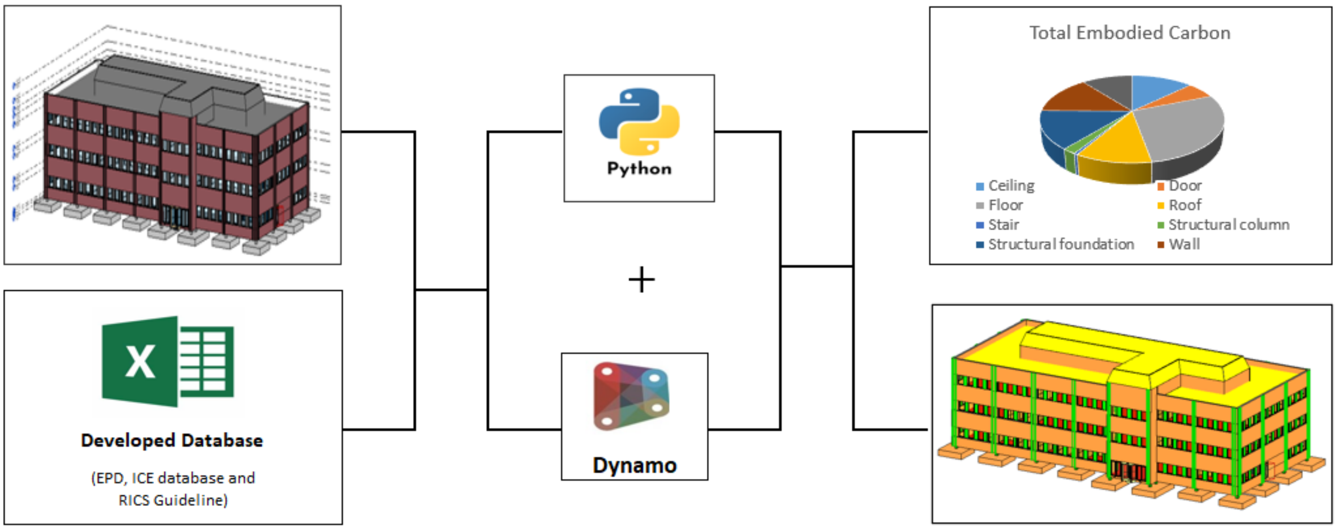


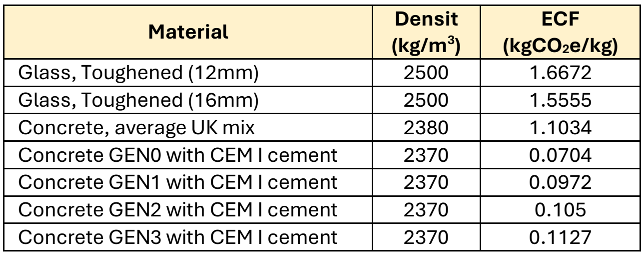
Figure 3.7: Automating EC assessment in Revit Using BIM, LCA Databases, and Python

3.5.1 Data Collection

The developed database is generated using data sourced from EPD, the ICE database, RICS guidelines, and relevant literature. This comprehensive database is systematically organized in an Excel file, with the EC data for each module separated into different sheets to ensure clarity, accessibility, and ease of use. For illustrative purposes, Table 3.8 provides detailed screenshots of the databases, showcasing the data structure across various modules for several different materials.

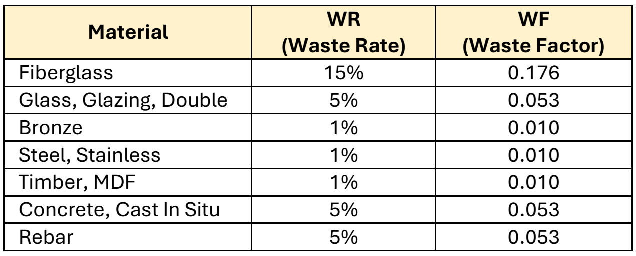
Table 3.8: Examples of the Developed Database for Embodied Carbon Assessment

A) EC data required for stages A1-A3



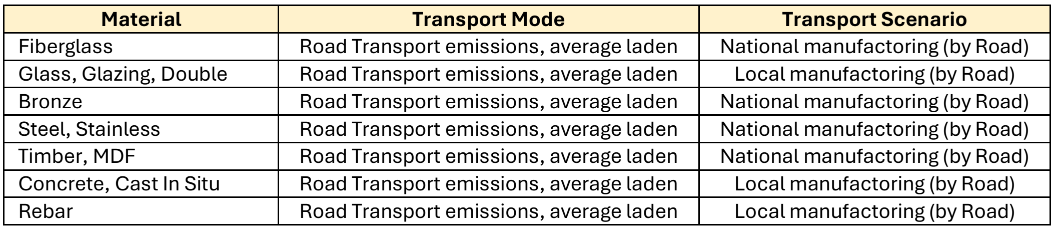
Material	Densit (kg/m^3)	ECF (kgCO$_2$e/kg)
Glass, Toughened (12mm)	2500	1.6672
Glass, Toughened (16mm)	2500	1.5555
Concrete, average UK mix	2380	1.1034
Concrete GEN0 with CEM I cement	2370	0.0704
Concrete GEN1 with CEM I cement	2370	0.0972
Concrete GEN2 with CEM I cement	2370	0.105
Concrete GEN3 with CEM I cement	2370	0.1127

B) EC data required for stage A5$_w$



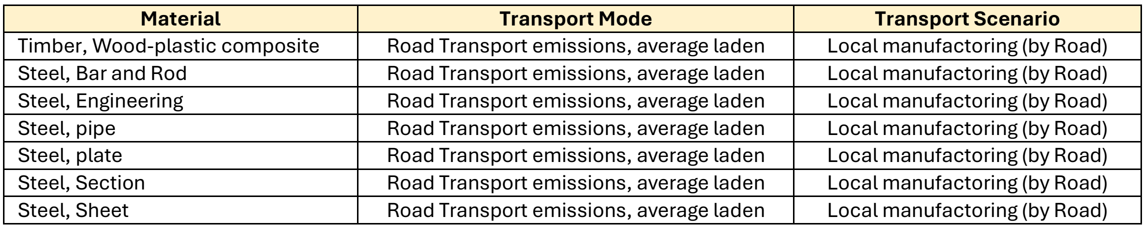
Material	WR (Waste Rate)	WF (Waste Factor)
Fiberglass	15%	0.176
Glass, Glazing, Double	5%	0.053
Bronze	1%	0.010
Steel, Stainless	1%	0.010
Timber, MDF	1%	0.010
Concrete, Cast In Situ	5%	0.053
Rebar	5%	0.053

C) EC data required for stage A4



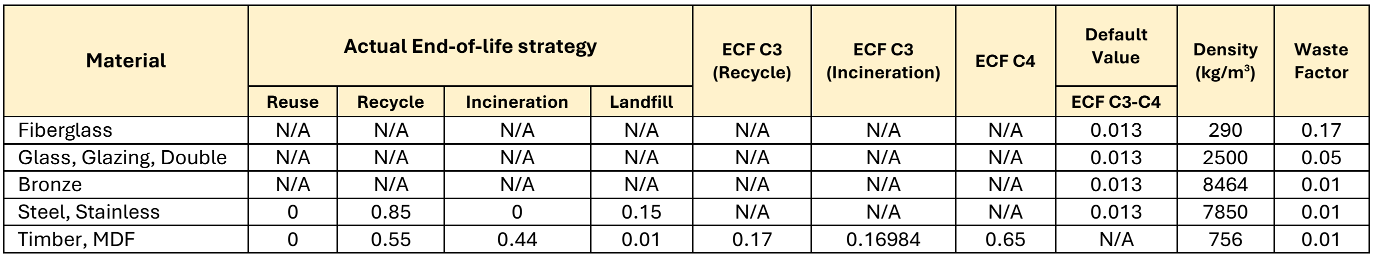
Material	Transport Mode	Transport Scenario
Fiberglass	Road Transport emissions, average laden	National manufactoring (by Road)
Glass, Glazing, Double	Road Transport emissions, average laden	Local manufactoring (by Road)
Bronze	Road Transport emissions, average laden	National manufactoring (by Road)
Steel, Stainless	Road Transport emissions, average laden	National manufactoring (by Road)
Timber, MDF	Road Transport emissions, average laden	National manufactoring (by Road)
Concrete, Cast In Situ	Road Transport emissions, average laden	Local manufactoring (by Road)
Rebar	Road Transport emissions, average laden	Local manufactoring (by Road)

D) EC data required for stage C2



Material	Transport Mode	Transport Scenario
Timber, Wood-plastic composite	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, Bar and Rod	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, Engineering	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, pipe	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, plate	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, Section	Road Transport emissions, average laden	Local manufactoring (by Road)
Steel, Sheet	Road Transport emissions, average laden	Local manufactoring (by Road)

E) EC data required for stages C3-C4



Material	Actual End-of-life strategy				ECF C3 (Recycle)	ECF C3 (Incineration)	ECF C4	Default Value	Density (kg/m^3)	Waste Factor
	Reuse	Recycle	Incineration	Landfill				ECF C3-C4		
Fiberglass	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.013	290	0.17
Glass, Glazing, Double	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.013	2500	0.05
Bronze	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.013	8464	0.01
Steel, Stainless	0	0.85	0	0.15	N/A	N/A	N/A	0.013	7850	0.01
Timber, MDF	0	0.55	0.44	0.01	0.17	0.16984	0.65	N/A	756	0.01

Concrete, Cast In Situ	0	0.9	0	0.1	0.0024	0	0.0014	N/A	2400	0.05
Rebar	0	0.92	0	0.08	N/A	N/A	N/A	0.013	7850	0.05

3.5.2 Dynamo

The integration of BIM and LCA is effectively implemented within the Dynamo environment in Autodesk Revit. Dynamo, a visual programming tool that is widely used in the fields of architecture and engineering, enables users to create custom logic and automate workflows specifically within the Revit software. It operates through a node-based system, where users connect various visual elements, commonly referred to as "nodes", to define data flows and processes, ultimately streamlining complex tasks and improving project efficiency. Figure 3.8 provides a comprehensive overview of the entire automation process in Dynamo, with each stage thoroughly explained in separate sections for better clarity.

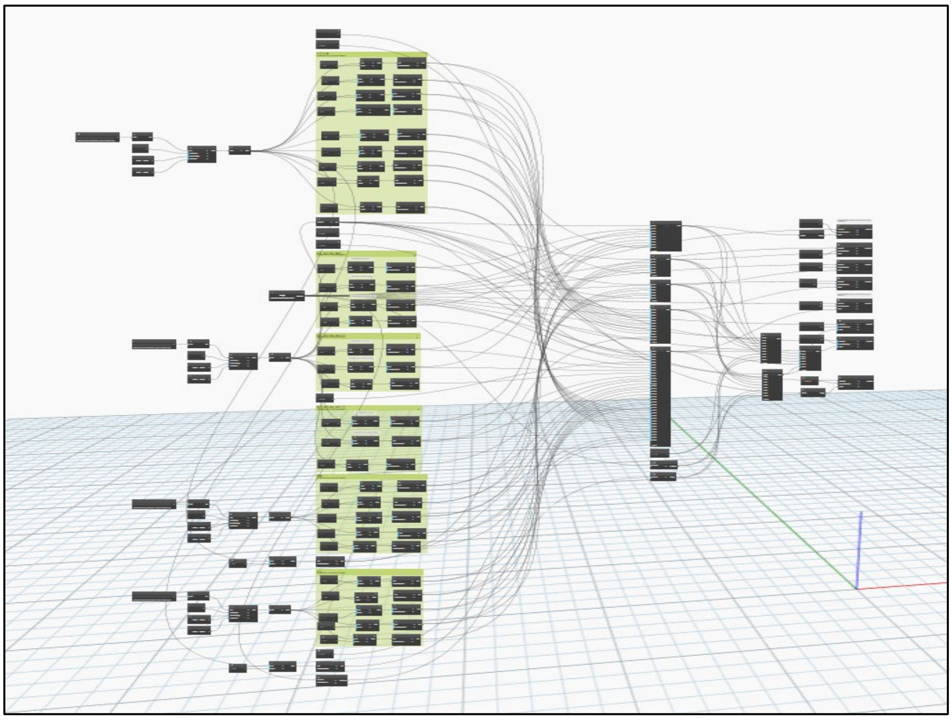


Figure 3.8: Overview of the entire automation process in Dynamo

3.5.3 Automating EC in stages A1-A3

Figure 3.9 provides a detailed focus on the automation process for Module A1-A3. This process begins with importing a sheet that contains EC data specifically for A1-A3 into Dynamo, where the imported information is methodically separated into distinct lists for better organization. Since the ECF data for A1-A3 is presented in a variety of units, such as $\text{KgCO}_2\text{e/kg}$, $\text{KgCO}_2\text{e/m}^2$, and KgCO₂e/m³, each unit type is carefully grouped into its respective category. These categorized lists are subsequently utilized as inputs for conducting EC assessments through Python scripts, ensuring an efficient and streamlined workflow.

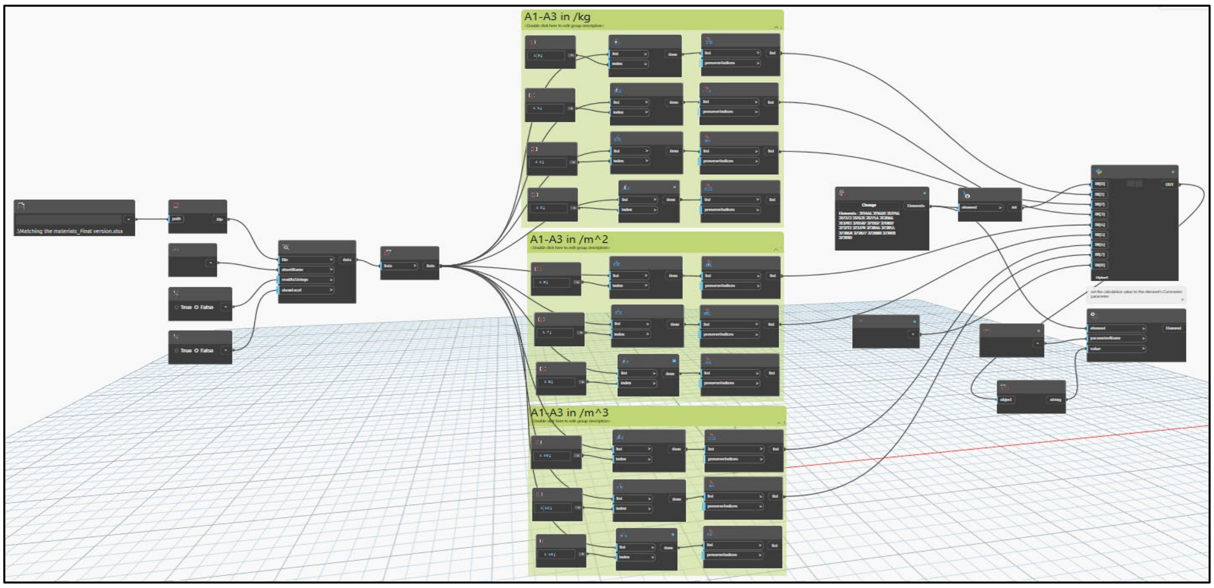


Figure 3.9: Automation process during module A1-A3

The flowchart presented in Figure 3.10 provides a detailed outline of the methodology employed for calculating EC of various construction materials using Python coding during stages A1-A3. This systematic process is specifically designed to process the individual elements of the model by extracting material data and subsequently applying the relevant ECF to calculate EC emissions based on the material's volume, area, or mass. The procedure initiates with the input of Element IDs alongside a developed database, which contains comprehensive material properties, including the ECF for materials (expressed in kg, m², or m³) as well as their respective densities. Following this, the algorithm proceeds to iterate over the entire list of element IDs, retrieving each element from the model in order to analyse and evaluate its associated materials.

Once an element is identified, the algorithm systematically iterates over its associated material IDs. For each individual material, the system begins by checking whether it belongs to one of the predefined material lists (i.e., kgMaterialList, m2MaterialList, or m3MaterialList), which serves to determine the appropriate method of calculation. After thoroughly processing all materials linked to an element, the algorithm accumulates the results, providing a summarized total EC for each specific element. This iterative process ensures that every element and its respective materials are fully evaluated, and the total EC emissions are precisely calculated. This structured and methodical approach guarantees that the EC is accurately computed for various types of materials, regardless of whether their contributions are measured based on mass, surface area, or volume.

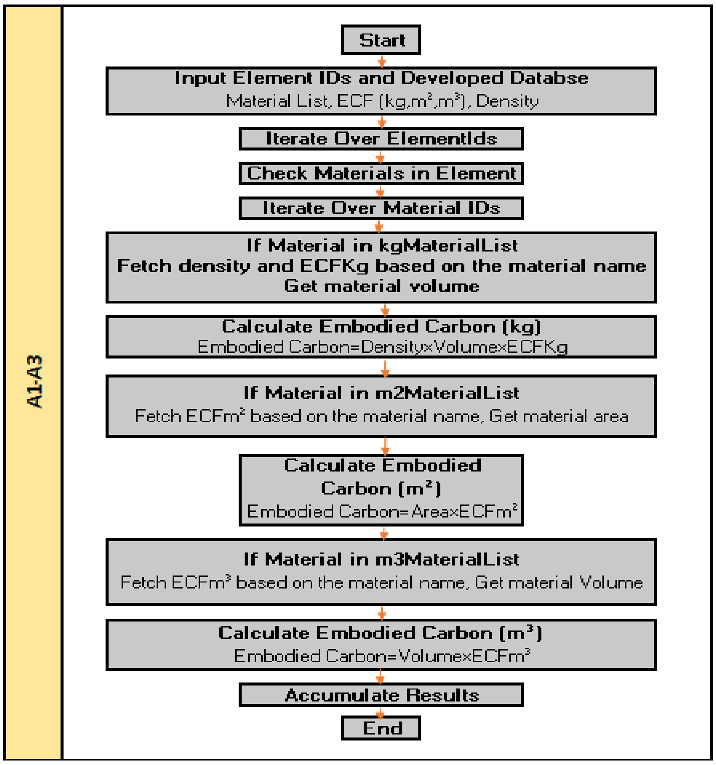


Figure 3.10: Overview of the EC assessment process (A1-A3) using Python coding

3.5.4 Automating EC in stages A4/C2

Figure 3.11 provides a detailed overview of the process for automating EC calculations specifically during stages A4 and C2. Stage A4 refers to the EC emissions that are generated during the transportation of building materials from their manufacturing site to the construction site, while stage C2 represents the EC emissions produced during the transportation of waste materials to either landfills or recycling facilities following the demolition phase of a building.

The process begins by importing the necessary database into Dynamo, ensuring compliance with the RICS guidelines for accurate and standardized calculations. This database contains comprehensive details, including transport modes (e.g., road transport, average laden conditions) and transport scenarios (e.g., local manufacturing and supply chains). The imported data is then organized into separate lists, which serve as critical inputs for the Python scripts used in the calculation process. After processing, the EC value for each individual element is calculated and subsequently added to the respective element properties, ensuring that the information is both precise and easily accessible for further analysis or reporting.

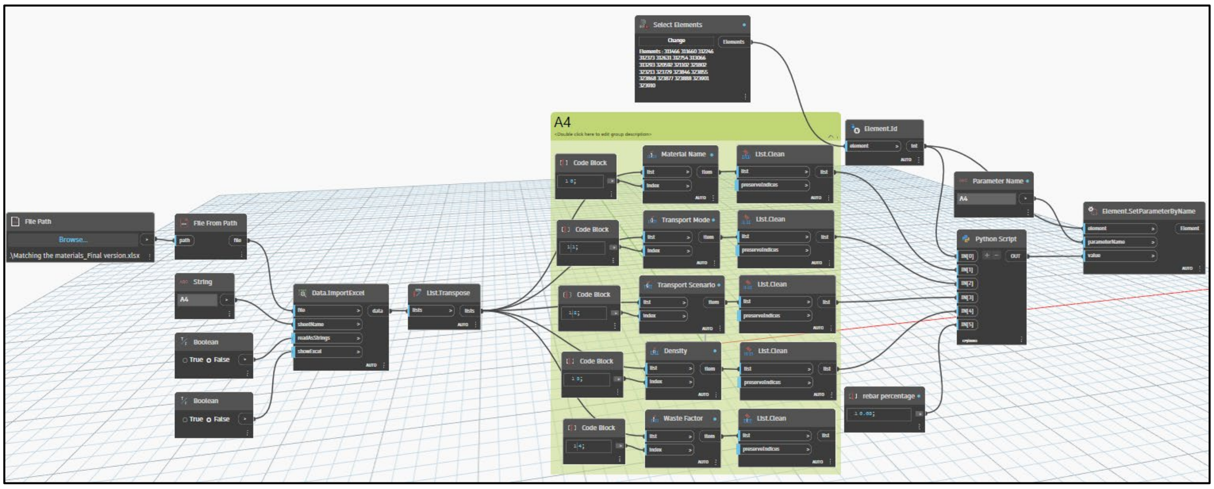


Figure 3.11: Automation process during module A4 and C2

Figure 3.12 presents a detailed flowchart that clearly outlines the step-by-step process for calculating EC emissions during the A4 and C2 transportation phases, utilizing a Python script.

In this comprehensive process, Element IDs and data from a specifically developed database, which includes material lists, transport modes, and relevant scenarios, are imported into Dynamo. Once imported, the system iterates over each element in the building model, checking whether materials are associated with each individual element. If materials are identified as being present, the algorithm continues to proceed further, analysing each material individually to ensure all relevant details are accounted for in the emissions calculations.

For each material, the system retrieves key details, including the transport mode (e.g., road or sea), the transport scenario, and the material's density, ensuring comprehensive data collection. Each of these factors is assigned to a specific coefficient, which directly contributes to calculating the material's EC. These parameters are crucial for accurately determining the EC for each material, as they account for the unique properties and transportation conditions of the material. The material's volume is subsequently calculated, and its weight is derived by considering its density. Based on the material's characteristics and the specific transportation conditions, the appropriate transport mode and scenario for both the A4 and C2 stages are assigned. Once the material's weight and detailed transportation data are determined, the EC for the transportation stages is calculated. Finally, the results for each material and element are systematically accumulated, providing a comprehensive total EC value for the A4 and C2 stages of the project.

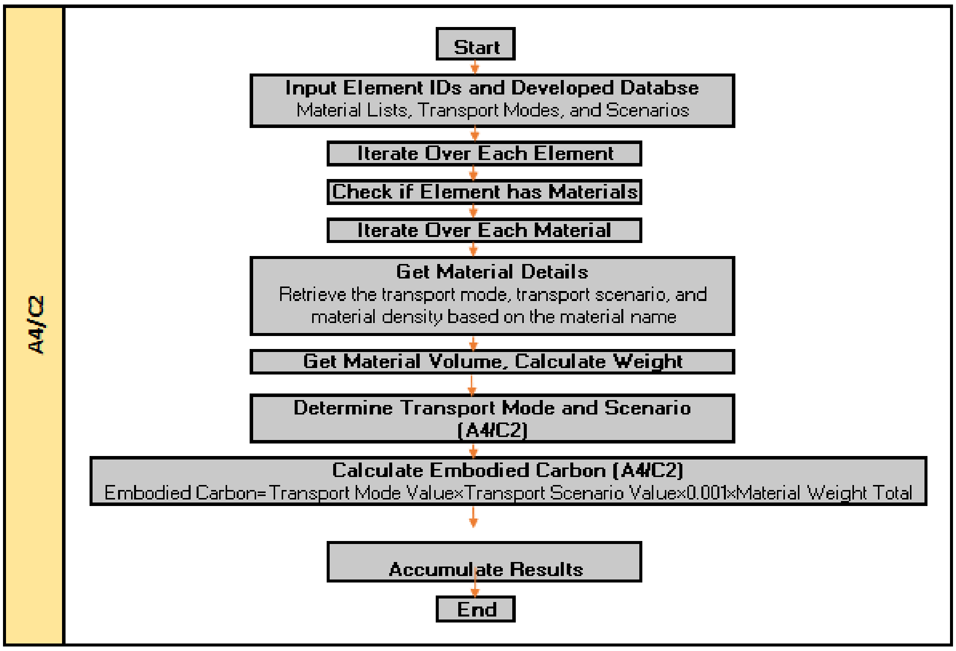


Figure 3.12: Overview of the EC assessment process (A4/C2) using Python coding

3.5.5 Automating EC in stages C3-C4

Figure 3.13 outlines the step-by-step process for assessing EC during the C3 and C4 stages. C3 represents the EC generated during the recycling, reuse, and incineration of materials, while C4 captures the EC produced by sending materials to landfills. The reuse of materials is uncommon in the UK and, as a result, has been excluded from this study to maintain relevancy and accuracy. The database for this module is divided into two categories: Actual values and Default values. Due to the limited availability of specific data on the end-of-life scenarios for UK building materials, default values are used in instances where specific information is unavailable. These default values follow the recommendations outlined in the RICS guidelines. After importing the database into the system, the information is systematically organized into different lists, which are then utilized as inputs for the Python script. Once the calculations are performed, the calculated EC for each element is automatically added to that element's properties within the model, ensuring seamless integration of results into the overall framework.

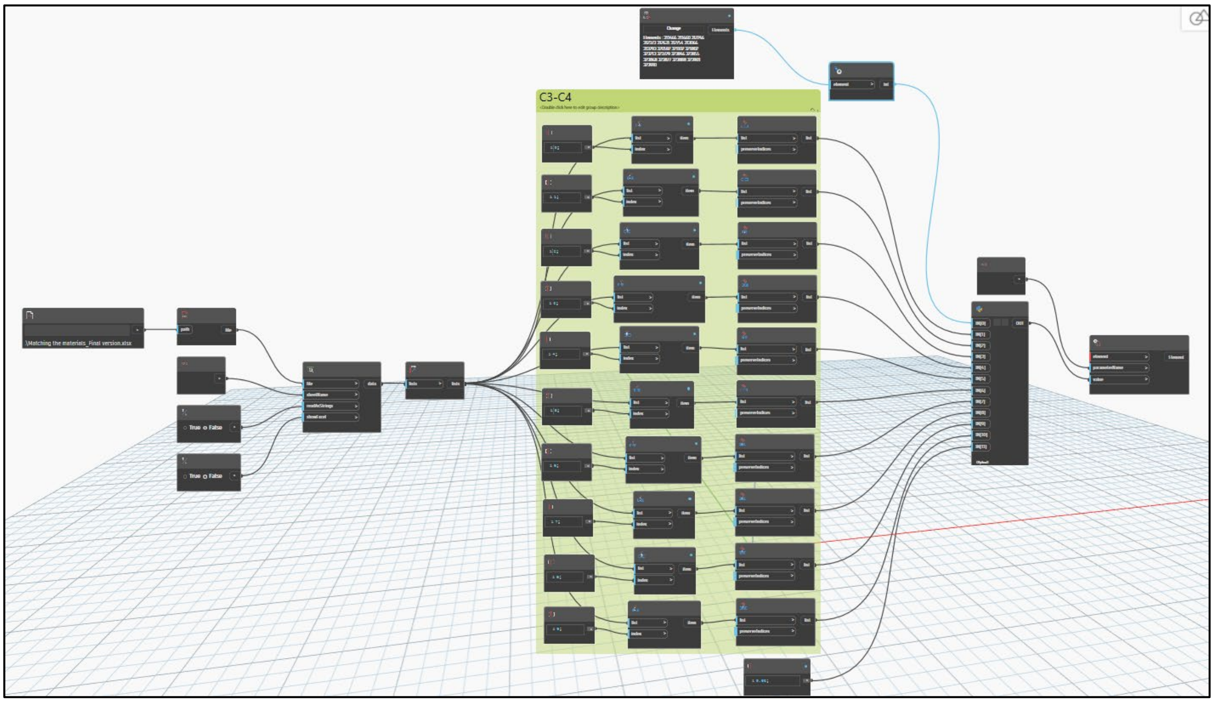


Figure 3.13: Automation process during module C3-C4

The flowchart in Figure 3.14 clearly outlines the step-by-step process for calculating EC emissions during the C3 and C4 stages of a building's lifecycle, utilizing Python coding. The procedure begins with the input of Element IDs and the subsequent use of a specially developed database that contains comprehensive end-of-life (EOL) data for materials. This database is structured to include multiple lists, such as the EOLReuseList, EOLRecycleList, EOLIncinerationList, EOLLandfillList, ECFC3RecycleList, ECFC3IncinerationList, ECFC4List, and also provides default values for materials with missing data. The system systematically iterates through each individual Element ID, performing a detailed check for the presence of materials within the given element and then retrieving the corresponding information from the database to facilitate accurate calculations.

For each material identified in the process, the algorithm thoroughly checks whether it has complete and accurate data for end-of-life scenarios. If all the required information is available, the material's volume and density are retrieved from the database, and the relevant values provided in the end-of-life lists are used to calculate its EC. In cases where specific data for recycling, incineration, or landfill scenarios are missing or incomplete, the system automatically applies default values derived from the RICS guidelines, thereby ensuring that the calculation process continues smoothly and without interruption.

This calculation method effectively captures the material's total end-of-life impact by considering the different ways it could be processed or disposed of after demolition, including recycling, incineration, or landfilling. Once the EC for each material is individually computed, the system accumulates the results to determine the total EC for both the C3 (waste processing) and C4 (disposal) phases of the building's lifecycle.

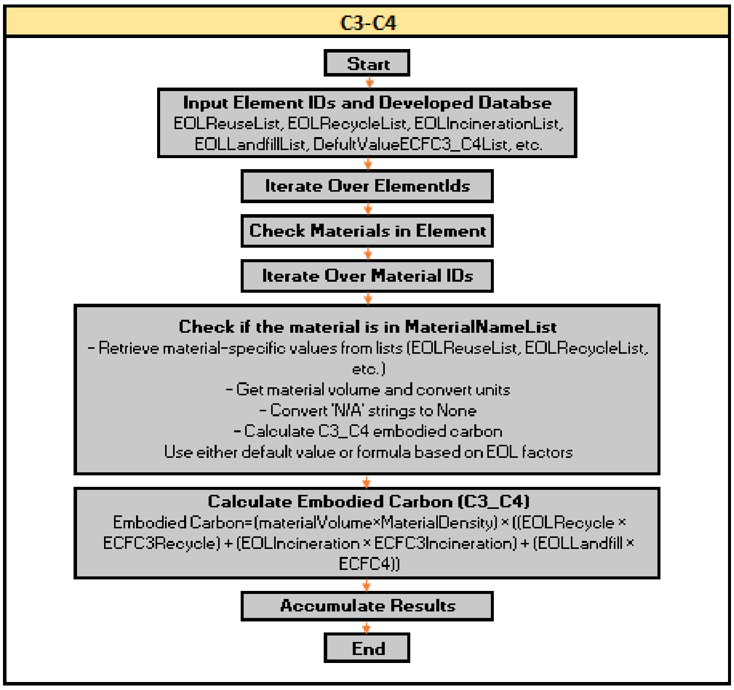


Figure 3.14: Overview of the EC assessment process (C3-C4) using Python coding

3.5.6 Automating EC in stages A5w

EC Emissions associated with the volume of each material that is wasted on site are identified as A5w emissions. The calculation for EC during A5w is based on multiplying the material’s waste factor by the combined EC from various lifecycle stages, including production (A1–A3), transportation to the construction site (A4), transportation to waste processing facilities (C2), and the waste processing or disposal stages (C3–C4). The required database for the assessment has already been imported and organized into distinct lists within Dynamo. Figure 3.15 illustrates a systematic approach for calculating EC during the A5w phase, using Python programming.

The process begins with the input of element IDs, along with the relevant database containing key lists and factors such as the MaterialNameList, ECF, Density, and Waste Factor. These inputs are essential for identifying the materials and their associated carbon impacts throughout the construction lifecycle. Once the element IDs are entered, the system iterates over them to check for the materials contained in each element. The core of the calculation involves processing the EC at different lifecycle modules. The process is divided into four distinct stages: A4 (transport), C2 (transport to disposal), C3-C4 (waste processing and disposal), and A1-A3 (material production).

These modules are processed individually for each material, and their EC contributions are accumulated accordingly. A waste factor is then applied to the materials, adjusting the carbon calculation to account for waste generated during the construction process. Once all relevant calculations are completed, the results are accumulated to provide an overall estimate of the EC for the waste-related stage (A5w) of the elements.

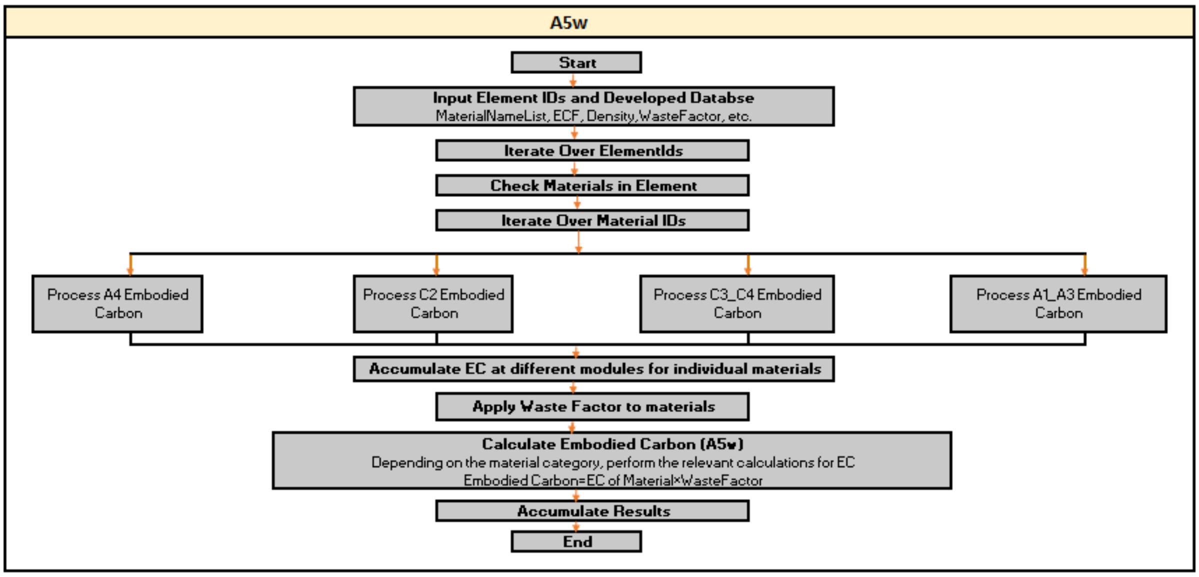


Figure 3.15: Overview of the EC assessment process (A5w) using Python coding

3.5.7 Automating EC in stages B4

B4 refers to the EC generated during the replacement of building materials over time. Since different materials have varying lifespans, some may need to be replaced multiple times throughout the life of a building. This building lifespan, known as the reference study period, is set at 60 years for UK buildings, as recommended by (Sturgis et al., 2023).

The flowchart below presents a detailed, step-by-step approach for calculating EC during the B4 phase, specifically addressing the impacts of material replacements over the building's lifespan, with Python programming employed to execute the process efficiently (Figure 3.16). The process starts with importing element IDs and a developed database, which contains essential lists such as A1-A3EmbodiedCarbonList, A4EmbodiedCarbonList, C2EmbodiedCarbonList, C3-C4EmbodiedCarbonList, and A5wEmbodiedCarbonList, along with the reference study period.

Once the element IDs are entered, the system iterates through each element to identify the materials present. After identifying the materials, the system then further iterates over the material IDs, checking the specific materials within each element to prepare for the next steps. Data related to the materials, such as category, type, and family type, is retrieved from relevant lists, enabling the system to categorize each material appropriately.

Based on this categorization, the expected lifespan of each material is set, which is crucial for calculating the material's EC over time. The expected lifespan is determined by checking the category name and material type. To account for the difference between the reference study period and the expected lifespan of the materials, the process calculates a "rounded-up ratio". This ratio is obtained by dividing the reference study period by the expected lifespan and rounding up to the nearest whole number, ensuring that the EC reflects the actual material usage over time. The next step is the calculation of EC for the B4 phase.

The EC is computed using the rounded-up ratio, which is multiplied by the sum of EC contributions from different lifecycle stages, including A1-A3 (material production), A4 (transport), C2 (transport to disposal), C3-C4 (waste processing and disposal), and A5w (waste management). Finally, the results of the EC calculations are accumulated, providing a comprehensive assessment of the EC associated with material replacements during stage B4.

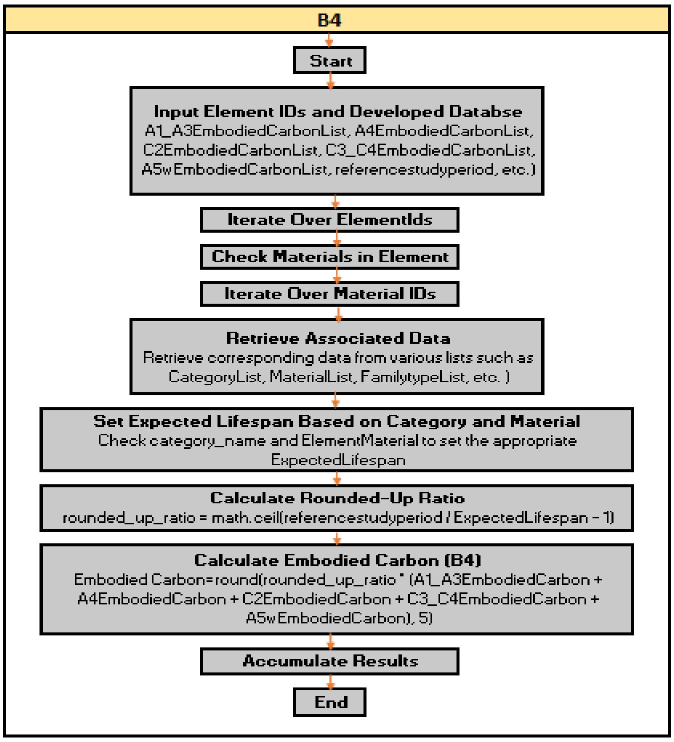


Figure 3.16: Overview of the EC assessment process (B4) using Python coding

Chapter 4 : An In-Depth Analysis of the embodied carbon in case studies

This chapter evaluates the accuracy of various databases and assessment approaches for calculating EC of construction materials. The chapter also conducted a thorough evaluation of the EC associated with all the modelled and studied case studies. It displays the major findings in various figures and tables; it then evaluates and discusses the primary findings in order to answer the research questions.

4.1 Case study 1: The Residential Building

4.1.1 Building Description

Our first case study is a four-bedroom typical detached residential building located in Bracknell, Berkshire, England. It is a double storey structure with a timber truss roof, concrete block walls, air-filled double-glazed windows and an area of 145.86 m^2. Table 4.1 shows Building Elements and structural components of the residential building. The selected case study building is modelled by BIM software Autodesk® Revit® (Figure 4.2) and will be based on design plan data provided by the constructor (Figure 4.1) to identify the quantity of materials applied in this building. The quantity of materials is calculated by Equation 4.1 and represented in Table 4.2 and Figure 4.3.

Table 4.1: Building Elements and structural components

Building Element	Structural Element and Component
Substructure	Strip Foundation
Superstructure	Structural framing: T-Beam Concrete, Universal Beam, I joist Floor: Floor block, Screed, Rock Wool, Polystyrene- Expanded Chipboard, Plasterboard, Timber stairs Roof: Steel- Galvanised Softwood, Polystyrene- Expanded
External Envelope	External Walls: Brick, Rock Wool, Autoclaved aerated concrete (AAC), Plasterboard
Interiors	Internal Walls: AAC, Plasterboard, Koolthermal insulation

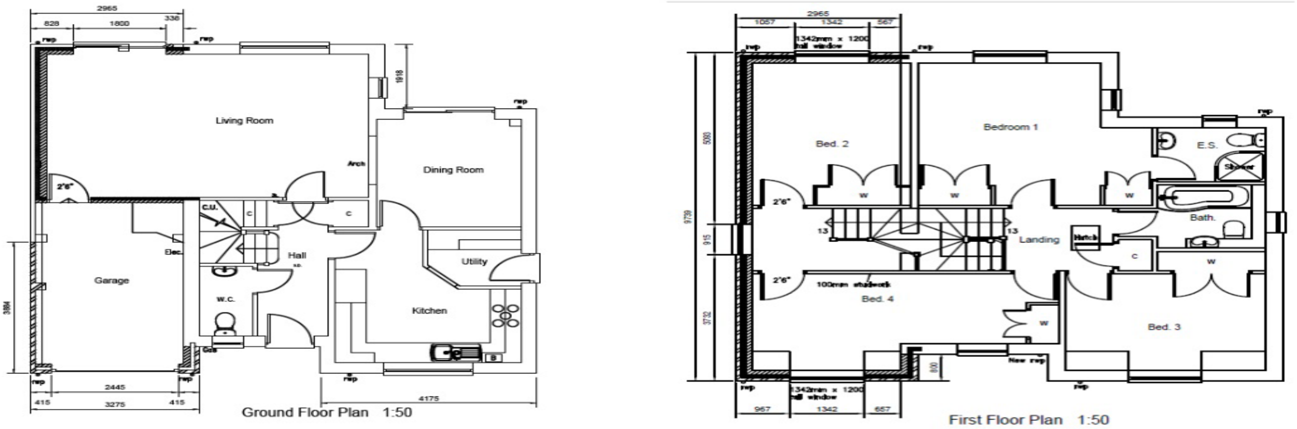
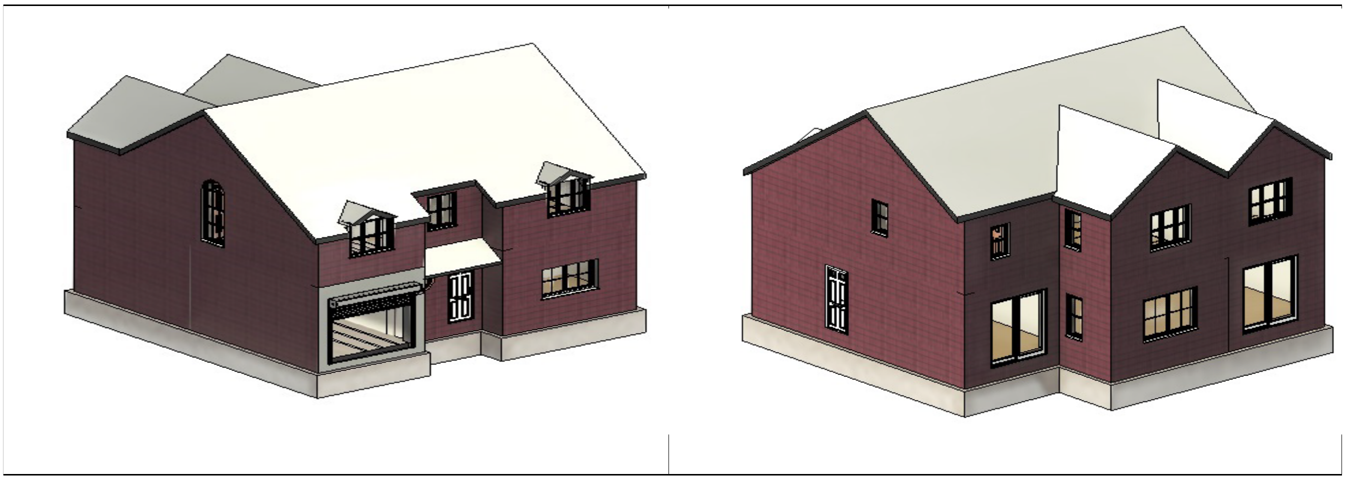


Figure 4.1: Ground Floor and First Floor of the residential building



4a) Front elevation 4b) Rear elevation

Figure 4.2: Revit 3D Modelling results of the residential building

$$\text{Quantity (kg)} = \text{Volume}(\text{m}^3) \times \text{Density}(\frac{\text{Kg}}{\text{m}^3}) \quad (4.1)$$

Table 4.2: The quantity of materials applied in the residential building

Building Element	**Structural Element**	**Component**	**Volume (m^3)**	**Weight (kg)**
Substructure	Strip Foundation	Concrete, Cast in Situ	28.28	71,705
Superstructure	Structural Framing	T-Beam Concrete	1.99	4,776
		Universal Beam	0.05	393
	Floor	I joist, Timber	0.61	137
		Floor block	10.22	15,342
		Screed	4.9	10,393
		Rock Wool	7.8	1561
		Polystyrene, Expanded	14.4	432
		Timber, Chipboard	3.78	3,024
		Plasterboard	1.95	609
		Timber Stairs	0.17	126
	Roof	Steel, Galvanised	0.1	808
		Softwood	8.83	5,167
		Polystyrene, Expanded	19.1	573
	Window	Glass	0.31	763
		PVC	0.52	728
External Envelope	External Walls	Brick	20.47	39,924
		Rock Wool	15.98	3197
		AAC	17.49	10,491
		Plasterboard	2.161	2,423
Interiors	Internal Walls	AAC	12.19	7,312
		Plasterboard	2.853	3,190
		Koolthermal insulation	0.42	15

Figure 4.3 clearly shows that concrete materials are the highest contributor to the building's overall quantity, accounting for 44% of the total quantity in the building. Furthermore, brick materials account for the second-highest quantity, constituting 21% of the overall total, highlighting their substantial presence. In addition, block work, with 17%, accounts for a

significant portion of the building's quantity, emphasizing its importance in the overall composition. The other materials, however, collectively contribute insignificantly, with each of them accounting for less than 10% of the total.

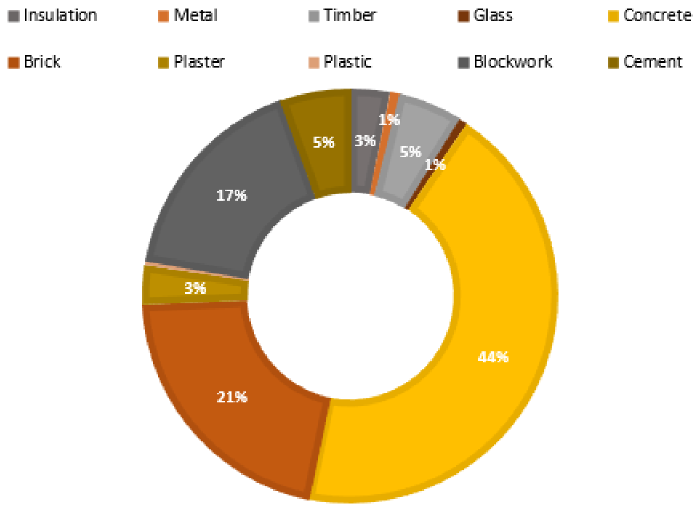


Figure 4.3: Weight composition per building materials in the residential building

4.1.2 Comparing the accuracy of databases

4.1.2.1 Embodied Carbon Database for Product Stage

The carbon factors for the product stage of this study are derived from three primary datasets, each serving as a crucial resource. EPDs are regarded as the most reliable and accurate source of information about a product's environmental impact, providing detailed LCA data. However, a limitation arises as manufacturers in the UK only produce a limited number of EPDs, making it challenging to obtain EPDs for all the materials used in the project. To maintain consistency and accuracy, the EPDs used in this study are specifically sourced from UK manufacturers to ensure that the geographical and regional conditions of production and procedures are accurately reflected. Within this section, EPDs for materials such as Rebar, plasterboard, expanded polystyrene, and brick are accessible and utilized for analysis. The ICE database is identified as the second database explored in this study. The ICE databases, created by Hammond and Jones in 2008, are widely regarded as the second-most current and commonly used databases in the UK for carbon factor data. This database contains comprehensive carbon factors from stages A1 to A3 for over 500 of the most prevalent construction materials, providing a broad foundation for carbon analysis. However, the ICE database does not include information about the operational phase, the construction process, or the end-of-life stages of materials, which presents a limitation in its application. The third and final database used in this study is derived from BEIS. This database categorizes ECFs into forty distinct categories, with construction materials further divided into twelve specific categories. These categories include Aggregates, Asbestos, Asphalt, Bricks, Concrete, Insulation, Metals, Soils, Mineral oil, Plasterboard, Tires, and Wood, all of which are commonly used in building projects. Table 4.3 illustrates the assigned ICE and BEIS EC databases along with their respective sources, providing a clear overview of the datasets employed in this study.

Table 4.3: Assigned ECF for each residential building material

Material	**ECF ICE Database ($kgCO_2e/kg$)**	**Source**	**ECF BEIS Database ($kgCO_2e/kg$)**	**Source**
Aluminium Profile	1.7063	ICE (Aluminium Extruded profile)	4.01	Metals
Glass, Glazing	1.6256	ICE (Double glazed-12mm)	1.40	Glass
Timber, MDF	0.86	ICE (Timber-MDF)	0.31	Wood
Steel, Stainless	4.407	ICE (Steel-Stainless)	4.01	Metals
Concrete, Cast in Situ	0.112	ICE (C20/25)	0.13	Concrete
Timber, Chipboard	0.4	ICE (Timber-chipboard)	0.31	Wood
Concrete Screed	0.149	ICE (Mortar 1:4-Mortar and Screed - Average UK Cement Mix)	0.13	Concrete
Rebar	1.2	ICE (Rebar with 85% recycled content)	4.01	Metals
Concrete Block	0.093	ICE (concrete block)	0.13	Concrete
Polystyrene, Expanded	3.29	ICE (Expanded Polystyrene)	1.86	Insulation
Plasterboard	0.39	ICE (Plasterboard)	0.12	Plasterboard
Rock wool	1.12	ICE (Rockwool)	1.86	Insulation

Table 4.3: Cont.

Material	ECF ICE Database ($kgCO_2e/kg$)	Source	ECF BEIS Database ($kgCO_2e/kg$)	Source
Steel, Galvanised (sheet)	3.01	ICE (coil (sheet) galvanised)	4.01	Metals
Oak	0.3056	ICE (Hardwood)	0.31	Wood
Brick	0.21	ICE (brick)	0.24	Bricks
AAC	0.28	ICE (AAC block)	0.13	Concrete
Koolthermal insulation	1.86	ICE (Insulation)	1.86	Insulation
PVC	3.1	ICE (PVC)	1.86	Insulation
Precast Concrete	0.1939	ICE (Precast concrete)	0.13	Concrete
Universal Beam	1.21	ICE (Steel, 85% recycled content)	4.01	Metals
I-Joist	0.4833	ICE (Timber, wood I-Beam)	0.31	Wood
Timber, Softwood	0.26	ICE (Timber, softwood)	0.31	Wood

In order to see the databases' differences, two approaches are taken in the assignment of appropriate ECFs. The first approach is to contrast the differences between the ICE database and EPDs. The second approach is to compare the BEIS database with the Enhanced database, to see how reliable the BEIS database can be. Enhanced database is the combination of EPDs, and the ICE database and the ICE database are used whenever EPDs are not available.

4.1.2.2 Embodied Carbon Database for end-of-life Stage

Module C comprehensively accounts for all emissions that result from disassembly, deconstruction, and demolition processes, as well as the transport, processing, and disposal of materials at the end of the project's life. However, there are not many databases available to accurately calculate EC at the end-of-life stage. For instance, the BEIS database is not applicable for this purpose, as this database only provides coverage for emissions associated with the collection of materials and their delivery to the point of treatment or disposal. It does not extend to cover the environmental impact of different waste management options, limiting its usability for end-of-life calculations (BEIS, 2022). End-of-life ECF can be extracted from EPDs and relevant research. Nevertheless, only a limited number of EPDs and research studies provide ECF information specifically for the end-of-life phase of building materials. Furthermore, the IStructE guideline titled *"How to Calculate Embodied Carbon"* offers end-of-life ECF specifically for a limited number of materials, which may restrict its broader applicability.

In addition, the RICS professional statement, *"Whole Life Carbon Assessment for the Built Environment"*, aims to provide detailed guidance on the interpretation and practical implementation of the EN 15978 methodology (Papakosta and Sturgis, 2017). This statement serves as a guideline for calculating EC as part of the WLC emissions, including those from the end-of-life phase. If no EPD, or relevant research is available to provide ECF, this study utilized the EC of the case study by applying the RICS guidance to ensure consistency and accuracy in the assessment.

4.1.2.3 Discrepancy between databases

The results presented in Table 4.4 show the significant effect that the choice of an A1–A3 ECF database can have on an LCA. EPDs are widely regarded as the most reliable database to calculate EC emissions. However, there was a limited number of EPDs available, primarily because it is not mandatory for manufacturers to produce them. In this research, the EPDs related to a few specific materials, including Rebar, Expanded Polystyrene, Plasterboard, and Brick, are applied, as shown in Table 4.4. The comparison of the EPDs to the ICE database revealed that using the ICE database overestimates the overall calculated EC by only 4.96%. The biggest significant difference is observed in Brick, where the ICE database overestimated the EC by 21.93%. For Rebar and Plasterboard, the ICE database similarly overestimates the EC calculated, with differences of 1.69% and 5.48%, respectively. On the other hand, the ICE database underestimates the EC for Expanded Polystyrene by only 7.04% when compared to the values provided by the EPD (Table 4.4 and Figure 4.4).

Table 4.4: The calculated EC using ICE and EPDs for material.

Material	Weight (kg)	ICE Value ($kgCO_2e$)	EPD Value ($kgCO_2e$)
Rebar	10,840.05	13,008.06	12,791.26
Polystyrene, Expanded	1,005.25	4,413.04	4,747.32
Plasterboard	5,737.45	2,237.61	2,121.45
Brick	39,924.16	7,030.64	5,765.89

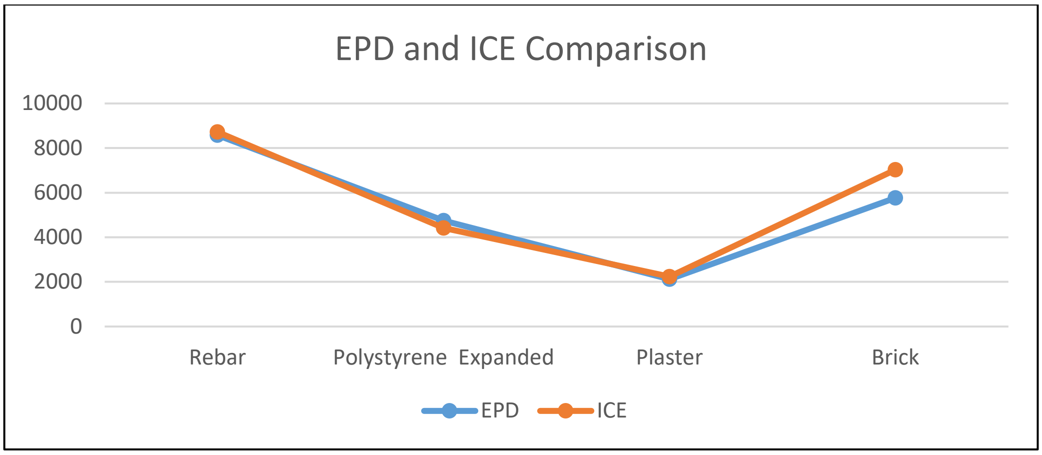


Figure 4.4: Comparison of EPDs and ICE sources EC of Building Materials.

The enhanced database, which is a combination of the ICE database and EPDs, serves as the most reliable and accurate database utilized in this research. In this section, a detailed comparison is performed between the enhanced database and the BEIS database to evaluate and assess the overall accuracy and reliability of the BEIS database.

Table 4.5 provides a comparison of the calculated EC values, for various construction materials, using the Enhanced Value database and the BEIS database. As the Enhanced Value database is considered the most reliable source in this research, it serves as the benchmark for assessing the accuracy of the BEIS database.

For materials such as Rebar and Universal Beam, the BEIS database reports significantly higher EC values compared to the Enhanced Value database, with differences of 101.26% and 231%, respectively. This discrepancy highlights the unreliability of the BEIS database in comparison to the Enhanced Value database. Similarly, for materials like Rock Wool and Brick, the BEIS database overestimates EC by 60% to 70%.

Conversely, for materials such as Timber-MDF, Polystyrene (Expanded), Plasterboard, Timber I-Joist, AAC, Blockwork, and PVC, the BEIS database underestimates EC by 50% to 70%.

The significant inconsistencies between these two databases for building materials demonstrate the lack of reliability in the BEIS database. As a result, it has not been used in this research.

Table 4.5: The calculated EC using Enhanced Value and BEIS databases for each material.

Material	CO_2 Emissions Enhanced Value ($kgCO_2e$)	CO_2 Emissions BEIS Value ($kgCO_2e$)
Aluminium Profile	1,482.06	1,169.70
Glass, Glazing	2,062.48	1,779.76
Timber, MDF	838.61	304.84
Steel, Stainless	59.16	53.76
Concrete, Cast in Situ	7,947.75	9,349.35
Timber, Chipboard	1,209.81	945.50
Screed	1,548.54	1,369.27
Rebar	21,571.70	43,415.89
Blockwork	1,428.14	2,021.31
Polystyrene, Expanded	4,747.32	1,871.53
Plasterboard	2,121.45	688.78
Rock wool	5,328.77	8,857.90
Steel, Galvanised (sheet)	2,432.79	3,237.10

Table 4.5: Cont.

Material	CO_2 Emissions Enhanced Value ($kgCO_2e$)	CO_2 Emissions BEIS Value ($kgCO_2e$)
Timber, Oak	38.55	39.43
Brick	5,765.89	9,651.72
AAC	4,618.92	2,173.39
Koolthermal insulation	27.57	27.59
PVC	2,257.06	1,355.51
Precast Concrete	926.07	629.24
Universal Beam	475.11	1,572.62
Timber, I-Joist	177.28	42.92
Timber, Softwood	1,343.50	1,615.36

4.1.3 Embodied Carbon Assessment of the residential building during module A and C

Table 4.6 shows the EC of the residential building from (A1-A5) to (C2-C4). The EC emissions, calculated with the Enhanced database and considering A5a and C1 as 5,105.13 and 495.92 $kgCO_2e$ respectively, equate to 75.64 $tonCO_2e$.

Figures 4.5 and 4.6 show hot zones in terms of EC. In other words, they will determine which materials and stage have the highest EC and have the potential to mitigate the total EC.

Table 4.6: EC of the residential building during module A1-A5 and C1-C4

Material	A1-A5 ($kgCO_2e$)	C2-C4 ($kgCO_2e$)	Total ($kgCO_2e$)
Aluminium Profile	1,507.26	5.35	1,512.61
Glass, Glazing	2,193.55	23.25	2,216.80
Timber, MDF	878.73	175.58	1,054.31
Steel, Stainless	60.19	0.25	60.44

Concrete, Cast in Situ	18,265.99	674.23	1,8940.23

Table 4.6: Cont.

Material	A1-A5 ($kgCO_2e$)	C2-C4 ($kgCO_2e$)	Total ($kgCO_2e$)
Timber, Chipboard	1,286.96	510.70	1,797.66
Screed	1,698.32	190.45	1,888.77
Blockwork	7,390.3	583.43	7,973.73
Polystyrene, Expanded	5,358.46	18.42	5,376.88
Plasterboard	2,775.16	320.73	3,095.89
Rock wool	6,414.46	87.19	6,501.65
Steel, Galvanised	2,483.60	14.81	2,498.41
Timber, Oak	40.50	16.35	56.86
Brick	9,639.28	731.61	10,370.89
AAC	5,432.72	302.29	5,735.02
Koolthermal insulation	36.26	0.27	36.53
PVC	2,303.49	13.34	2,316.83
Precast Concrete	1,274.85	36.42	1,311.27
Universal Beam	492.65	7.20	499.85
Timber, I-Joist	210.74	23.63	234.37
Timber, Softwood	1,509.60	785.71	2,295.32

Figure 4.5 emphasizes the critical need to reduce EC in the A1-A3 stage, as this stage represents the highest carbon impact across the lifecycle of most materials. The A1-A3 stage accounts for over 80% of the EC emissions in the majority of materials analysed. Among the materials, plasterboard and brick exhibit higher A5w values compared to other materials, primarily due to their relatively greater levels of on-site wastage during construction activities. Timber materials, on the other hand, display higher C3-C4 emissions in comparison to other materials, which can be attributed to the significant energy consumed during the incineration and recycling processes. Notably, while most materials only consider recycling in their emissions assessments, timber materials incorporate both incineration and recycling factors, making their emissions profile more comprehensive.

Furthermore, Figure 4.6 highlights that concrete materials account for the highest proportion of EC, totalling 29%. This is significant, considering that around half of the building's composition is made of concrete, and it contributes the most to EC. Therefore, reducing its EC is the key to significantly lowering the overall EC emissions of the structure. Concrete is followed by insulation materials, which contribute to 17% of total emissions. Brick and blockwork materials, on the other hand, account for 15% and 11% of emissions, respectively. The impact of other materials remains less than 10%.

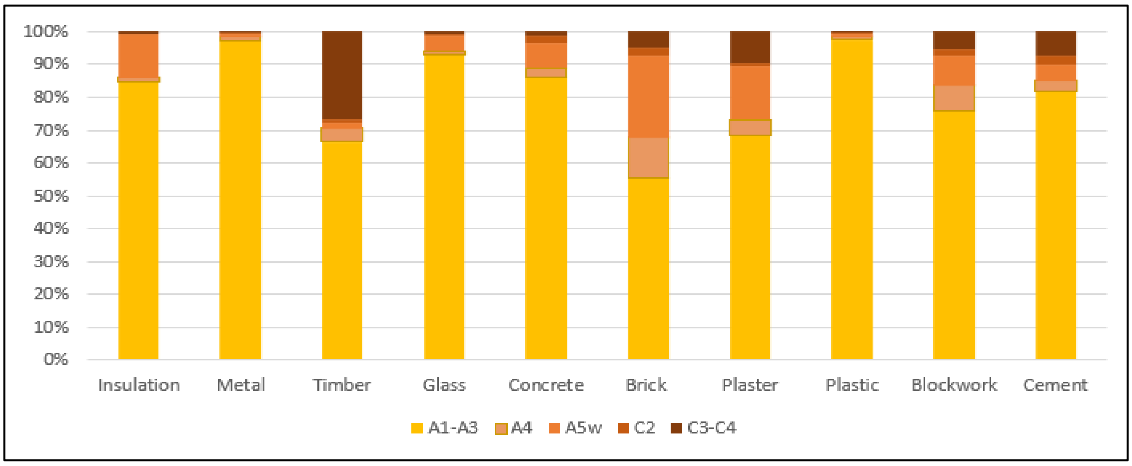


Figure 4.5: EC associated with each material during A1-A5 and C1-C4 stages of the residential building's life cycle.

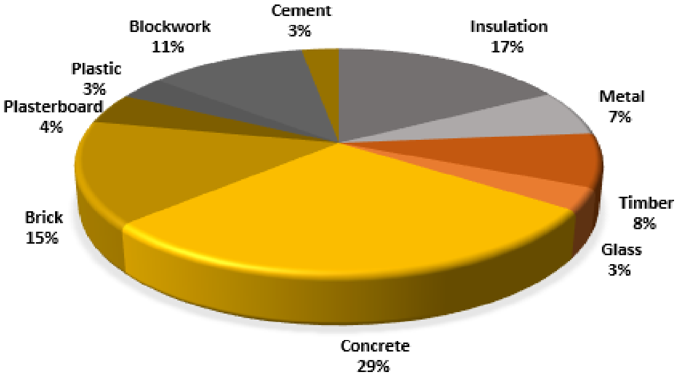


Figure 4.6: EC associated with each material during A1-A5 and C2-C4 stages of the residential building

4.1.4 Embodied carbon assessment of the residential building during module B

According to (Sturgis et al., 2023), the RSP of the buildings is assumed to be 60 years. During this period, building components require maintenance, repair, and replacement, thus requiring the calculation and consideration of the EC associated with these stages of the buildings' life. During the replacement of materials, it is essential to treat these materials with the same level of consideration as primary materials at the end of their lifecycle.

Table 4.7 and 4.8 show the EC during module B of the residential building from building completion to the end of the RSP. Table 4.7 indicates that the façade and roof of the building undergo material replacement based on the expected lifespan of the building materials. In total, 13,035.25 kgCO$_2$e is emitted during the use stage of the building.

Table 4.7: EC of the residential building during module B4

Building part	Material	Expected lifespan (year)	Embodied carbon (B4) kgCO$_2$e
Façade	Window	30	3,640.92
	Door	20	5,072.66
Roof	Roof covering	30	2,498.41

Table 4.8: Total EC of the residential building during B2-B4

Area (m^2)	ECF (B2) (kgCO$_2$e/m^2)	EC (B2) (kgCO$_2$e)	EC (B3) (kgCO$_2$e)	EC (B4) (kgCO$_2$e)	EC (B2-B4) (kgCO$_2$e)
145.861	10	1,458.61	364.65	11,211.99	13,035.25

4.1.5 Module D outside the LCA for the residential building

The standard EN 15804 uses a modular approach for the three product life cycle stages: production (Module A), in use (Module B) and end-of-life stage (Module C), combined with a cut-off rule which does not allow consideration of the recycling aspects from a full product life cycle. As a result, a complementary Module D is included to consider the additional aspect of recycling which is not addressed through the recycled content metric (Delem and Wastiels, 2019). This study examines the environmental impact of building materials beyond the scope of LCAs (Module D), showing the significance of end-of-life strategies during a building's lifecycle. It's important to note that Module D is applicable exclusively to materials present in the available database. Tables 4.9 to 4.14 provide a detailed illustration of the environmental impact associated with the recycling of building materials and the incineration processes for timber materials in Module D. These tables demonstrate the EC savings that are achieved through both the recycling of various building materials and the incineration of timber materials within Module D. Additionally, the benefit of energy generated as a result of the incineration of timber materials is typically in the form of electrical energy in the UK (Sturgis et al., 2023). In table 4.10, $M_{INC\ out}$ is the mass of timber to be incinerated, $X_{INC\ elec}$ is the electrical energy generated per ton of timber for waste wood plants (Tolvik, 2019), and $E_{SE\ elec}$ is the carbon factor of UK grid electricity production.

Table 4.9: EC saving during recycling of timber materials in the residential building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	$E_{MR\ seq}$ (kgCO$_2$e/kg)	$E_{MR\ after\ EoW\ out}$ (kgCO$_2$e/kg)	$E_{VMSub\ out}$ (kgCO$_2$e/kg)	$E_{VMSub\ seq}$ (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)
MDF	536.32	0	-1.5	0.17	0.86	-1.5	1	-370.06
Chipboard	1,663.49	0	-1.52	0.15	0.4	-1.52	1	-415.87
Oak	69.377	0	-1.59	0.08	0.3056	-1.59	1	-15.65
I-Joist	75.50	0	-1.53	0.14	0.48	-1.53	1	-25.67
Softwood	2,842.02	0	-1.55	0.12	0.26	-1.55	1	-397.88

Table 4.10: Timber energy recovery in the residential building, considering electrical energy only

Material	$M_{INC\ out}$ (kg)	$X_{INC\ elec}$ (kWh/kg)	$E_{SE\ elec}$ (kgCO$_2$e/kWh)	Module D (kgCO$_2$e)
MDF	429.06	1.05	0.19	-86.95
Chipboard	1330.79	1.05	0.19	-269.68
Oak	55.50	1.05	0.19	-11.25
I-Joist	60.40	1.05	0.19	-12.24
Softwood	2273.61	1.05	0.19	-460.75

Table 4.11: EC saving during recycling of metal materials in the residential building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)

Aluminium	277.45	90.54	-0.8	1	-149.53
Steel, Galvanised	687	484.94	-1.41	1	-284.90
Universal Beam	333.75	235.59	-0.41	1	-40.25

Table 4.12: EC saving during recycling of concrete materials in the residential building

Material	**$M_{MR\ out}$ (kg)**	**$M_{MR\ in}$ (kg)**	**Avoided impacts ($kgCO_2e/kg$)**	**QR_{out}/Q_{sub} (value correction factor)**	**Module D ($kgCO_2e$)**
Concrete, Cast in Situ	63,865.83	0	-0.00137	1	-87.28
Precast Concrete	4,298.40	0	-0.00123	1	-5.28

Table 4.13: EC saving during recycling of brick in the residential building

Material	**$M_{MR\ out}$ (kg)**	**$M_{MR\ in}$ (kg)**	**Avoided impacts ($kgCO_2e/kg$)**	**QR_{out}/Q_{sub} (value correction factor)**	**Module D ($kgCO_2e$)**
Brick	35,931.75	0	-0.016	1	-574.90

Table 4.14: EC saving during recycling of rebar in the residential building

Material	**$M_{MR\ out}$ (kg)**	**$M_{MR\ in}$ (kg)**	**Avoided impacts ($kgCO_2e/kg$)**	**QR_{out}/Q_{sub} (value correction factor)**	**Module D ($kgCO_2e$)**
Rebar	6,684.62	7,113.31	0.264	1	113.17

Table 4.15 illustrates that timber materials offer significant advantages beyond the life cycle scope, particularly in terms of EC savings through incineration and recycling. In this building, Timber, Oak has the highest influence on the EC saving outside LCA, saving 47.31% of its total emissions, followed by Timber, MDF saving 43.35%. In addition, Timber materials such as Chipboard, Softwood, and I-joist demonstrate significant carbon savings, with reductions of

38.14%, 37.41%, and 16.18%, respectively. For Aluminium Profile made of 31% recycled material which is recycled at a rate of 95% at end-of-life, Module D reports the additional benefits resulting from the 64% of recycled Aluminium which is not addressed by the recycled content approach. The environmental benefit of Aluminium in this research is 9.89% of the total EC emissions of this material. According to (Steel for Life, 2021), the constructional steelwork used in the UK contains an average of 60% recycled content. Therefore, it was assumed that the Steel, Galvanised, and Universal beam used in this study incorporated a 60% recycled content. Taking into account the end-of-life strategy for these materials, which involves an 85% recycling rate, the extra 25% recycled materials results in a notable 11.40% and 8.05% reduction in EC compared to the total EC. In addition, 90% recycling brick resulted in the 5.54% EC reduction. For concrete materials the environmental benefit is very low. In the recycling process, concrete is typically converted into aggregate for use in new projects, and the EC associated with this material tends to be minimal. While the mentioned materials enhance environmental advantages, it's crucial to note that rebar carries an environmental burden. It comprises 97.9% recycled content during production and exhibits 92% recyclability at the end of its life cycle. Therefore, the discrepancy between the recycled content during manufacturing and the recycling capability at the end-of-life raises an important consideration. Therefore, the higher recycled content during the product stage implies a greater demand for recycling rebar to produce an equivalent quantity of material.

Table 4.15: Relative importance of Module D in the residential building, for each building variant compared to their total life cycle

Material	Share of Benefit / Burden (%)
Timber, Oak	-47.31%
Timber, MDF	-43.35%
Timber, Chipboard	-38.14%

Timber, Softwood	-37.41%
Timber, I-Joist	-16.18%
Steel, Galvanised	-11.40%
Aluminium Profile	-9.89%
Universal Beam	-8.05%
Brick	-5.54%
Concrete, Cast in Situ	-0.93%
Precast Concrete	-0.40%
Rebar	1.18%

4.1.6 WLEC of the residential building

Figure 4.7 shows the WLEC of the residential building. WLEC emissions encompass all EC emissions and removals associated with an asset throughout its life cycle, including disposal. This includes emissions from upfront production to end-of-life stages, categorized into modules A1-A5 (Upfront), B1-B5 (In Use), and C1-C4 (End of Life). Additionally, WLEC asset performance involves separately reporting potential benefits from future energy recovery, reuse, and recycling (Module D). Module D quantifies the potential carbon benefits that may result from a design decision made today in the future.

By comprehensively assessing EC throughout the building's lifecycle, insight can be gained into the distribution of EC across various stages, allowing for informed decisions to be made on strategies to minimize it effectively. Figure 4.7 illustrates the potential for minimizing upfront carbon emissions. However, caution must be taken to ensure that the reduction of EC during stages A1–A5 does not disproportionately impact stage B. It's imperative to avoid utilizing materials of inferior quality and shorter lifespans in an attempt to lower upfront carbon emissions, as this may inadvertently increase the burden during stage B. Figure 4.7 illustrates a significant storage of biogenic carbon in timber materials during the upfront carbon phase. In addition, when timber materials are replaced at the building's ages of 20 and 40 years, additional biogenic carbon is generated. This carbon storage is reduced during end-of-life stages, as 44% of timber materials are incinerated, releasing their stored biogenic carbon. Figure 4.7 also illustrates that the amount of EC generated varies throughout the lifespan of the building, largely depending on the longevity of the building materials used. Module A has the largest share of EC, significantly surpassing the other two modules. Following Module A, Module B ranks as the second highest, accounting for 18.38% of Module A. In contrast, Module C exhibits the lowest proportion of EC. Module D shows that the total EC saving of the end-of-life strategies is 3,094.98 $kgCO_2e$.

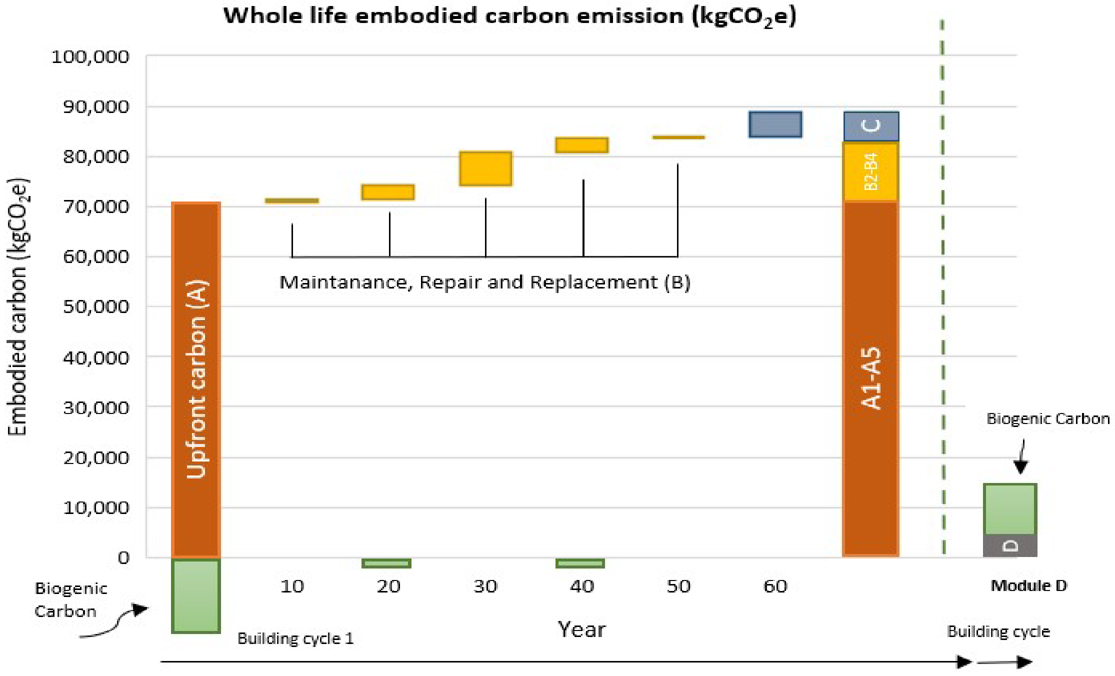


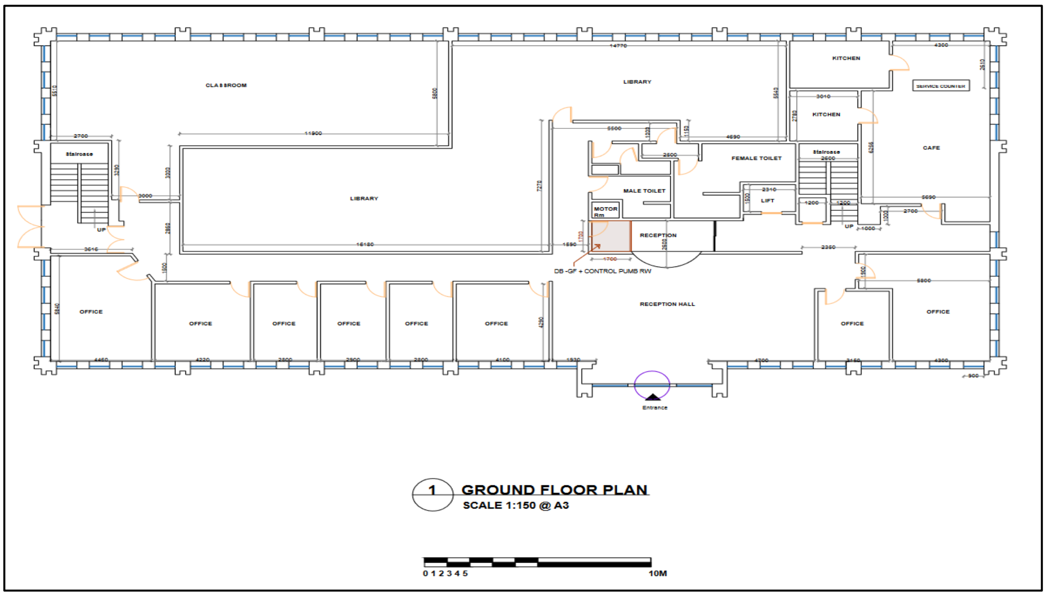
Figure 4.7: WLEC of the residential building

4.2 Case study 2: The College Building

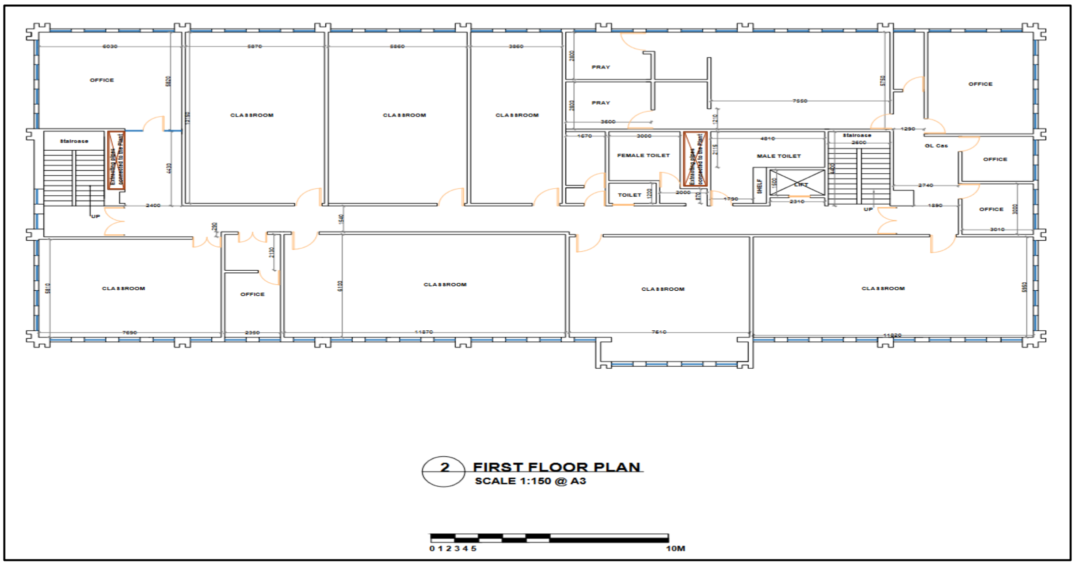
4.2.1 Building Description

As a case study, this investigation used The London College, which is a large, detached educational building. This building is coated in red bricks and has double glazed windows of a dark brown colour. The total floor area of this educational facility is approximately 2500 m², and it is constructed across three levels. The ground floor level accommodates various essential functional areas, including the kitchen, café, library, multiple offices, and the main reception area, serving as the central access point to the building. The first floor primarily accommodates staff rooms along with several classrooms, providing designated spaces for both administrative and educational activities. The second floor includes additional classrooms, laboratory spaces, and offices, ensuring a well-distributed arrangement for both teaching and research purposes.

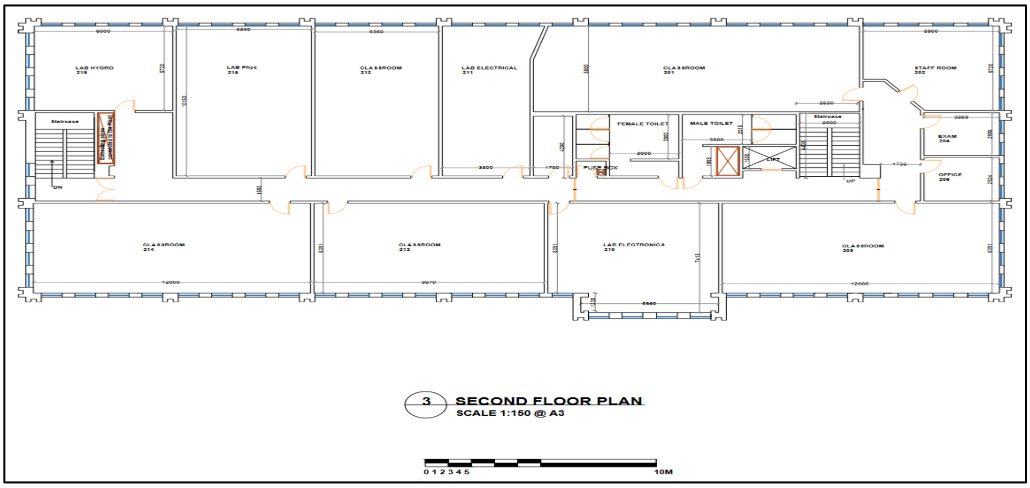
The building has been thoroughly surveyed and subsequently simulated within Autodesk® Revit®, version 2023, which is a well-known BIM software used for architectural design, structural engineering, and construction analysis. Table 4.16 provides a detailed breakdown of the quantity of materials applied in the construction of this building. Additionally, Figures 4.8 and 4.9 visually illustrate the floor plans along with the Revit-generated 3D model of the structure, offering a comprehensive representation of the building’s layout and design.



a) Ground floor plan of the college building

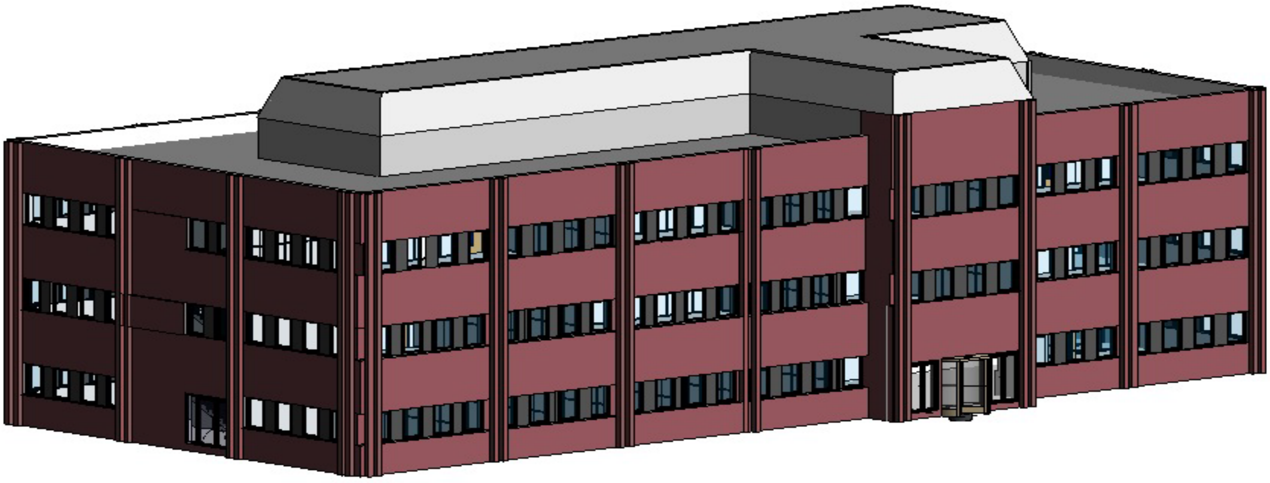


b) First floor plan of the college building

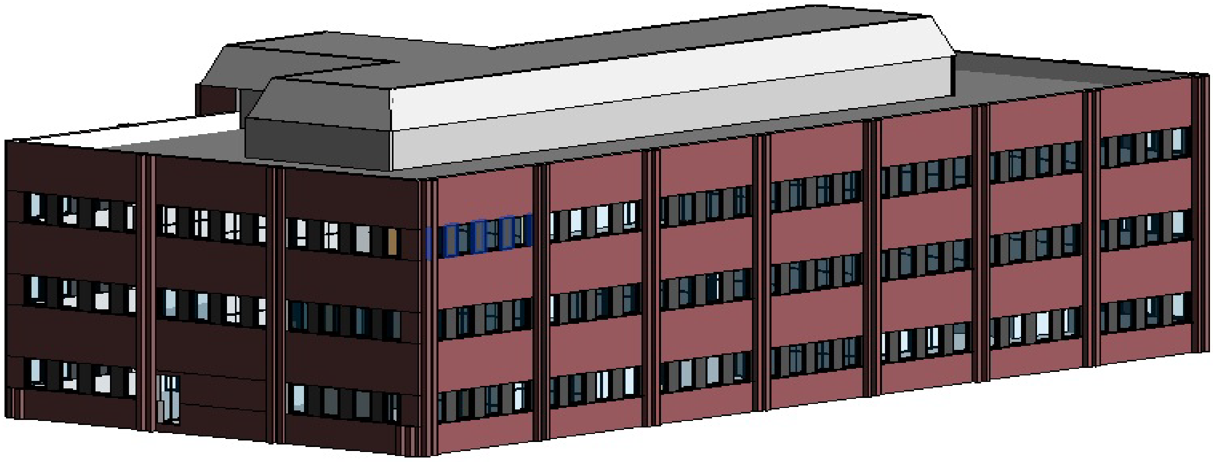


c) Second floor plan of the college building

Figure 4.8: Illustration of floor plans in different levels of the college building



a) Front elevation



b) Rear elevation

Figure 4.9: Revit 3D model of the College building

Table 4.16: The quantity of materials applied in the college building

Building Element	Structural Element	Component	Volume (m^3)	Weight (kg)
Substructure	Pad Foundation	Concrete, Cast in Situ	311.67	797,491.76
Superstructure	Structural Framing (Column)	Concrete, Cast in Situ	44.44	113,732.37
	Floor	Concrete, Cast in Situ	596.35	1,525,914.91
		Screed	39.39	90,601.60
	Roof	Concrete, Cast in Situ	204.77	523,966.39
		Rock Mineral Wool	39.76	2,027.86
		Steel, Galvanised	0.391	3,069.35
		Polystyrene, Expanded	47.65	740.4
	Ceiling	Fiberglass batt	32.11	6,608.94
		Aluminium Profile	3.44	9,473.07
	Stair	Concrete, Cast in situ	12.03	30,782.64
	External Walls	AAC	107.88	64,729.80
		Brick	121.57	237,069.3
		Plasterboard	13.47	10,529.63
		Steel, Galvanised	0.64	2,669
		Polystyrene, Expanded	47.65	740.4
		Aluminium Plate	3.051	8,390.25
	Internal Walls and Partitions	AAC	68.16	40,897.20
		Aluminium Profile	1.44	3,978.09
		Timber, Softwood	18.98	9,413.59

	Glass	2.77	6,895
	Fiberglass	81.81	23,725.19
	Plasterboard	42.07	32,901.87
Windows	Glass	4.93	12,320
	Aluminium Profile	7.67	21,121.02
Doors	Timber, MDF	5.19	3,928.18
	Bronze	0.53	4,452.06
	Steel, Galvanised	0.01	124.89
	Aluminium Profile	0.3	825.9
	Glass, Glazing	0.76	1,915

Figure 4.10 reveals that a substantial 83% of the building's composition is attributed to concrete, signifying a considerable proportion. Consequently, diminishing the EC of concrete holds the potential for a notable positive influence on the overall EC of the building. Following concrete, Brick accounts for 7% of the total quantity. The remaining materials constitute a relatively insignificant proportion.

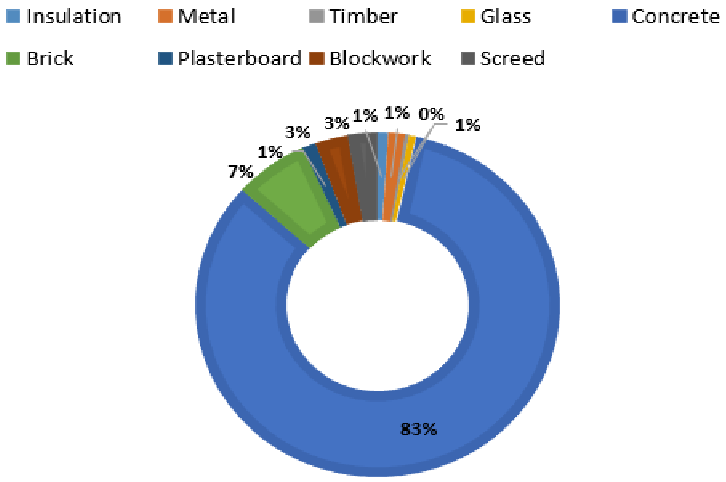


Figure 4.10: Weight composition per building materials in the London College

4.2.2 Embodied carbon variations in concrete database

4.2.2.1 Embodied Carbon comparison of Concrete without reinforcement

This section offers a thorough comparison of the EC in concrete materials utilized for residential and college buildings, considering two distinct scenarios. Detailed descriptions of the case studies can be found in section 4.1.1 and 4.2.1. Table 4.17 comprehensively illustrates the EC of concrete materials within the case studies, treating them as singular entities in the first scenario. In contrast, Table 4.18 provides a more detailed analysis by exploring the EC of concrete materials, dissecting, and thoroughly analysing their individual component parts in the second scenario. A closer examination of the ECFs distinctly reveals that the C20/25 concrete used in the residential building exhibits lower carbon emissions in direct comparison to the C32/40 concrete utilised in the college building. This observation underscores the importance of considering both the structural requirements and the broader aspects of environmental sustainability in the process of material selection.

Table 4.17: The EC of concrete as a singular material

	Residential building			**College building**		
Material	**Concrete, Cast in Situ (C20/25)**	**Screed**	**Autoclaved aerated concrete**	**Concrete, Cast in Situ (C32/40)**	**Screed**	**Autoclaved aerated concrete**
Quantity (kg)	67,098.61	10,392.86	16,496.15	2,611,233.70	90,601.60	105,627.00
ECF (kgCO$_2$e/m^2)	0.112	0.149	0.28	0.138	0.127	0.28
Embodied Carbon (kgCO$_2$e)	7,515.04	1,548.54	4,618.92	360,350.25	11,506.40	29,575.56

Table 4.18: The EC of concrete as a its component parts

		Residential building			**College building**		
Material	**Admixture**	**Quantity (kg)**	**ECF (kgCO$_2$e/kg)**	**Embodied Carbon (kgCO$_2$e)**	**Quantity (kg)**	**ECF (kgCO$_2$e/kg)**	**Embodied Carbon (kgCO$_2$e)**
Concrete, Cast in Situ	CEM I	5,672.98	0.912	5,173.76	220,771.80	0.912	201,343.88
	GGBS	2,694.67	0.0416	112.10	104,866.61	0.0416	4,362.45
	Fly Ash	425.47	0.004	1.70	16,557.89	0.004	66.23
	Aggregate	54,318.80	0.00747	405.76	2,113,890.02	0.00747	15,790.76
	Water	3,942.72	0.000344	1.36	153,436.40	0.00034400	52.78
	Admixture	43.97	1.67	73.25	1,710.98	1.67	2,850.78
Screed	Sand	7,627.80	0.00747	56.98	70,233.80	0.00747	524.65
	Cement	1,906.95	0.912	1,739.14	14,046.76	0.912	12,810.64
	Water	858.13	0.000344	0.30	6,321.04	0.000344	2.17
Autoclaved aerated concrete	Aggregate	12,372.11	0.00747	92.42	79,220.25	0.00747	591.78
	Cement	2,309.46	0.912	2,106.23	14,787.78	0.912	13,486.46
	Quicklime	1,319.69	1.136	1,499.17	8,450.16	1.136	9,599.38
	Water	494.88	0.000344	0.17	3,168.81	0.000344	1.09

In Table 4.19, for the residential building, the EC of “Concrete, cast in situ (C20/25)” is recorded as 7,515.04 $kgCO_2e$ in the first scenario, which is 30.29% higher than in the second scenario. Similarly, for the college building, the variation between the two scenarios is even more pronounced for “Concrete, cast in situ (C32/40),” where the EC in the first scenario is significantly 60.54% higher than in the second scenario. This pattern suggests that as the strength of the concrete increases, the percentage gap between the two scenarios also widens, indicating a stronger impact of scenario selection on higher-strength concrete types.

AAC was employed in both buildings under analysis. Upon closer scrutiny of the two scenarios, there is a distinct and measurable 24.9% elevation in the EC during the first scenario in comparison to the second scenario. This substantial disparity underscores the influence of varying scenarios on the overall environmental impact of AAC, emphasizing the critical importance of utilizing the correct database in the context of sustainable construction practices. In the case of "Screed," a unique and distinctive trend becomes evident. Unlike other materials where the first scenario typically results in an increase in EC values, "Screed" behaves differently, demonstrating a notable reduction in the first scenario relative to the second scenario. Specifically, in the residential building, the EC in the first scenario exhibits a decrease of -13.8% when compared to the second scenario. This downward trend in EC is consistently mirrored in the college building, where the difference remains nearly identical, staying at approximately -13.73%.

Table 4.19: Comparison between scenarios for the residential and the college buildings

	Residential building			College building		
Material	**Scenario 1**	**Scenario 2**	**Comparison**	**Scenario 1**	**Scenario 2**	**Comparison**
Concrete, Cast in Situ	7,515.04	5,767.93	30.29%	360,350.25	224,466.89	60.54%
Screed	1,548.54	1,796.41	-13.80%	11,506.40	13,337.47	-13.73%
AAC	4,618.92	3,697.99	24.90%	29,575.56	23,678.70	24.90%

4.2.2.2 Embodied carbon comparison of Reinforced Concrete

In this section, the integration of reinforcing steel into the “Concrete, cast in situ” mixture is explored, allowing us to assess its impact on the overall EC. In the residential building, a quantity of 7265.90 kg of reinforcing steel is introduced, accompanied by an associated ECF for rebar of 0.121 $kgCO_2e/kg$. Conversely, in the college building, a more substantial amount of 276644.71 kg of reinforcing steel is utilized, with an ECF for rebar measuring 0.149 $kgCO_2e/kg$. The analysis indicates that for “Reinforced Concrete (RC20/25)” in the residential building, the variation between the two scenarios is high, approximately -36.13%. This suggests that the addition of reinforcing steel has a high impact on the EC in this context. In addition, in the college building, the scenario divergence is markedly pronounced for “Reinforced Concrete (RC32/40)”, revealing a relatively high contrast of -22.67% between the two scenarios (Table 4.20).

Table 4.20: The EC of reinforced concrete in two scenarios

Materials	Scenario 1	Scenario 2	Comparison
Concrete, Cast in Situ (RC20/25)	9,465.58	14,819.11	-36.13%
Concrete, Cast in Situ (RC32/40)	430,293.88	556,440.54	-22.67%

4.2.2.3 Embodied Carbon comparison of Concrete with different strength

Given the significant differences in EC among various concrete strengths, a more detailed and comprehensive analysis is examined to understand how changing the concrete strength in the residential building specifically affects the EC. This detailed and thorough analysis aims to reveal and highlight the patterns in EC variations that emerge based on different concrete strength levels. Table 4.21 presents a detailed and structured breakdown of the EC assessment for various concrete mixtures, including C20/25, C25/30, C28/35, C32/40, C35/45, and C40/50, considered as a single material in the analysis. For the C20/25 concrete mixture, the quantity is calculated as 67,098.61 kg, with an ECF value of 0.112 $kgCO_2e/m^2$, leading to a resulting EC of 7,515.04 $kgCO_2e$. In a similar manner, the table provides the corresponding values for the

C25/30, C28/35, C32/40, C35/45, and C40/50 concrete mixtures, illustrating a gradual and incremental increase in the EC as the concrete strength class progressively increases.

Table 4.21: The EC of Concrete as a single material at various strength

Concrete (in situ)	C20/25	C25/30	C28/35	C32/40	C35/45	C40/50
Quantity (kg)	67,098.61	71,807.29	76,515.96	84,756.14	91,819.15	98,882.17
ECF ($kgCO_2e/m^2$)	0.112	0.119	0.126	0.138	0.149	0.159
Embodied Carbon ($kgCO_2e$)	7,515.04	8,545.07	9,641.01	11,696.35	13,681.05	15,722.26

Table 4.22 provides a comprehensive and detailed breakdown of the EC assessment for various concrete mixtures, considering their individual component parts. Each specific mixture comprises precise quantities of its constituent materials, including CEM I, GGBS, Fly Ash, Aggregate, Water, and Admixture, with corresponding values assigned for ECF per kilogram. The data presented in the table clearly illustrates that CEM I constitute the component with the highest EC content among all the materials used in concrete production. Therefore, substituting CEM I with a less carbon-intensive alternative material has the potential to significantly diminish the overall ECF of concrete.

Table 4.22: The EC of Concrete as component parts at Various Strength

Material	Admixture	Quantity (kg)	ECF ($kgCO_2e/kg$)	Embodied Carbon ($kgCO_2e$)
Concrete, Cast in Situ (C20/25)	CEM I	5,672.98	0.912	5,173.76
	GGBS	2,694.67	0.0416	112.10
	Fly Ash	425.47	0.004	1.70
	Aggregate	54,318.80	0.00747	405.76
	Water	3,942.72	0.00034400	1.36
	Admixture	43.97	1.67	73.25
Concrete, Cast in Situ (C25/30)	CEM I	6,071.09	0.912	5,536.83
	GGBS	2,883.77	0.0416	119.96
	Fly Ash	455.33	0.004	1.82
	Aggregate	58,130.65	0.00747	434.24
	Water	4,219.40	0.00034400	1.45
	Admixture	47.05	1.67	78.39
Concrete, Cast in Situ (C28/35)	CEM I	6,469.19	0.912	5,899.90
	GGBS	3,072.87	0.0416	127.83
	Fly Ash	485.19	0.004	1.94
	Aggregate	61,942.49	0.00747	462.71

	Water	4,496.09	0.00034400	1.55
	Admixture	50.14	1.67	83.54
Concrete, Cast in Situ (C32/40)	CEM I	7,165.87	0.912	6,535.28
	GGBS	3,403.79	0.0416	141.60
	Fly Ash	537.44	0.004	2.15
	Aggregate	68,613.22	0.00747	512.54
	Water	4,980.28	0.00034400	1.71
	Admixture	55.54	1.67	92.53
Concrete, Cast in Situ (C35/45)	CEM I	7,763.03	0.912	7,079.88
	GGBS	3,687.44	0.0416	153.40
	Fly Ash	582.23	0.004	2.33
	Aggregate	74,330.99	0.00747	555.25
	Water	5,395.30	0.00034400	1.86
	Admixture	60.16	1.67	100.24
Concrete, Cast in Situ (C40/50)	CEM I	8,360.18	0.912	7,624.49
	GGBS	3,971.09	0.0416	165.20
	Fly Ash	627.01	0.004	2.51
	Aggregate	80,048.76	0.00747	597.96
	Water	5,810.33	0.00034400	2.00
	Admixture	64.79	1.67	107.95

Table 4.23 and Figure 4.11 presents the EC assessment results for various concrete mixtures in the two different scenarios. The observed differences in EC between scenario 1 and scenario 2 are noteworthy, ranging from 30.29% for C20/25 to 84.97% for C40/50. These disparities underscore the significance of considering concrete as a composition of its individual components (scenario 2) rather than treating it as a singular material (scenario 1) when assessing EC. The variations in EC percentages highlight the necessity for accurate assessments of EC in buildings. The disparities in EC percentages are particularly pronounced for higher-strength concrete mixtures, such as C32/40, C35/45, and C40/50, where the variations exceed 60%. This heightened sensitivity underscores the importance of accurate accounting for concrete components in assessing environmental impacts, especially for structures with higher strength requirements.

Table 4.23: Comparison between the scenarios for concrete with different strength

Materials	Scenario 1	Scenario 2	Comparison
Concrete, Cast in Situ (C20/25)	7,515.04	5,767.93	30.29%
Concrete, Cast in Situ (C25/30)	8,545.07	6,172.70	38.43%

Concrete, Cast in Situ (C28/35)	9,641.01	6,577.466	46.58%
Concrete, Cast in Situ (C32/40)	11,696.35	7,285.808	60.54%
Concrete, Cast in Situ (C35/45)	13,681.05	7,892.959	73.33%
Concrete, Cast in Situ (C40/50)	15,722.26	8,500.109	84.97%

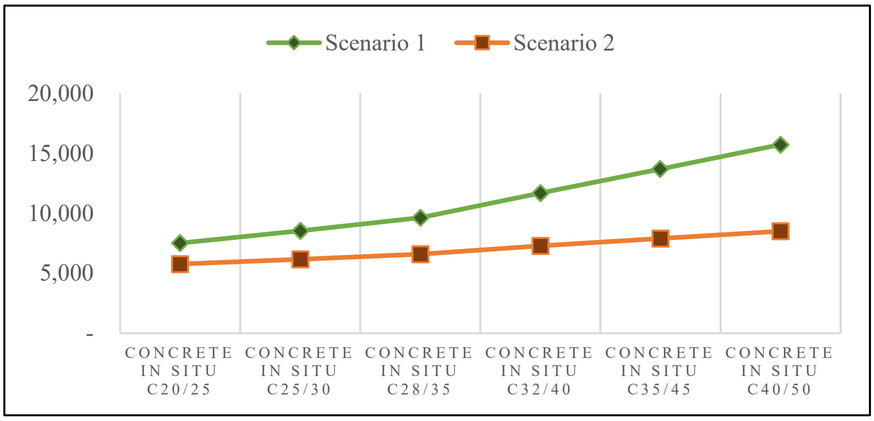


Figure 4.11: Comparative trends in concrete strength across two scenarios

In conclusion, the detailed comparison between scenario 1, which involves treating concrete as a singular material, and scenario 2, which focuses on examining its individual components, clearly reveals substantial variations in the results.

In the context of “concrete, cast in situ” for the residential building, the first scenario shows a 30.29% higher level of EC in comparison to the second scenario. This indicates that the first scenario overestimates the EC by 30.29%. In the first scenario, the “AAC” also resulted in a 24.9% overestimation. However, it has been observed that in the case of “Screed”, the first scenario underestimates the EC by -13.8%. In the college building, the disparity between the two scenarios for “concrete, cast in situ” is notably pronounced, clearly indicating a substantial overestimation of EC by as much as 60.54% in the first scenario. This significant difference underscores the sensitivity of scenario discrepancies to the strength of the concrete. The difference between the two scenarios arises from the lack of clarity regarding the materials used in the second scenario. As can be seen in Table 4.18 concrete is made of CEM I, GGBS, Fly Ash, Aggregate, Water, and Admixture. For example, the ECF of the aggregate in the second scenario is based on an average value, with no specification of whether it is fresh or recycled. Additionally, since no data was available for sand, the database assumed the same ECF as the aggregate. Similarly, the ECF assigned to the admixture is derived from an average of six EPDs, which may not accurately reflect the specific admixture used in the first scenario.

The comparison of two scenarios for reinforced concrete in both residential and college buildings clearly reveal a notable and significant underestimation in the first scenario, with the calculated percentages indicating values of -36.13% and -22.67%, respectively. The difference between the two scenarios arises from the lack of detailed information about the rebar used in the first scenario, particularly its recycled content, which significantly affects its ECF. Therefore, the primary factor contributing to this discrepancy is the absence of precise material specifications.

4.2.3 Embodied Carbon Assessment of the college building during module A and C

Similarly, as undertaken for the residential building, a comprehensive assessment of the EC associated with the college building has been conducted across the life cycle stages (A1-A5) and (C1-C4) utilizing the Enhanced database. Table 4.24 presents a detailed breakdown of the EC for various building materials at different phases of their life cycle. Furthermore, the EC values for stages A5a and C1 are recorded at 140,000 $kgCO_2e$ and 8,670 $kgCO_2e$, respectively.

Table 4.24: The total EC of the college building

Material	A1-A5 ($kgCO_2e$)	C2-C4 ($kgCO_2e$)	Total ($kgCO_2e$)
AAC	33,705.78	1,935.85	35,641.63
Aluminium	128,459.66	802.42	129,262.08
Brick	44,766.18	4,344.29	49,110.47
Bronze	18,132.64	81.58	18,214.23
Concrete, Cast in Situ	747,736.70	25,741.78	773,478.48
Fibreglass	54,710.01	605.44	54,775.45

Galvanised sheet	25,335.91	364.50	25,700.42
Glass, Glazing	36,364.58	387.44	36,752.02
Plasterboard	18,676.79	2,483.75	21,160.54
Polystyrene, Expanded	8,067.94	103.26	8,171.2
Rock Mineral Wool	3,283.09	37.16	3,320.26
Screed	15,933.18	1,660.27	17,593.45
Steel, Stainless	560.02	2.29	562.31
Timber, MDF	3,539.78	707.29	4,247.06
Timber, Softwood	2,969.82	1,431.38	4,401.20

This research identifies the key stages and materials characterized by the highest EC. The Product Stage (A1-A3) dominates, constituting approximately 80% of the overall EC, as illustrated in Figure 4.12. Furthermore, as depicted in the Figure 4.13 for this building, concrete materials account for the highest proportion of EC, contributing to 65% of the emissions. Following are metal materials, with 15%, marking the second-highest emissions. The contribution from other materials is relatively minimal, each accounting for less than 10% of the total EC emissions.

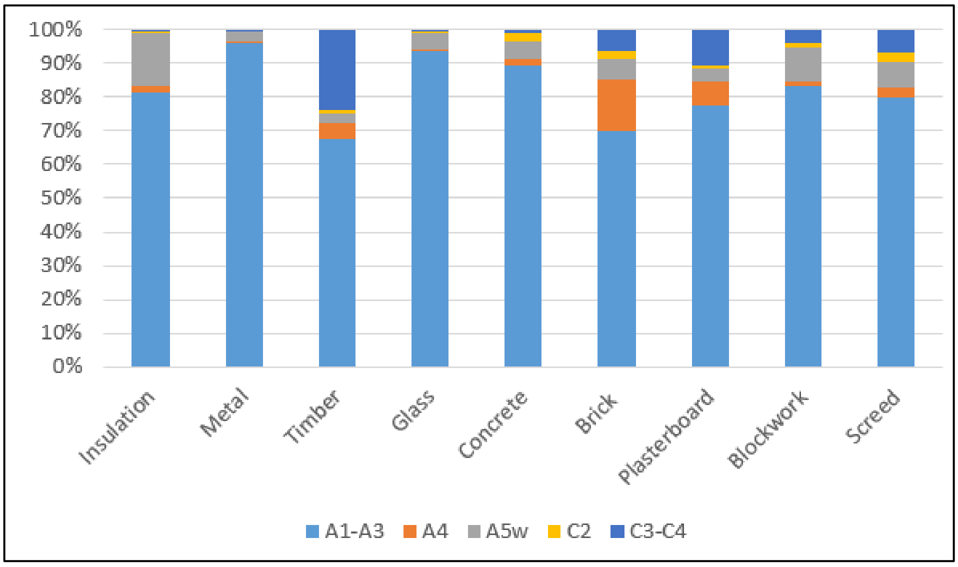


Figure 4.12: EC associated with each material throughout various stages of the college building's life cycle

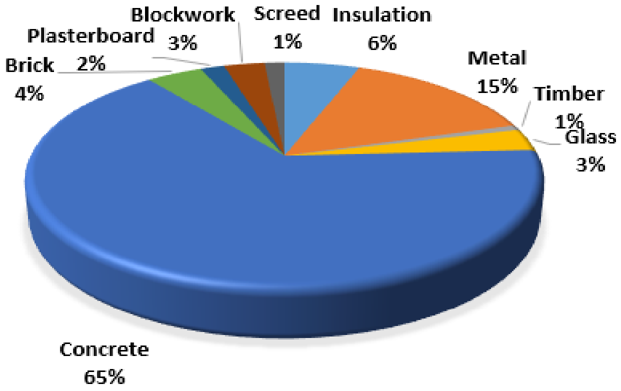


Figure 4.13: EC associated with each material of the college building

4.2.4 Embodied carbon assessment of the college building during module B

Module B thoroughly assesses the EC that results from the ongoing processes of maintenance, repair, and eventual replacement of various building materials throughout the use stage of the building. Table 4.25 indicates that the replacement of the façade leads to a substantial carbon burden of 135,615.22 kgCO$_2$e, whereas the replacement of the roof covering and ceiling finishes results in emissions of 12,817.73 kgCO$_2$e and 123,934.24 kgCO$_2$e, respectively. As illustrated in Table 4.26, stage B4 demonstrates a significantly higher level of EC emissions when compared to both stages B2 and B3, which are responsible for considerably lower emissions of only 25,000 kgCO$_2$e and 6,250 kgCO$_2$e, respectively.

Table 4.25: EC of the college building during module B4

Building part	Material	Expected lifespan (year)	Embodied carbon (B4) kgCO$_2$e
Facade	Window	30	76,857.36
	Door	20	58,757.86
Roof	Roof Covering	30	12,817.72
Finishes	Ceiling finishes	25	123,934.24

Table 4.26: Total EC of the college building during B2-B4

Area (m^2)	ECF (B2) (kgCO$_2$e/m^2)	EC (B2) (kgCO$_2$e)	EC (B3) (kgCO$_2$e)	EC (B4) (kgCO$_2$e)	EC (B2-B4) (kgCO$_2$e)

2,500	10	25,000	6,250	272,367.19	303,617.19

4.2.5 Module D outside the LCA for the college building

Table 4.27 to 4.32 underscores the critical role of end-of-life strategies in LCA, emphasizing the significant impact on EC emissions. The comprehensive data presented in these tables clearly illustrates the potential carbon savings that can be achieved through the implementation of optimal end-of-life scenarios. Specifically, by recycling Aluminium at high rates of 95%, substantial carbon savings amounting to 22,419.62 $kgCO_2e$ can be effectively realized. While concrete materials inherently exhibit a notably high EC content, the recycling process for these materials results in relatively limited savings in EC. This is primarily due to the fact that the recycling process typically transforms concrete into aggregate, which possesses a lower carbon intensity compared to its original form. Notably, cement, which serves as the primary contributor to concrete's overall carbon footprint, remains the dominant factor responsible for the highest carbon emissions within the material, further highlighting its significant environmental impact.

Table 4.27: EC saving during recycling of timber materials in the college building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	$E_{MR\ seq}$ ($kgCO_2e/kg$)	$E_{MR\ after\ EoW\ out}$ ($kgCO_2e/kg$)	$E_{VMSub\ out}$ ($kgCO_2e/kg$)	$E_{VMSub\ seq}$ ($kgCO_2e/kg$)	QR_{out}/Q_{sub} (value correction factor)	Module D ($kgCO_2e$)
Timber, MDF	2,160.50	0	-1.5	0.17	0.86	-1.5	1	-1490.74
Timber, Softwood	5,177.47	0	-1.55	0.12	0.26	-1.55	1	-724.85

Table 4.28: Timber energy recovery in the college building, considering electrical energy only

Material	$M_{INC\ out}$ (kg)	$X_{INC\ elec}$ (kWh/kg)	$E_{SE\ elec}$ ($kgCO_2e/kWh$)	Module D ($kgCO_2e$)
Timber, MDF	1,728.40	1.05	0.19	-350.26

Timber, Softwood	4,141.98	1.05	0.19	-839.37

Table 4.29: EC saving during recycling of metal materials in the college building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO_2e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO_2e)
Aluminium	41,598.91	13,574.38	-0.8	1	-22,419.62
Galvanised sheet	4,877.60	3,443.01	-1.41	1	-2,022.77

Table 4.30: EC saving during recycling of brick in the college building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO_2e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO_2e)
Brick	213,362.37	0	-0.016	1	-3,413.80

Table 4.31: EC saving during recycling of concrete materials in the college building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO_2e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO_2e)
Screed	81541.44	0	-0.00568	1	-463.16
Concrete, Cast in Situ	2,478,709.34	0	-0.00137	1	-3,387.57

Table 4.32: EC saving during recycling of rebar in the college building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO_2e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO_2e)
Rebar	245,958.01	261,731.41	0.264	1	-4,164.18

By looking at Table 4.33, it becomes evident that timber materials possess the greatest potential for EC savings when compared to other materials. However, despite their notable potential, their overall contribution to carbon reduction is not particularly substantial due to their relatively low quantity in buildings. Dividing the total carbon savings by the overall carbon emissions in timber materials reveals that MDF and softwood demonstrate the ability to achieve EC savings of 50.42% and 49.44%, respectively, when compared to their total EC emissions. Recycling metal materials, such as aluminium and galvanized steel, results in considerable savings in EC, with reductions of 15.79% and 8.26%, respectively, making it an impactful environmental choice in terms of lowering EC emissions. In contrast, the EC savings for concrete materials and brick remain relatively low, amounting to less than 6%, which highlights the limited potential of these materials in reducing overall carbon emissions through recycling. Rebar features an impressive 97.9% recycled content, with a 92% recycling rate at the end of its life cycle. However, the data in the table underscores the need for an increased recycling rate for rebar to align with the growing demand for high recycled content during the product stage.

Table 4.33: Relative importance of Module D in the college building, for each building variant compared to their total life cycle

Material	Share of benefit / burden %
Timber, MDF	-50.42%
Timber, Softwood	-49.44%
Aluminium	-15.79%
Galvanised steel	-8.26%
Brick	-5.54%
Concrete, Cast in Situ	-0.78%
Rebar	1.18%

4.2.6 WLEC of the college building

Figure 4.14 illustrates the lifetime EC of building materials, comprehensively spanning from the initial stage of raw material supply (A1) to the final phase of benefits and loads that extend beyond the system boundary (D). Additionally, it effectively highlights that the amount of biogenic carbon present at various different stages of the entire building's lifecycle remains relatively low. Importantly, stages A1-A5 represent the phase with the highest EC, thereby presenting a significant potential for reduction in emissions. Module B has the second-highest EC emissions, representing 23.69% of the EC in Module A. In addition, Module C shows a relatively low EC share in comparison to other stages. Moreover, the graph distinctly indicates that the environmental benefits that are derived from end-of-life strategies remain relatively modest, thereby suggesting that there is considerable room for improvement in this particular aspect.

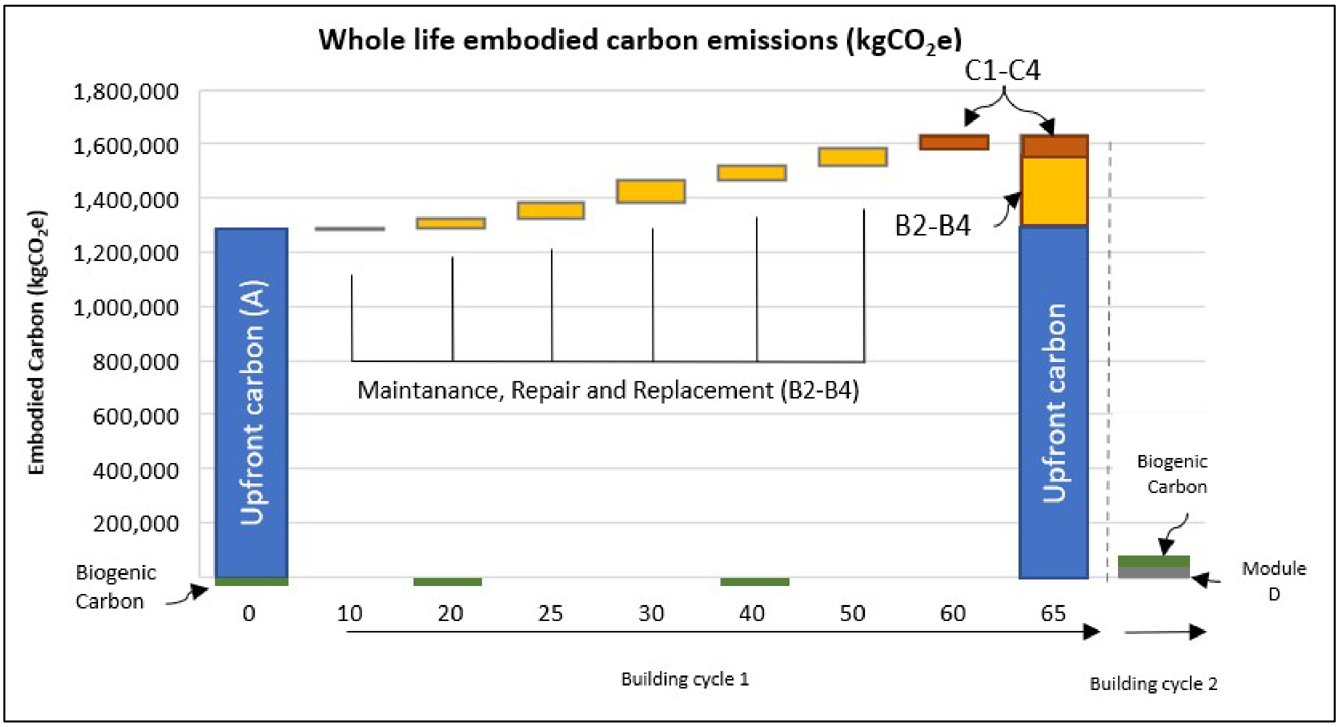
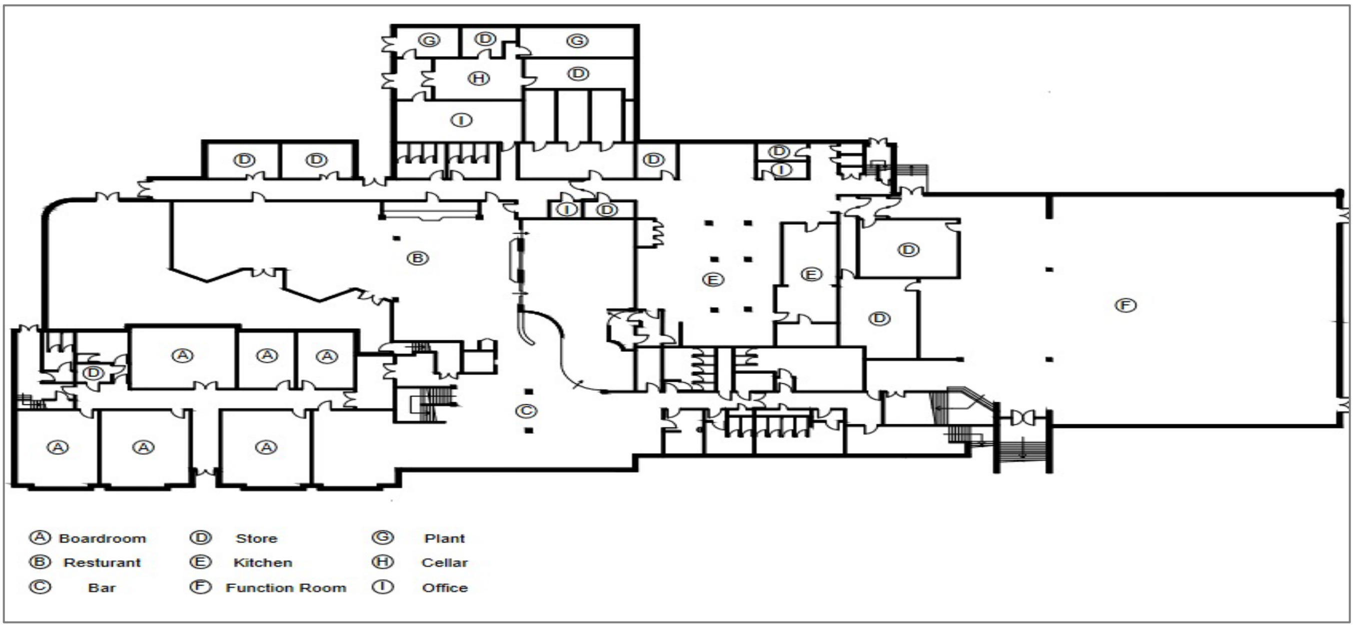


Figure 4.14: WLEC of the college building

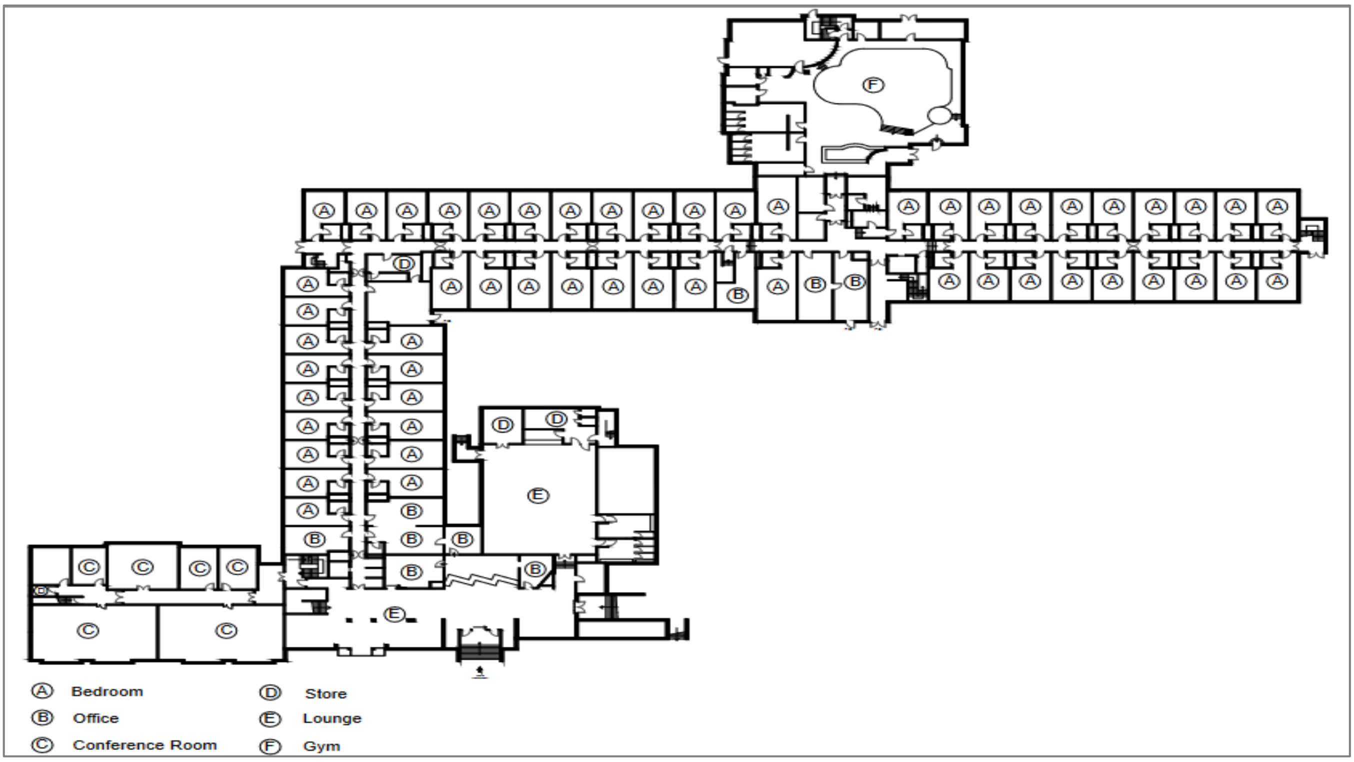
4.3 Case study 3: The Hotel Building

4.3.1 Building Description

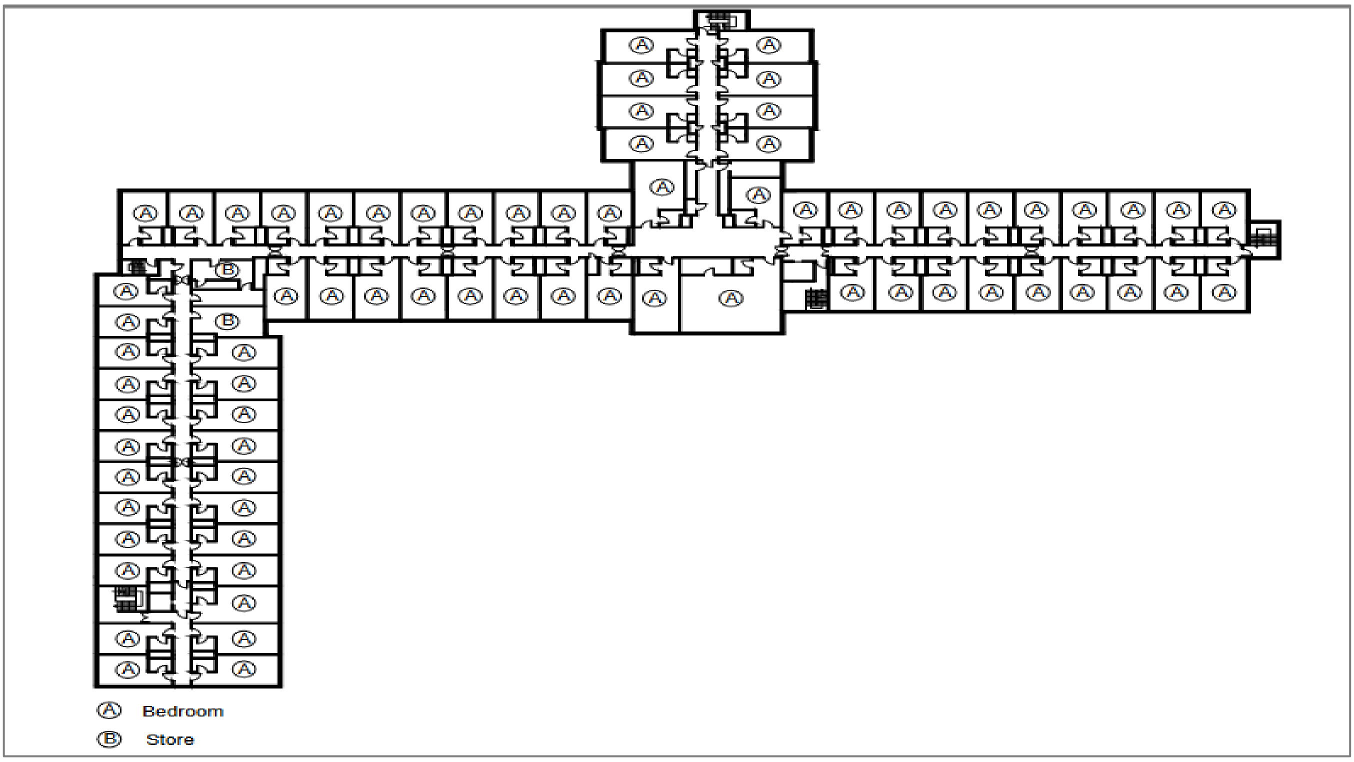
Within the scope of the research, the Hilton Watford, a hotel establishment constructed during the 1970s, has also been chosen as a focus. The total floor area of the entire building is estimated to be around 11,843.29 m², and it is constructed in a total of four levels. The lower ground floor level of the building accommodates various functional areas such as the kitchen, the restaurant and bar, several meeting rooms, and a spacious function room. The upper ground floor level serves as the entrance level and accommodates the reception area, the lounge area, multiple conference rooms, and a selection of guest rooms. There are a total of 202 guest rooms in the building, which are distributed across the upper ground floor, the first floor, and the second floor. The entire structure was modelled using the BIM software Autodesk® Revit® (Figure 4.16) and was developed based on the detailed architectural plans (Figure 4.15) to accurately identify and quantify the amount of materials that have been applied throughout the construction of this building. Table 4.34 provides a comprehensive and detailed overview of the various materials that were utilized in the construction of this building.



a) Lower GF plan of the hotel building

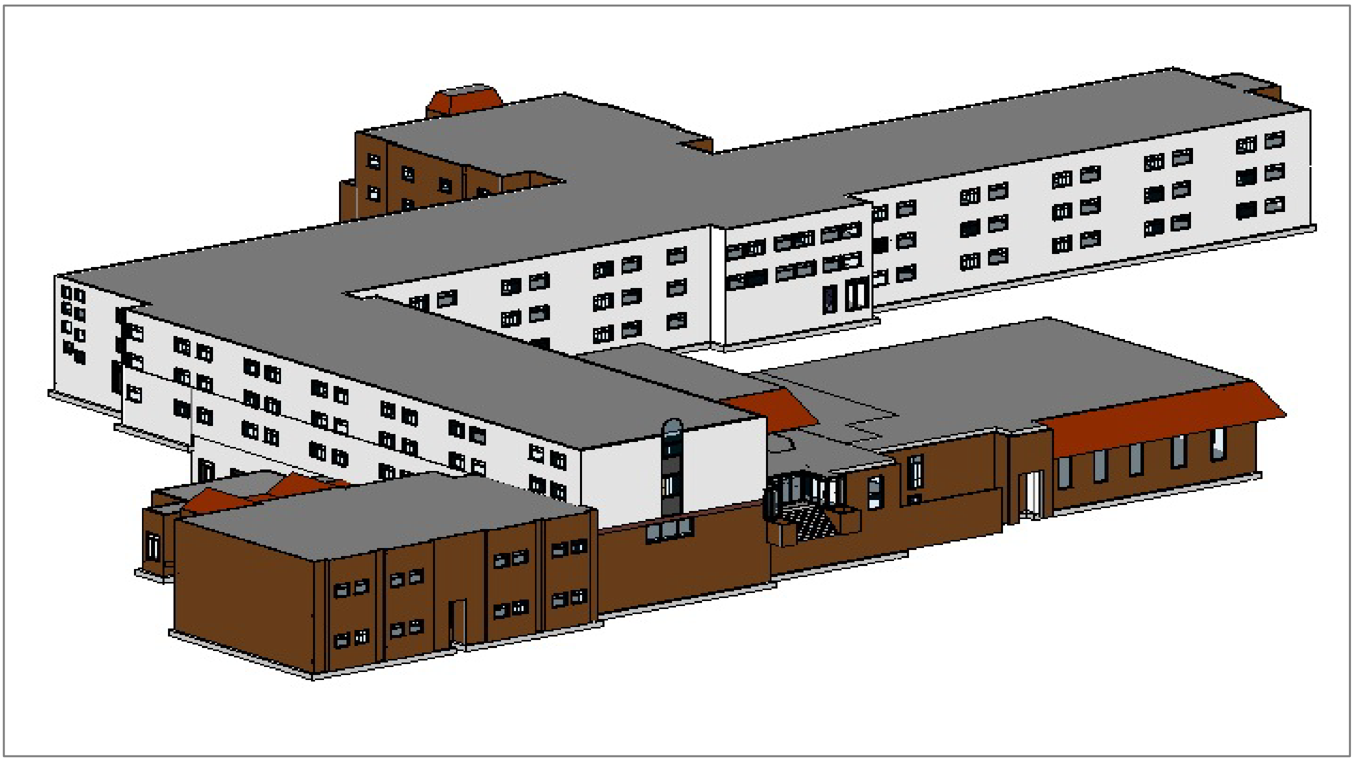


b) Upper GF plan of the hotel building

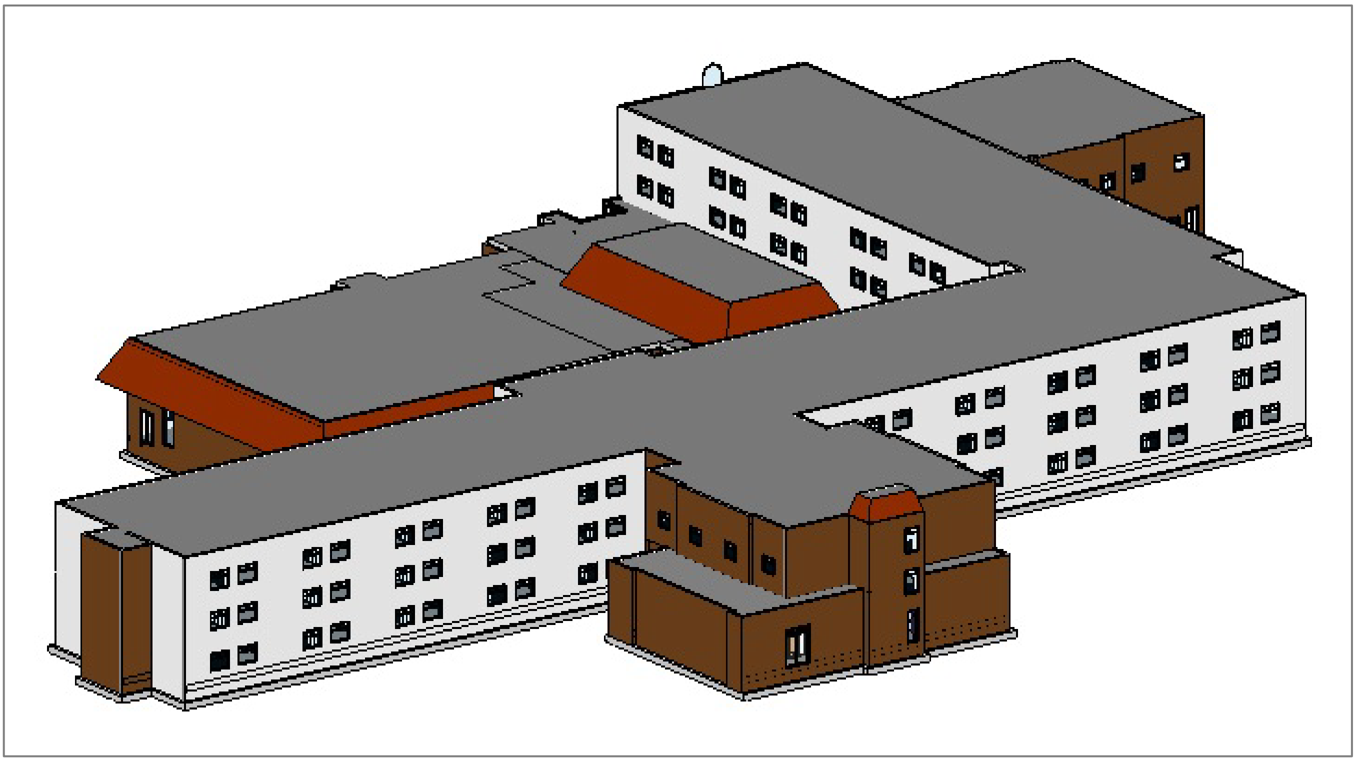


C) First and second floor plan of the hotel building

Figure 4.15: Illustration of floor plans in different levels of the hotel building



a) Front elevation



b) Rear elevation

Figure 4.16: Revit 3D model of the hotel building

Table 4.34: The quantity of materials applied in the college building

Building Element	Structural Element	Component	Volume (m^3)	Weight (kg)
Substructure	Foundation	Concrete, Cast in Situ	243.18	622,236.28
Superstructure	Floor	Concrete, Cast in Situ	1,639.92	4,196,258.91
		Screed	206.99	476,081.60
		Polyurethane Foam	413.98	13247.46
	Roof	Polystyrene, Expanded	23.77	713.01
		Gypsum Wall Board	5.42	4,333.60
		Timber, Softwood	12.25	6,077.98
		Timber, Glulam	33.8	21,394.13
		Roofing (Tile)	9.48	18,008.2
		Concrete, Cast in situ	601.86	1,540,001.72
		Polyethylene (High Density)	3.90	3,700.25
		Asphalt Shingle	74.02	125,827.20
		Extruded Polystyrene	623.29	654,449.25
	Ceiling	Plasterboard	602.52	482,016.8
		Fiberglass	198.47	57,556.01
		Aluminium Profile	86.60	238,429.07
	Column	Concrete, Cast in Situ	13.95	35,703.12
	Stair	Concrete, Cast in Situ	18.73	47,931.84
	Door	Aluminium Profile	2.46	6,775.13
		Glass, Glazing	1.55	3,877.5
		Timber, MDF	45.79	34,619.51
		Glass, Glazing	8.46	21,145

	Window	PVC	13.58	18,565.66
		Aluminium Profile	0.11	291.6

Table 4.34: Cont.

Building Element	Structural Element	Component	Volume (m^3)	Weight (kg)
External Envelope	External Wall	Brick	1,033.28	2,014,899.9
		Plasterboard	62.24	49,788.8
Interiors	Internal Wall	Plasterboard	235.08	188,066.4
		Aluminium	0.04	99
		PVC	16.79	23,508.80
		Rock Wool	739.54	147,907.2
		Softwood lath (stud)	196.42	97,425.81

According to Figure 4.17, the contribution of concrete materials accounts for more than half of the total quantity of the building, making it the most dominant material used in the construction process. Following concrete, brick makes up a significant portion, representing 18% of the total materials used. Insulation materials, while not as substantial as concrete or brick, still play a notable role, comprising 8% of the overall quantity. In comparison, the proportion of other materials used in the building is relatively insignificant, contributing only a minor fraction to the total material composition.

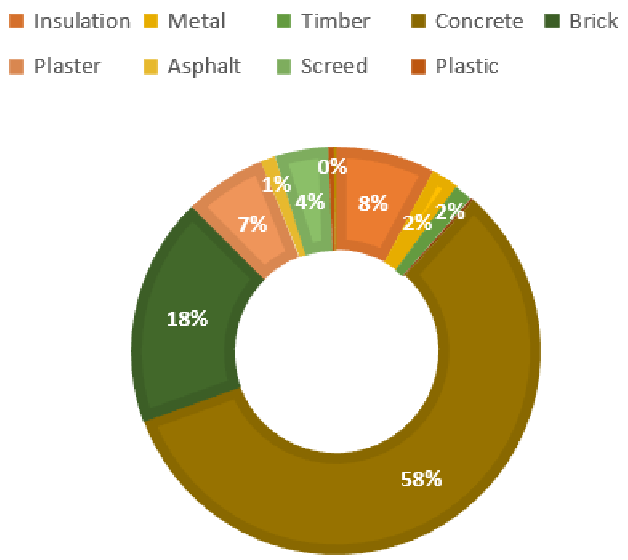


Figure 4.17: Quantity of the materials in the hotel building

4.3.2 Embodied Carbon Assessment of the hotel building during module A and C

Table 4.35 provides a detailed breakdown of the EC for various building materials at different stages of their lifecycle. In addition to this, the values for stages A5a and C1 are recorded at 380,487.25 kgCO_2e and 36,961.62 kgCO_2e, respectively. Furthermore, Figure 4.19 and Figure 4.20 visually illustrate the identified hot zones, effectively revealing the proportional EC share of different building materials across multiple stages of the building's lifecycle.

Table 4.35: The total EC of the hotel building

Material	A1-A5 (kgCO_2e)	C2-C4 (kgCO_2e)	Total (kgCO_2e)
Aluminium	662,545.30	4,500.52	667,045.83
Asphalt Shingle	8,611.58	2,305.78	10,917.36
Brick	380,410	36,923.04	417,333.04
Concrete, Cast in Situ	1,607,470.33	55,280.70	1,662,751.02
Extruded Polystyrene	2,639,412.11	11,992.78	2,651,404.89
Fiberglass	93,762.04	1,054.28	94,816.32
Glass	43,869.62	458.54	44,328.15
Plasterboard	142,757.31	40,483.82	183,241.13

Polyethylene (High Density)	8,436.89	67.81	8,504.70
Polystyrene, Expanded	5,982.78	32.05	6,014.83
Polyurethane Foam	75,558.40	242.76	75,801.16
PVC	131,293.84	771.01	132,064.85
Rock Wool	196,294.39	2,710.40	199,004.79
Roofing (Tile)	9,528.51	330.00	9,858.51
Screed	83,723.61	8,724.20	92,447.80
Timber, Glulam	13,893.43	4,930.38	18,823.81
Timber, MDF	31,197.19	6,233.40	37,430.59
Timber, Softwood	32,830.87	15,738.23	48,569.1

Similar to the two previous case studies, the EC during the A1-A3 stages significantly surpasses that of the other stages in the building's lifecycle, as illustrated in Figure 4.18. According to Figure 4.19, insulation, which constitutes a substantial 48% of the total EC emissions, clearly emerges as the primary contributor to EC. Despite its seemingly modest quantity of only 8%, its overall impact on emissions remains substantial due to its high ECF. Following insulation, concrete materials account for a notable 26% of the total EC emissions, while metal materials are responsible for approximately 10% of the total EC emissions.

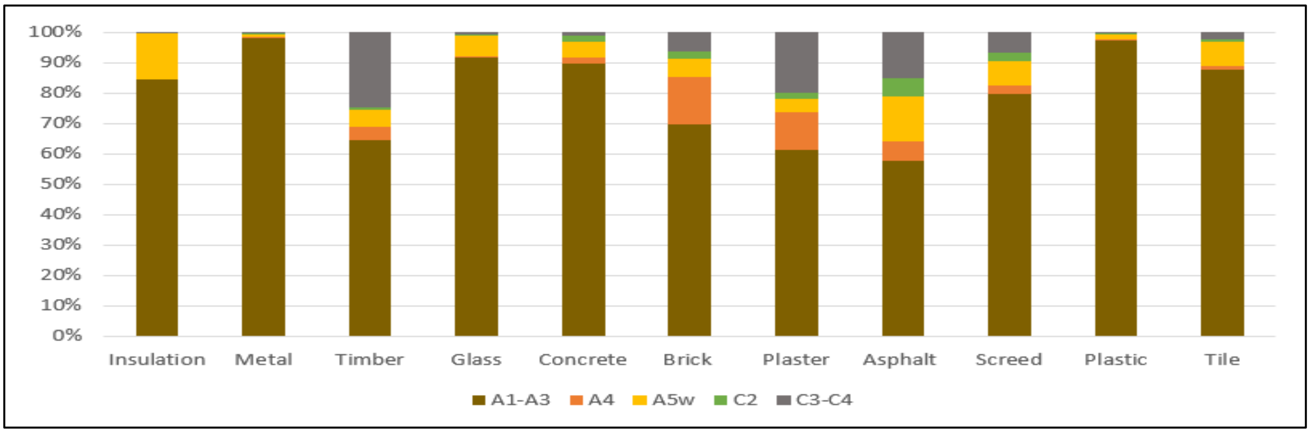


Figure 4.18: EC associated with each material throughout various stages of the hotel building's life cycle

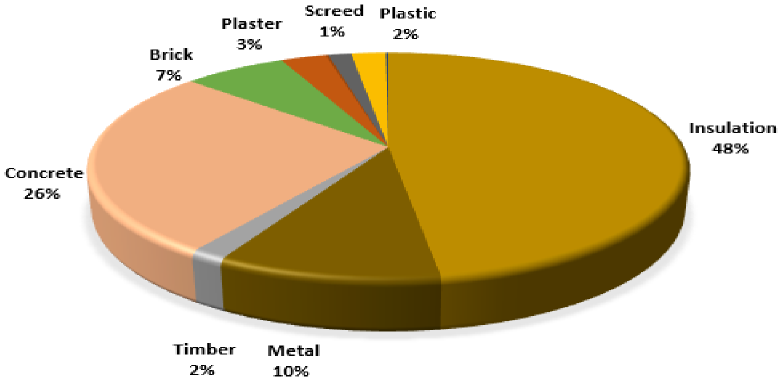


Figure 4.19: EC associated with each material of the hotel building

4.3.3 Embodied Carbon Assessment of the hotel building during module B

Table 4.36 provides a detailed illustration of the EC emissions that are generated during the replacement of various building materials. It highlights that the replacement of suspended ceilings can result in a substantial EC emission of approximately 1,608,558.39 kgCO$_2$e. This is particularly significant given that, considering its expected lifespan, suspended ceilings need to be replaced twice throughout the entire RSP. The replacement of other materials exhibits comparatively lower EC emissions, indicating a variation in environmental impact depending on the type of material being replaced.

Furthermore, Table 4.37 presents a comprehensive overview of the total EC emissions occurring during module B, with B4 accounting for the highest proportion at an estimated 2,361,958.03 kgCO$_2$e. In contrast, B2 and B3 contribute significantly lower EC emissions, with B2 amounting to 118,432.9 kgCO$_2$e and B3 totalling 29,608.22 kgCO$_2$e, respectively. This data underscores the differences in EC emissions across different sub-modules, emphasizing the importance of material selection and replacement frequency in minimizing the overall environmental impact.

Table 4.36: EC of the hotel building during module B4

Building part	Material	Expected lifespan (year)	Embodied carbon (B4) kgCO$_2$e
Facade	Window	30	95,796.78

	Door	20	100,804.33
Roof	Roof Covering	10	556,798.53
Finishes	Ceiling finishes	25	1,608,558.39

Table 4.37: Total EC of the hotel building during B2-B4

Area (m^2)	**ECF (B2) ($kgCO_2e/m^2$)**	**EC (B2) ($kgCO_2e$)**	**EC (B3) ($kgCO_2e$)**	**EC (B4) ($kgCO_2e$)**	**EC (B2-B4) ($kgCO_2e$)**
11,843.29	10	118,432.9	29,608.22	2,361,958.03	2,509,999.16

4.3.4 Module D outside the LCA for the hotel building

Table 4.38 to 4.43 provides a comprehensive and detailed view of the various environmental impacts associated with the hotel building, encompassing both the positive and negative aspects that extend beyond its defined life cycle boundaries. Notably, among these construction materials, there is a substantial EC saving that remarkably surpasses a total of 210 tonCO_2e. A particularly significant contributor to this overall reduction is the recycling of Aluminium, which demonstrates the highest impact by successfully saving an impressive amount of over 125,744.54 kgCO_2e. Subsequently, brick emerges as another highly influential factor in this context, contributing to further savings that exceed a notable 29,014.56 kgCO_2e. On the other hand, rebar introduces a considerable environmental burden, being responsible for emissions amounting to 8,966.30 kgCO_2e. This is attributed to its demand for a higher quantity of recycled steel than it generates, resulting in a net negative environmental impact.

Table 4.38: EC saving during recycling of timber materials in the hotel building

Material	**$M_{MR\ out}$ (kg)**	**$M_{MR\ in}$ (kg)**	**$E_{MR\ seq}$ ($kgCO_2e/kg$)**	**$E_{MR\ after\ EoW\ out}$ ($kgCO_2e/kg$)**	**$E_{VMSub\ out}$ ($kgCO_2e/kg$)**	**$E_{VMSub\ seq}$ ($kgCO_2e/kg$)**	**QR_{out}/Q_{sub} (value correction factor)**	**Module D ($kgCO_2e$)**
MDF	19,040.73	0	-1.5	0.17	0.86	-1.5	1	-13,138.1
Softwood lath	53,584.19	0	-1.55	0.12	0.26	-1.55	1	-7,501.79
Timber truss	11,766.77	0	-1.41	0.26	0.51	-1.41	1	-2,941.69

Table 4.39: Timber energy recovery in the hotel building, considering electrical energy only

Material	$M_{INC\ out}$ (kg)	$X_{INC\ elec}$ (kWh/kg)	$E_{SE\ elec}$ (kgCO$_2$e/kWh)	Module D (kgCO$_2$e)
MDF	15,232.58	1.05	0.19	-3,086.88
Softwood lath	42,867.36	1.05	0.19	-8,687.07
Timber truss	9,413.42	1.05	0.19	-1,907.63

Table 4.40: EC saving during recycling of metal materials in the hotel building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)
Aluminium	233,315.06	76,134.39	-0.8	1	-125,744.54

Table 4.41: EC saving during recycling of brick in the hotel building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)
Brick	1,813,409.91	0	-0.016	1	-29,014.56

Table 4.42: EC saving during recycling of concrete materials in the hotel building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)
Concrete, Cast in Situ	5,279,834.88	0	-0.00137	1	-7,215.77

Table 4.43: EC saving during recycling of rebar in the hotel building

Material	$M_{MR\ out}$ (kg)	$M_{MR\ in}$ (kg)	Avoided impacts (kgCO$_2$e/kg)	QR_{out}/Q_{sub} (value correction factor)	Module D (kgCO$_2$e)
Rebar	529,596.77	563,560.04	0.264	1	8,966.30

As previously discussed, dividing the EC savings of each material by their total EC emissions (see Table 4.44) indicates that timber materials show the highest potential for carbon emissions reduction, with metal materials ranking second. Table 4.44 further indicates the need for increased recycling of rebar materials, emphasizing that the current recycling levels fall short of what is necessary.

Table 4.44: Relative importance of Module D in the hotel building, for each building variant compared to their total life cycle

Material	Share of benefit/burden %
Timber, MDF	-43.35%
Timber, Softwood	-35.40%
Timber, Glulam	-25.76%
Aluminium	-18.85%
Brick	-6.95%
Concrete, Cast in Situ	-0.77%
Rebar	1.23%

4.3.5 WLEC of the hotel building

In Figure 4.20, the EC emissions throughout the entire life cycle of the hotel building are clearly depicted. Similar to the other two building types analysed, module A1-A5 exhibits the highest levels of EC emissions, while module C is responsible for the lowest proportion of EC emissions across the life cycle. The EC of Module B is 38.33% of that of Module A. It is worth mentioning the relatively high levels of EC emissions observed during the B stage, particularly at 25- and 50-years post-construction. This notable increase is primarily attributed to the high EC content associated with suspended ceilings, which typically have a lifespan of approximately 25 years and, as a result, require replacement twice during the RSP.

Furthermore, Figure 4.20 also illustrates that the total biogenic carbon present during the production phase and after the demolition phase remains relatively low, with values recorded at 202,939.26 kgCO2e and 168,738.78 kgCO2e, respectively.

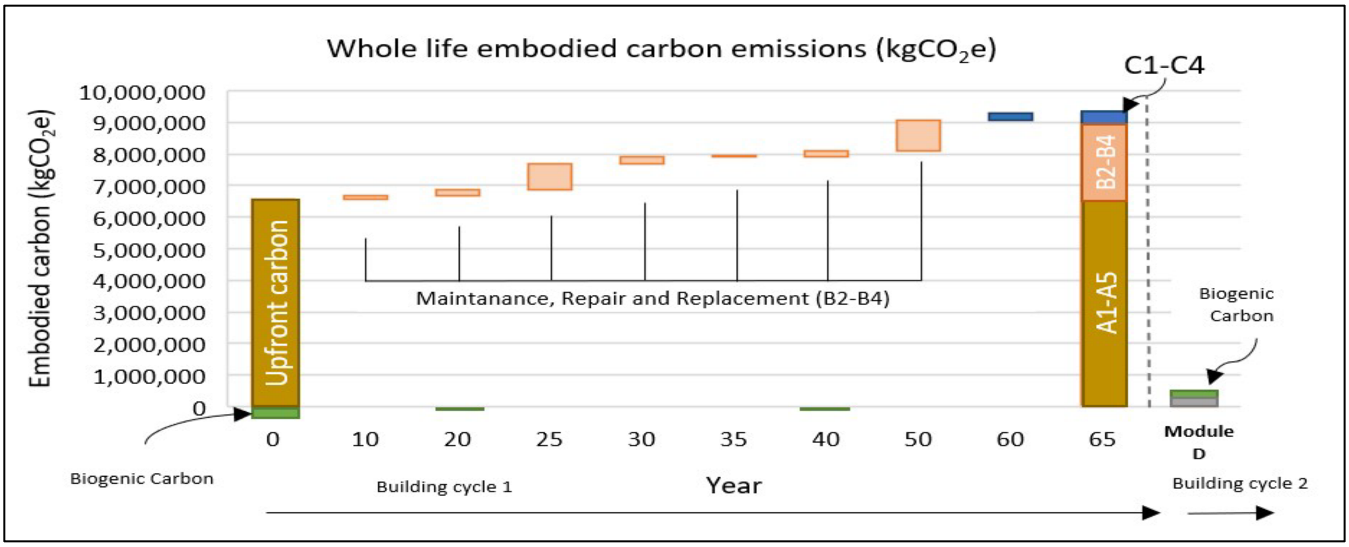


Figure 4.20: WLEC of the hotel building

4.4 Summary

This chapter provides a detailed and in-depth analysis of EC in buildings through a comprehensive and thorough examination of EC databases used in various case studies. It begins by discussing the fundamental importance of evaluating EC as a crucial aspect of addressing pressing climate change challenges and then proceeds to evaluate and assess the accuracy and reliability of EC databases.

The chapter provides a detailed comparison of the accuracy of these databases and thoroughly discusses the various discrepancies that exist between them. EPDs are widely considered to be the most reliable source of data; however, their overall availability remains significantly limited. Additionally, the BEIS database is evaluated, with particular attention given to its reliability. The enhanced database, which is formed by combining EPDs and the ICE database, is ultimately deemed to be the most comprehensive and reliable source of information.

A detailed comparison of EC in concrete materials is provided, considering different scenarios and strengths. Scenario 1 treats concrete as a singular material, while scenario 2 analyses its individual components. The primary factor contributing to discrepancy between two scenarios is the absence of precise material specifications.

This chapter also analyses the EC of three types of buildings: residential, educational, and hotel. It utilizes Revit software to model the buildings and analyse the quantity of materials used. The materials with the highest contribution to EC are identified as insulation, concrete, and metal. The chapter emphasizes the importance of reducing EC, particularly during the early stages of the building's life cycle (A1-A3).

The EC assessment is divided into modules A, B, and C, covering different stages of the building's life cycle, including production, in-use, and end-of-life. Module D is introduced to address recycling aspects not covered in the standard LCA framework. The chapter provides detailed tables showing EC emissions for various materials and stages, with a focus on timber materials' significant EC savings through incineration and recycling.

Furthermore, the chapter discusses the importance of considering end-of-life strategies and recycling in reducing EC, particularly for materials like timber, metal, and brick. Tables illustrate the avoided impacts and EC savings achieved through recycling and incineration processes for different materials.

Lastly, the chapter presents the WLEC assessment of the buildings, highlighting the distribution of EC across different life cycle modules and emphasizing the importance of making informed decisions to minimize upfront carbon emissions without compromising the performance and longevity of the building materials.

Chapter 5 : BIM-LCA integration for automated embodied carbon assessment

This chapter explores the integration of BIM and LCA for automating WLEC assessments in buildings, using the London College and Hotel Buildings as case studies. The findings confirm that the automated method achieves over 98% accuracy, closely aligning with manual calculations while significantly reducing assessment time by over 90%. Radar charts highlight strong accuracy, particularly in the product stage (A1-A3), while color-coded visualizations help identify carbon “hot spots” for better material choices. Minor discrepancies (<2%) between automated and manual methods demonstrate the reliability and efficiency of automation. The study concludes that integrating automated EC assessments into BIM workflows enhances sustainability in construction, enabling real-time updates, faster decision-making, and better carbon reduction strategies to support net-zero goals.

5.1 College Building

5.1.1 Comparison of WLEC Assessment Using Type IV and Type I Approaches in the educational Building

This section presents the detailed findings derived from the EC assessments that were systematically conducted using both the Type I and Type IV methods, as outlined in Tables 5.1 and 5.2, for the London College building, which was thoroughly described in Section 4.2. The comprehensive results obtained from these assessments highlight the notable accuracy, overall efficiency, and significant potential benefits associated with automating EC calculations. These findings demonstrate how this automated approach can streamline the assessment process while maintaining a consistently high level of precision. Furthermore, key outcomes specifically related to measurable time savings, improved accuracy across various building components, are examined and discussed in detail within this section.

Table 5.1: WLEC Assessment Results Utilizing Type I Method (kgCO$_2$e)

A	**A1-A3**	**A4**	**A5w**	**C2**	**C3-C4**	**B4**
Ceiling	58,506.94	356.42	2,759.49	100.04	244.23	123,934.24
Door	27,822.52	286.4	428.40	59.95	781.66	58,745.73
Floor	366,697.15	8,607.95	21,222.77	8,607.95	6,146.38	-
Roof	134,667.98	2,926.71	9,017.22	2,926.71	1,783.64	12,817.72
Stair	7,114.17	163.92	399.74	163.92	100.23	-
Structural column	26,284.67	605.62	1,487.95	605.62	370.33	-
Structural foundation	184,308.20	4,246.64	10,356.11	4,246.64	2,596.73	-
Wall	167,166.48	11,147.91	17,434.73	2,547.25	8,726.57	-
Window	74,442.38	178.07	1,624.10	178.07	434.73	76,857.36

Table 5.2: WLEC Assessment Results Utilizing Type IV Method (kgCO$_2$e)

	A1-A3	**A4**	**A5w**	**C2**	**C3-C4**	**B4**
Ceiling	58,507.21	356.41	2,780.87	100.78	245.34	123,997.46
Door	27,949.19	286.74	426.90	59.91	778.39	59,002.29
Floor	366,698.87	8,607.92	21,223.56	8,607.92	6,146.42	-
Roof	134,667.37	2,926.69	9,013.09	2,926.69	1,783.63	12,817.72
Stair	7,114.17	163.92	399.74	163.92	100.23	-
Structural column	26,399.35	605.61	1,462.42	605.61	370.31	-

Structural foundation	184,309.31	4,246.66	10,284.18	4,246.66	2,596.74	-
Wall	167,410.31	11,176.28	17,443.43	2,553.42	8,739.35	-
Window	74,442.64	178.07	1,626.04	178.07	434.73	76,595.47

5.1.2 Accuracy Comparison at different modules in the educational

Figure 5.1 showcases the accuracy of an automated EC assessment method in comparison to a manual method across various building components. Each building component, such as the ceiling, door, floor, roof, stair, structural column, and others, is represented in a radar chart, illustrating the level of accuracy for different stages of its life cycle. The stages of the life cycle include A1-A3 (product stage), A4 (transport to site), A5w (waste processing), B4 (repair and maintenance), C2 (transport), and C3-C4 (end-of-life). The radar charts use percentage scales (from 90% to 100%) to demonstrate how closely the automated method aligns with the manual method in assessing EC for each stage. The radar charts reveal that the automated method demonstrates a high level of accuracy (over 98%) for most building components, particularly in the product stage (A1-A3), which has the greatest impact on EC calculations. Additionally, the charts show that the automated method maintains consistent accuracy across other life cycle stages, closely aligning with the manual method, with accuracy rates exceeding 98%.

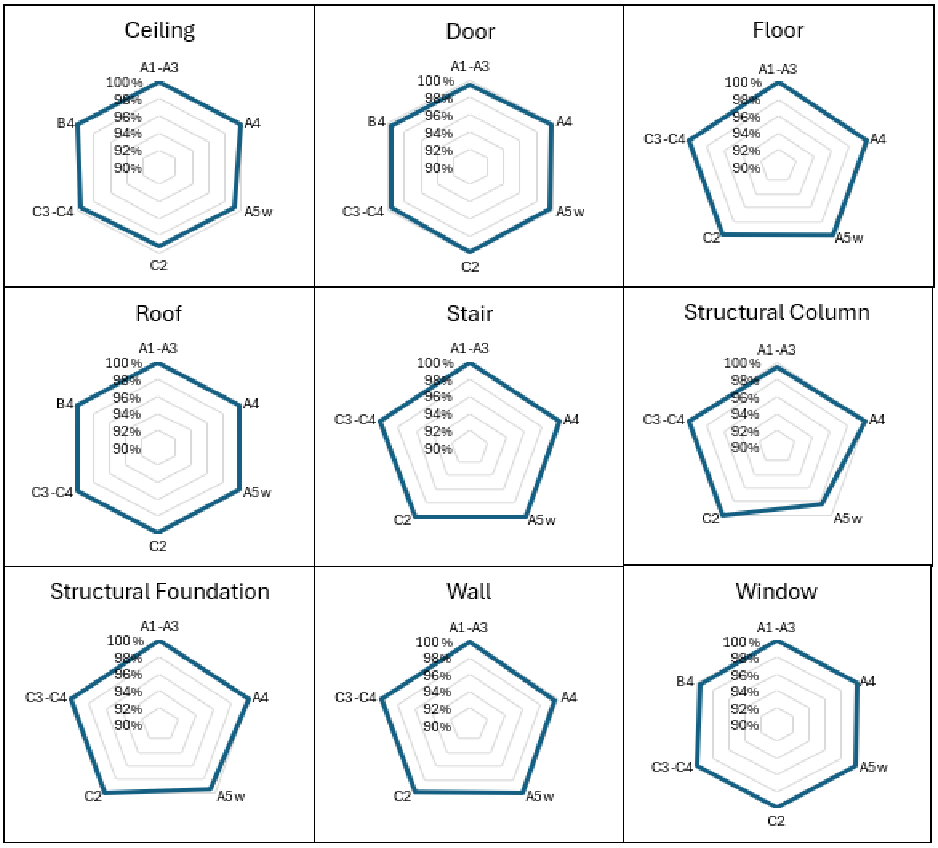


Figure 5.1: Comparison of the accuracy between the automated EC assessment method and the manual method in the educational building

5.1.3 Material-Oriented Accuracy Comparison in the educational building

Table 5.3 and 5.4 evaluates and compares the EC emissions of various construction materials in the educational building across life cycle stages as calculated by two methods: Type I and Type IV integrated assessment methods.

For foundations constructed with cast in situ concrete, the EC results show a remarkable alignment between the traditional and integrated methods across all stages. For example, the emissions for A1-A3 are calculated as 184,308.20 kgCO$_2$e in the Type I method and 184,309.31 kgCO$_2$e in the Type IV method. Differences are negligible, such as in A5w, where the Type I method reports 10,356.11 kgCO$_2$e, while the Type IV method slightly adjusts this to 10,284.18 kgCO$_2$e. These small variations highlight the reliability of the automated system in reproducing results similar to manual calculations while refining the precision of specific stages.

For floor made of cast in situ concrete, the EC emissions are consistent between the two methods. The emissions for A1-A3 are reported as 352,653.90 kgCO$_2$e in the Type I method and 352,655.63 kgCO_2e in the Type IV approach, with differences observed only in decimal values. Similarly, for screed flooring, the values remain identical across all lifecycle stages, with the only exception being the A5w stage, where the Type IV method records 1,408.18 kgCO_2e compared to 1,407.48 kgCO_2e in the Type I method.

The walls category includes several materials, including autoclaved AAC, aluminium plates, bricks, softwood timber, Glass, aluminium profile, plasterboard, galvanised steel, expanded polystyrene and fiberglass. For AAC, the Type I and Type IV methods have consistent results across all lifecycle stages, such as A4, where the values are 562.53 kgCO_2e and 562.51 kgCO_2e, respectively. Slight variations are observed for galvanized steel across all lifecycle stages. For A1-A3, the Type I method calculates 13,909.57 kgCO_2e, while the Type IV system reports 14,082.90 kgCO_2e. In the A4 stage, the Type I method records 161.02 kgCO_2e, compared to 163.02 kgCO_2e from the Type IV system. Similarly, for A5w, the values are 2,516.29 kgCO_2e (Type I) and 2,547.65 kg CO_2e (Type IV). In the C2 stage, the Type I method is 161.02 kgCO_2e, while the Type IV system calculates 163.02 kgCO_2e. Finally, for C3-C4, the EC is 65.52 kgCO_2e using the Type I method and 66.33 kgCO_2e using the Type IV approach. These discrepancies are minimal and demonstrate the reliability of the Type IV method. For the other materials in the wall category, there are minor differences in the EC values across various lifecycle stages.

Ceiling systems, including fiberglass batt and aluminium profiles, reveal minor differences between the two methods. Fiberglass batt demonstrates consistent results across most stages, with the C2 stage showing the largest difference: 49.6 kgCO_2e in the Type I method compared to 50.35 kgCO_2e in the Type IV method. For aluminium profile the Type IV method reports slightly higher emissions in the A5w stage, with values of 464 kgCO_2e compared to 458.02 kgCO_2e in the Type I assessment.

For doors and windows, the two methods show a strong alignment across all materials, with slight differences observed in the aluminium profile across various lifecycle stages in both categories. For example, in the door category, aluminium profiles exhibit higher emissions in the Type I method for the A4, C2, and C3-C4 stages compared to the integrated approach. Similarly, in the window category, the Type I method records slightly higher emissions for aluminium profiles in the A5w stage when compared to the Type IV method.

In the ceiling category, there are minor differences between the two methods for materials across the A5w, C2, and C3-C4 stages. For structural columns, the results from both methods are nearly identical, with only slight variations observed in the A1-A3 and A5w stages.

For other elements such as roofs and stairs, the results remain largely consistent between the two methods. For example, emissions for cast in situ concrete used in roofs are identical across stages A1-A3 to C3-C4, with minor differences in decimal values. These results demonstrate the effectiveness of both methods in assessing key components, validating the reliability of the Type IV approach.

Table 5.3: Comparison of EC Between Type I and Type IV Integration Methods Across Different Life Cycle Stages of the Educational Building

Category	**Material**	**Type I BIM&LCA integration method**						**Type IV BIM&LCA integration method**					
		A1-A3	**A4**	**A5w**	**C2**	**C3-C4**	**B4**	**A1-A3**	**A4**	**A5w**	**C2**	**C3-C4**	**B4**
Foundation	**Concrete, Cast in Situ**	184,308.20	4,246.64	10,356.11	4,246.64	2,596.73	-	184,309.31	4,246.66	10,284.18	4,246.66	2,596.74	-
Floor	**Concrete, Cast in Situ**	352,653.90	8,125.50	19,815.29	8,125.50	4,968.56	-	352,655.63	8,125.47	19,815.38	8,125.47	4,968.60	-
	Screed	14,043.25	482.45	1,407.48	482.45	1,177.82	-	14,043.25	482.45	1,408.18	482.45	1,177.82	-
Wall	**AAC**	29,579.09	562.53	3,564.16	562.53	1,373.31	-	29,578.08	562.51	3,560.48	562.51	1,373.27	-
	Aluminium Plate	15,528.67	268.07	493.31	44.68	109.07	-	15,447.24	266.39	490.37	44.40	108.38	-
	Brick	34,237.80	7,574.36	2,954.01	1,262.39	3,081.90	-	34,391.56	7,608.38	2,967.28	1,268.06	3,095.74	-
	Timber, Softwood	2,447.53	300.76	221.52	50.13	1,381.25	-	2,448.28	301.46	221.78	50.24	1,384.45	-
	Glass	11,265.41	36.72	608.17	36.72	89.64	-	11,265.41	36.84	600.46	36.84	89.92	-
	Aluminium Profile	7,892.57	21.18	79.87	21.18	51.72	-	7,891.04	21.25	80.64	21.25	51.90	-
	Plaster	16,442.13	1,419.58	854.51	236.60	2,247.15	-	16,442.13	1,417.81	854.31	236.30	2,244.36	-
	Steel, Galvanized	13,909.57	161.02	2,516.29	161.02	65.52	-	14,082.90	163.02	2,547.65	163.02	66.33	-
	Polystyrene, Expanded	3,834.70	45.67	295.85	45.67	18.58	-	3,834.69	45.66	295.84	45.66	18.58	-
	Fiberglass	32,029.01	758.02	5,847.04	126.34	308.43	-	32,028.98	752.95	5,824.62	125.13	306.41	-
Ceiling	**Fiberglass Batt**	12,928.50	305.97	2,301.47	49.60	121.08	31,413.24	12,929.19	305.97	2,316.87	50.35	121.36	31,434.08
	Aluminium Profile	45,578.44	50.44	458.02	50.44	123.15	92,521.00	45,578.02	50.43	464.00	50.43	123.98	92,563.38
Column	**Concrete, Cast in Situ**	26,284.67	605.62	1,487.95	605.62	370.33	-	26,399.35	605.61	1,462.42	605.61	370.31	-

Table 5.3: Cont.

Door	**Glass, Glazing, Double**	3,113.02	10.26	168.60	10.26	25.06	6,654.42	3,121.15	10.22	167.83	10.22	24.96	6,668.78
	Timber, MDF	3,378.23	125.51	42.11	20.92	686.37	8,494.13	3,361.33	124.88	41.90	20.81	682.93	8,463.70
	Steel, Stainless	550.41	3.99	5.62	0.67	1.62	1,124.62	550.41	3.99	5.57	0.67	1.62	1,124.50
	Bronze	17,808.26	142.24	182.14	23.71	57.88	36,428.45	17,943.68	143.33	181.69	23.89	58.32	36,701.80
	Aluminium Profile	2,972.60	4.40	29.92	4.40	10.74	6,044.11	2,972.63	4.32	29.92	4.32	10.56	6,043.51
Roof	**Concrete, Cast in Situ**	121,093.79	2,790.12	6,804.15	2,790.12	1,706.10	-	121,093.18	2,790.11	6,804.11	2,790.11	1,706.09	-
	Rock Mineral Wool	2,775.39	10.80	496.91	10.80	26.36	-	2,775.39	10.80	496.91	10.80	26.36	-
	Steel, Galvanized	8,471.41	98.07	1,536.61	98.07	39.90	8,788.03	8,471.41	98.07	1,532.51	98.07	39.90	8,788.03
	Polystyrene, Expanded	2,327.39	27.72	179.56	27.72	11.28	4,029.69	2,327.39	27.72	179.56	27.72	11.28	4,029.69
Stair	**Concrete, Cast in Situ**	7,114.17	163.92	399.74	163.92	100.23	-	7,114.17	163.92	399.74	163.92	100.23	-
Window	**Glass, Glazing, Double**	20,027.39	65.60	1,069.41	65.60	160.16	21,388.17	20,027.39	65.60	1,076.89	65.60	160.16	21,395.65
	Aluminium Profile	54,414.99	112.47	554.69	112.47	274.57	55,469.19	54,415.25	112.47	549.15	112.47	274.57	55,199.82

Table 5.4: Comparative Percentage Differences Between Type I and Type IV Integration Methods Across Various Life Cycle Stages of the Educational Building

Category	Material	A1-A3	A4	A5w	C2	C3-C4	B4
Foundation	**Concrete, Cast in Situ**	-0.001%	0%	0.694%	0%	0%	N/A
Floor	**Concrete, Cast In Situ**	0.000%	0.0004%	0%	0.0004%	0%	N/A
	Screed	0%	0%	-0.05%	0%	0%	N/A
Wall	**AAC**	0%	0.003%	0.103%	0.003%	0.003%	N/A
	Aluminium Plate	0.524%	0.628%	0.596%	0.628%	0.633%	N/A
	Brick	-0.449%	-0.449%	-0.449%	-0.449%	-0.449%	N/A
	Timber, Softwood	-0.031%	-0.232%	-0.114%	-0.232%	-0.232%	N/A
	Glass	0%	-0.330%	1.266%	-0.33%	-0.319%	N/A
	Aluminium Profile	0%	-0.296%	-0.968%	-0.296%	-0.352%	N/A
	Plaster	0%	0.124%	0.024%	0.124%	0.124%	N/A
	Steel, Galvanized	-1.246%	-1.246%	-1.246%	-1.246%	-1.246%	N/A
	Polystyrene, Expanded	0%	0.023%	0.001%	0.023%	0.023%	N/A
	Fiberglass	0%	0.669%	0.383%	0.957%	0.653%	N/A
Ceiling	**Fiberglass Batt**	-0.005%	0%	-0.669%	-1.528%	-0.233%	-0.066%
	Aluminium Profile	0%	0.026%	-1.305%	0.032%	-0.676%	-0.046%
Column	**Concrete, Cast in Situ**	-0.436%	0.003%	1.716%	0.003%	0.003%	N/A
Door	**Glass, Glazing, Double**	-0.261%	0.389%	0.459%	0.389%	0.389%	-0.216%
	Timber, MDF	0.5%	0.5%	0.5%	0.5%	0.5%	0.358%
	Steel, Stainless	0%	0%	1%	0%	0%	0.010%
	Bronze	-0.760%	-0.76%	0.247%	-0.760%	-0.760%	-0.750%
	Aluminium Profile	-0.001%	1.667%	0.01%	1.667%	1.667%	0.010%
Roof	**Concrete, Cast in Situ**	0%	0.0005%	0.001%	0.001%	0.001%	N/A
	Rock Mineral Wool	0%	0%	0%	0%	0%	N/A
	Steel, Galvanized	0%	0%	0.267%	0%	0%	N/A
	Polystyrene, Expanded	-0.0001%	0.003%	0.00005%	0.003%	0.003%	N/A
Stair	**Concrete, Cast in Situ**	0%	0%	0%	0%	0%	N/A
Window	**Glass, Glazing, Double**	0%	0%	-0.7%	0%	0%	0%
	Aluminium Profile	-0.0005%	0%	1%	0%	0%	0%

Figure 5.2 illustrates the discrepancies between the two methods during the A1-A3 life cycle stage for various materials within different building components.

For foundation and floor components, there are no discrepancies, as materials such as Concrete, cast in situ and screed show percentage differences of 0%. In the case of wall components, discrepancies are observed for certain materials. For example, Aluminium Plate shows a positive discrepancy of 0.52%, indicating slightly higher values calculated by the Type I method. In addition, galvanized steel exhibits the largest negative discrepancy in the chart at -1.25%, suggesting higher values from the Type IV method. Other materials, such as brick and softwood timber, show smaller discrepancies of -0.45% and -0.03%, respectively.

For ceiling components, the discrepancies are negligible for all materials, including fiberglass batt and aluminium profile, with values consistently at or near 0%. This indicates a high degree of alignment between the two methods for this component. Similarly, for column components, there are minor variations, with concrete, cast in situ showing a negative discrepancy of -0.44%.

The door components show mixed results, with Bronze displaying a negative discrepancy of -0.76%. Other materials in this category, however, show minimal or no variation. For roof, stair, and window components, discrepancies are negligible or non-existent.

The largest discrepancies, such as those observed for steel (galvanized) in walls (-1.25%), bronze in doors (-0.76%), and aluminium plate in walls (0.52%), demonstrate that the differences between the two methods during the A1-A3 stages are relatively minor. These variations are likely due to differences in the level of precision applied by each method when calculating EC for these materials.

Figure 5.3 illustrates the percentage discrepancies between the two methods during A4 life cycle stage. For foundation and floor components, there are no discrepancies observed. Materials such as concrete, cast in situ and screed consistently show percentage differences of 0%, indicating perfect alignment between the Type I and Type IV methods for these elements.

The wall components, on the other hand, exhibit higher discrepancies. aluminium plate and fiberglass show positive discrepancies of 0.63% and 0.67%, reflecting higher values calculated by the Type I method. In contrast, galvanized steel exhibits the largest negative discrepancy of -1.25%, indicating higher values from the Type IV approach. Smaller discrepancies are observed for materials such as brick (-0.45%), softwood timber (-0.23%), glass (-0.33%), and aluminium profile (-0.30%).

For ceiling components, the discrepancies are minimal, with materials such as aluminium profile displaying a positive discrepancy of 0.03%. This demonstrates a relatively strong alignment between the Type I and Type IV methods for this component. In addition, column components show no variations.

In the case of door components, discrepancies are slightly more pronounced. For example, aluminium profile, timber (MDF) and glass, glazing show a positive discrepancy of 1.67%, 0.5% and 0.39%, respectively, whereas bronze has a negative difference of -0.76%.

For roof, stair, and window components, there are no discrepancies recorded across all analysed materials. This includes materials such as concrete, cast in situ, rock mineral wool, galvanized steel, expanded polystyrene and etc.

The most significant discrepancy in the chart is observed for aluminium profile in the door category, which shows a positive difference of 1.67%. Similarly, a notable negative discrepancy is observed for galvanized steel in the wall components, with a value of -1.25%.

Figure 5.4 illustrates the percentage discrepancies between the two methods during A5w life cycle stage. For foundation and floor components, the discrepancies are relatively small. concrete, cast in situ shows a moderate positive discrepancy of 0.69% in foundation, suggesting slightly higher values calculated by the Type I method, while other materials such as screed display minimal variations, with 0.05% discrepancy.

In wall components, some materials show higher variations. Glass has the largest positive discrepancy within this category, at 1.27%, indicating a difference in calculations by the Type IV method. Smaller positive discrepancies are also observed for aluminium plate and fiberglass, at 0.6% and 0.38%, respectively. In contrast, galvanized steel shows a negative discrepancy of -

1.25%, reflecting higher results from the Type IV method. Smaller negative discrepancies are also observed for brick and aluminium profile, at -0.45% and -0.97%, respectively.

For ceiling components, significant discrepancies are observed. Fiberglass batt shows a negative discrepancy of -0.67%, while aluminium profile demonstrates the largest negative difference for this category, at -1.30%.

The column components display the highest positive discrepancy across all materials in the chart. Concrete, cast in situ has a positive discrepancy of 1.72%, indicating a difference in results from the Type IV method.

For door components, discrepancies are moderate. Stainless steel shows a positive discrepancy of 1%, while timber (MDF) exhibits a smaller positive variation of 0.50%.

The roof components show minimal discrepancies. For example, galvanized steel has a small positive difference of 0.27%, while other materials, such as concrete, cast in situ and rock mineral wool, display negligible variations. Similarly, for stair materials, discrepancies are negligible, with values close to 0%. However, for window components, aluminium profile shows a positive discrepancy of 1%, while glass presents a notable negative difference of -0.70%, highlighting minimal inconsistencies in these materials.

The most significant discrepancies in the chart are observed for concrete, cast in situ in column components (1.72%), glass in wall components (1.27%), and aluminium profile in windows and doors (1.00%). On the other hand, large negative discrepancies, such as for galvanized steel in walls (-1.25%) and aluminium profile in ceilings (-1.30%), indicate instances where the Type IV method calculates higher values. These differences result from the precision of numerical inputs used by the two methods.

Figure 5.5 illustrates the percentage discrepancies between the two methods during C2 life cycle stage. For foundation and floor components, the discrepancies are negligible, with materials such as concrete, cast-in-situ, and screed showing minimal percentage differences close to zero.

In wall components, some materials exhibit notable discrepancies. Fiberglass and aluminium plate show positive discrepancy of 0.96% and 0.63%, indicating slightly higher values from the Type I method. In contrast, brick, timber (softwood), glass and aluminium profile display negative discrepancies of -0.45%, -0.23%, -0.33% and -0.3%, respectively. The largest negative discrepancy in this category is observed for galvanized steel, with a value of -1.25%.

For ceiling components, higher variations are evident. Fiberglass batt shows the largest negative discrepancy across all materials, at -1.53%, indicating that the Type IV method calculates higher values for this material. However, aluminium profile displays a minimal positive discrepancy of 0.03%.

In column components, there is no discrepancy for concrete, cast in situ. In door components, moderate positive discrepancies are observed. Timber (MDF) and glass, glazing exhibit positive differences of 0.50% and 0.39%, respectively, reflecting slightly higher values calculated by the Type I method. These differences are relatively minor compared to other categories. Aluminium profile shows the largest positive discrepancy across all materials, at 1.67%, indicating that the Type I method calculates higher values for this material. However, bronze displays a minimal negative discrepancy of -0.76%.

For roof components, the discrepancies are negligible or non-existent. Materials such as concrete, cast in situ, rock mineral wool, and expanded polystyrene show differences close to 0%, indicating strong alignment between the Type I and Type IV methods. Similarly, for stair and window components, discrepancies are minimal, with values near 0%.

The largest discrepancies are observed for fiberglass batt in ceiling components (-1.53%), galvanized steel in wall components (-1.25%), and aluminium profile in door components (1.67%).

Figure 5.6 presents the percentage differences between the two methods during the C3-C4 life cycle stage. For foundation and floor components, the discrepancies are negligible. Materials such as Concrete, Cast in Situ and screed show percentage differences of 0%, indicating strong consistency between the Type I and Type IV methods for these components.

In wall components, more variations are observed. For instance, aluminium plate shows a positive discrepancy of 0.63%, indicating slightly higher results from the Type I method. Conversely, materials like brick, timber (softwood), and glass display negative discrepancies of -0.45%, -0.23%, and -0.32%, respectively, suggesting higher values from the Type IV method. The most significant discrepancies in this category are a negative discrepancy of -1.25% for steel (galvanized) and a positive discrepancy of 0.65% for Fiberglass.

Discrepancies in ceiling components are negative. Aluminium profile and fiberglass exhibit negative discrepancies of -0.68% and -0.23%, indicating that the Type IV method calculates higher values for this material. These discrepancies, while present, are relatively minor compared to other categories.

For column components, there is no discrepancy. In the door components, mostly positive discrepancies are observed. Aluminium profile, timber (MDF) and glass display positive differences of 1.67%, 0.50% and 0.39%, respectively, indicating slightly higher results from the Type I method.

The roof components show negligible or non-existent discrepancies. Materials such as concrete, cast in situ, rock mineral wool, and expanded polystyrene exhibit percentage differences close to 0%, indicating strong alignment between the Type I and Type IV methods for this category. Similarly, for stair and window components, the discrepancies are negligible, with values close to 0%, reflecting consistent results for these materials.

The most significant discrepancies in the chart include aluminium profile in door components (1.67%), galvanized steel in wall components (-1.25).

Figure 5.7 presents the percentage differences between the two methods during the B4 life cycle stage. For ceiling components, minimal negative discrepancies are observed. Fiberglass batt shows a discrepancy of -0.07%, while aluminium profile exhibits a slightly smaller difference of -0.05%.

In door components, higher variations are observed. Timber (MDF) displays the largest positive discrepancy in the chart, at 0.36%, indicating higher values calculated by the Type I method. On the other hand, stainless steel shows a negligible positive discrepancy of 0.01%. However, bronze demonstrates the most significant negative discrepancy across all materials, with a value of -0.75%. This indicates that the Type IV method calculates higher values for Bronze.

For window components, good alignment is observed. Glass shows no discrepancies, with percentage differences of 0%. However, aluminium profile displays positive difference of 0.49%, indicating slightly higher results from the Type I method.

The most notable discrepancies in the chart are the negative discrepancy for bronze (-0.75%) and the positive discrepancy for aluminium profile (0.49%).

In conclusion, as the highest discrepancies range between -1.5% and 2%, these charts highlight a strong level of alignment between the Type I and Type IV methods across all materials and life cycle stages, with particularly consistent results observed for foundation and floor components.

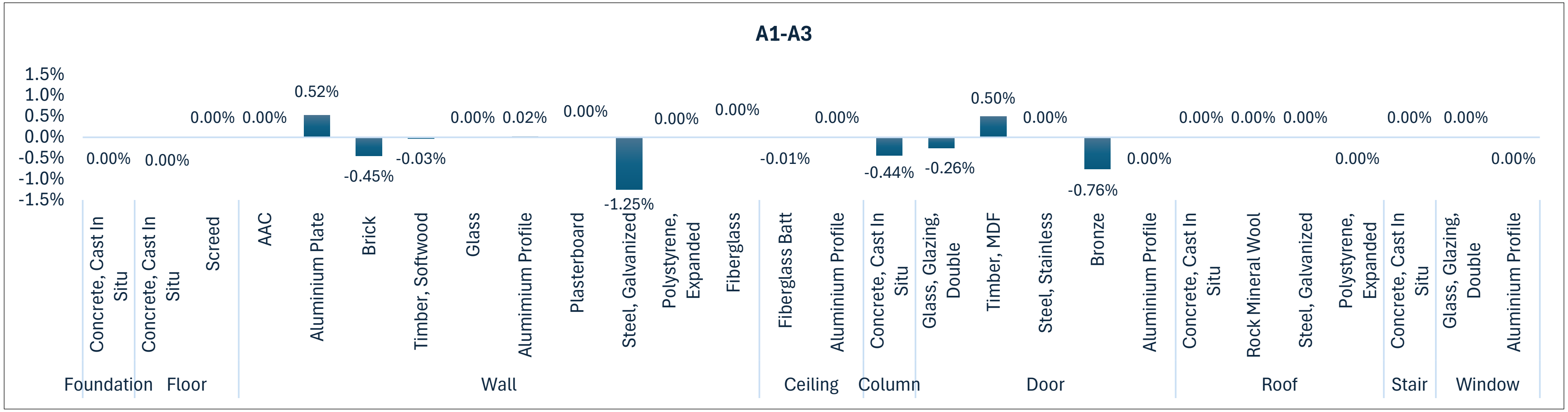


Figure 5.2: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the A1-A3 Life Cycle Stage

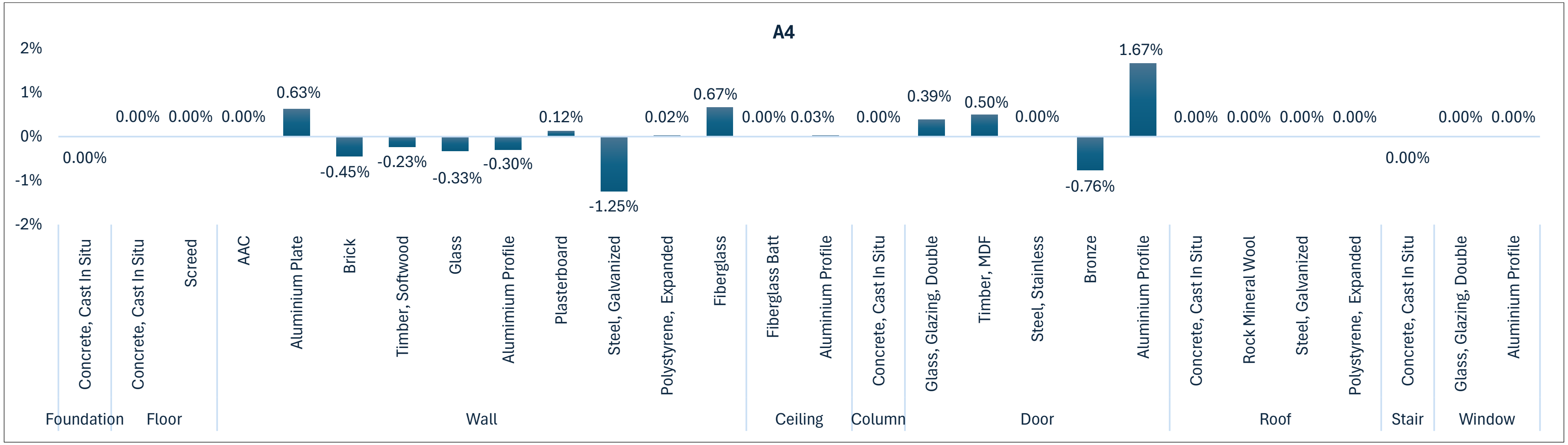


Figure 5.3: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the A4 Life Cycle Stage

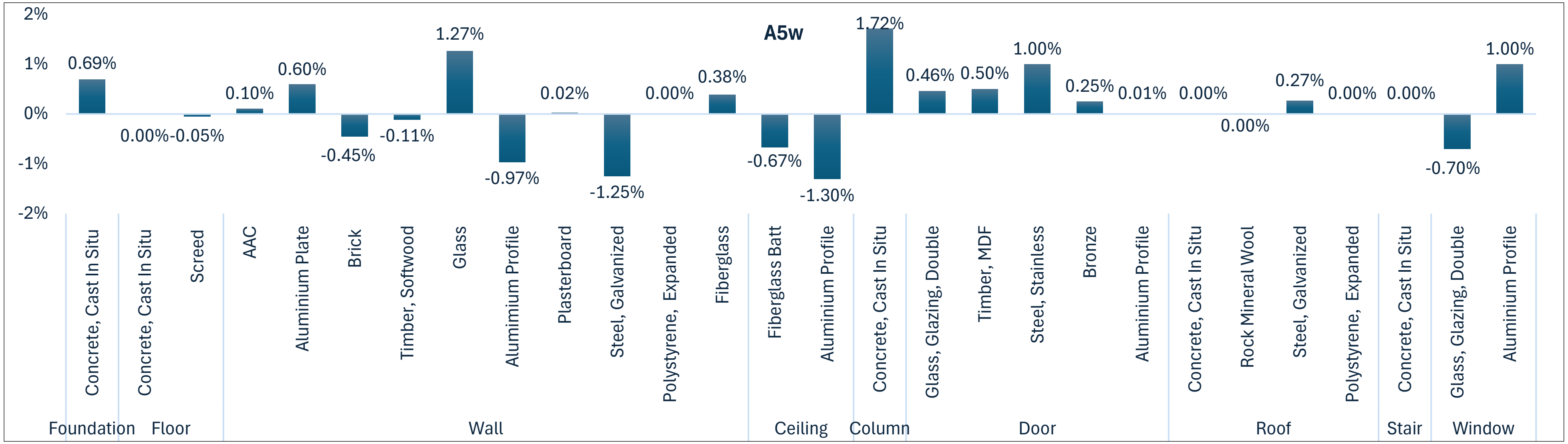


Figure 5.4: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the A5w Life Cycle Stage

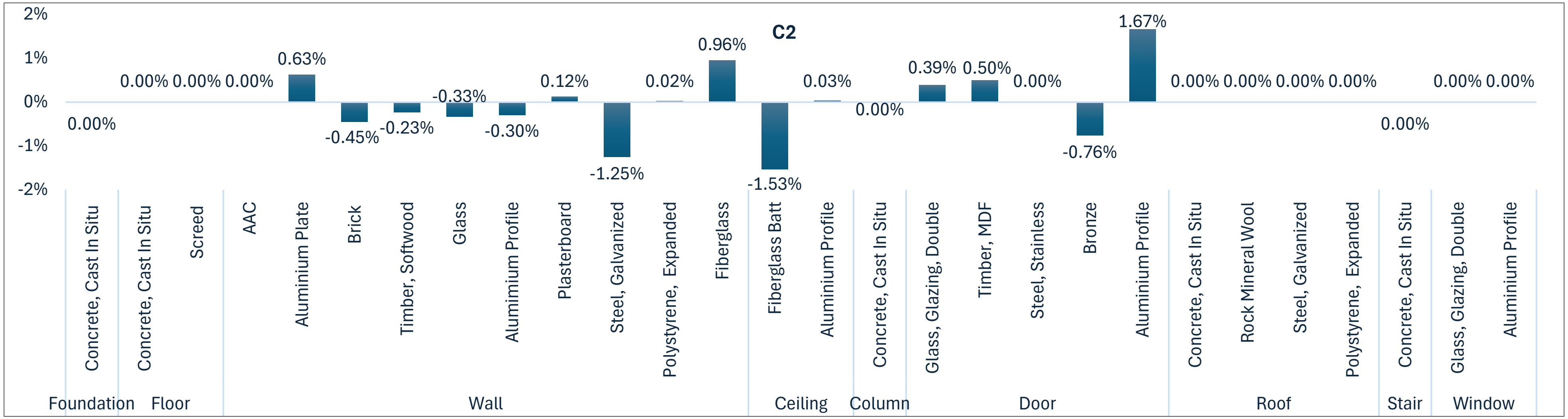


Figure 5.5: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the C2 Life Cycle Stage

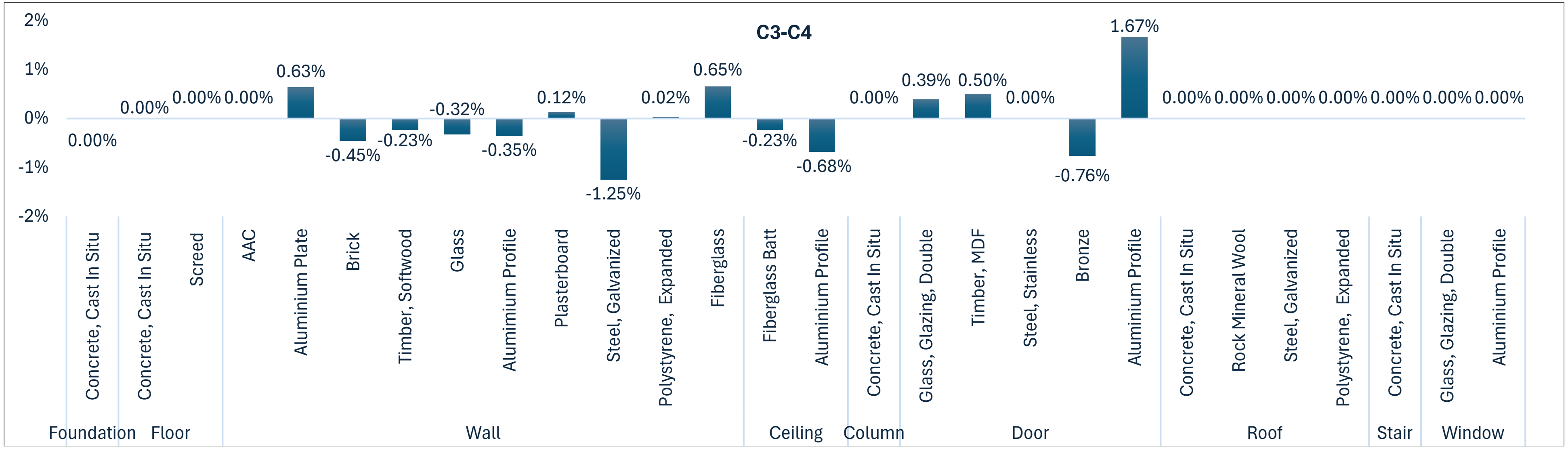


Figure 5.6: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the C3-C4 Life Cycle Stage

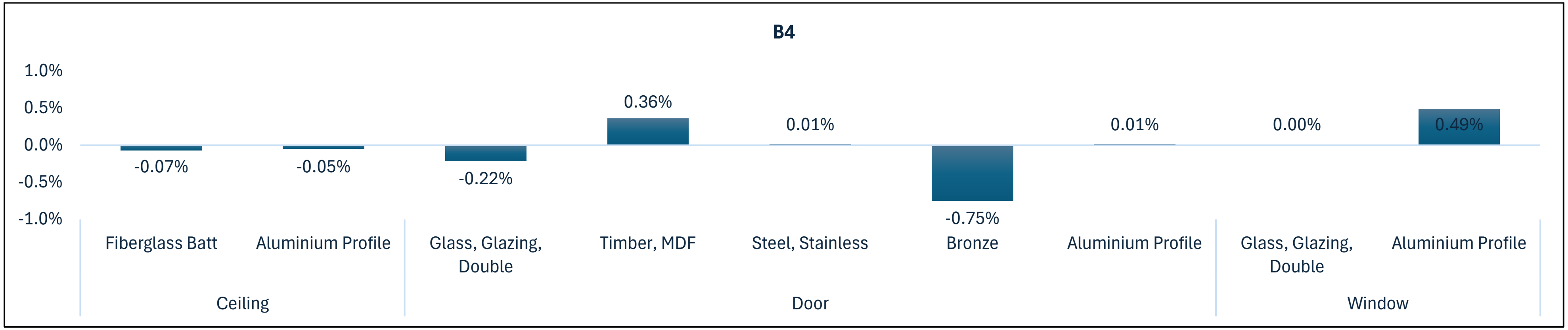
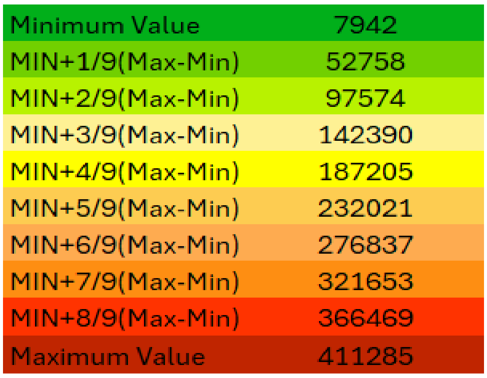


Figure 5.7: Percentage Variation Between the Two Methods for Building Components in the Educational Building During the B4 Life Cycle Stage

5.1.4 Visualization through a color-coded system in the educational building

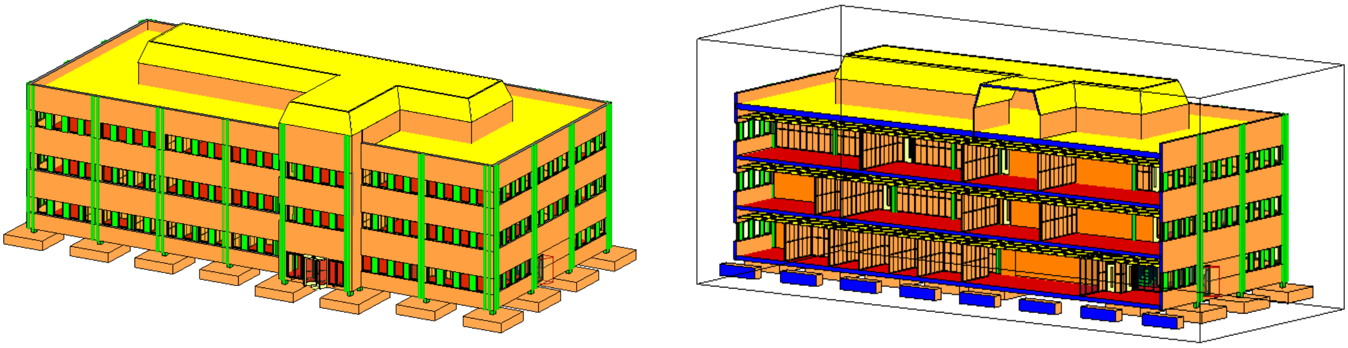
A visualization of WLEC can be effectively presented using a color-coding system. This approach breaks down the EC impact across the entire lifecycle of a product or building, spanning from extraction and production of materials to the end-of-life disposal. The visualizations presented in Figure 5.8 utilize a color-coded system to represent the distribution of EC across the building's components, providing valuable insights into its environmental impact. By assigning specific colours to represent varying levels of EC emissions, designers can quickly interpret which components contribute the most to the WLEC emission. Figure 5.8 illustrates a color-coding system that categorizes the EC of the building components. The colour legend spans from green, representing the minimum EC value, to red, indicating the maximum value, segmented into nine equal intervals. Each interval corresponds to a distinct range, facilitating a clear and systematic interpretation of the data. The Minimum Value represents the component with the lowest EC, which is 7,942 kgCO$_2$e for the London college building, while the Maximum Value represents the highest EC, set at 411,285 kgCO$_2$e. The range between the minimum and maximum values is divided into nine equal intervals. Each interval is assigned a specific colour, transitioning from green at the lowest value, through yellow and orange, to red at the highest value. This gradient effectively visualizes the distribution of EC across different building components, allowing stakeholders to easily identify where EC emissions are more significant and where they fall in between the minimum and maximum values.



Minimum Value	7942
MIN+1/9(Max-Min)	52758
MIN+2/9(Max-Min)	97574
MIN+3/9(Max-Min)	142390
MIN+4/9(Max-Min)	187205
MIN+5/9(Max-Min)	232021
MIN+6/9(Max-Min)	276837
MIN+7/9(Max-Min)	321653
MIN+8/9(Max-Min)	366469
Maximum Value	411285

Figure 5.8: Color-coded system for visualizing EC distribution in the educational building (kgCO$_2$e)

Figure 5.9 illustrates a color-coding system used to indicate EC potential of building materials, enabling early identification of hot spots during the design stage. The external visualization highlights variations in EC across the building's facade, including walls, windows, and the roof, emphasizing the materials or sections contributing significantly to the overall carbon emission. Similarly, the internal cutaway view reveals the EC distribution across structural elements such as floors, columns, and internal walls. Figure 5.9 shows that the floor, walls, and foundation have the highest levels of EC, while the wall sweep, and doors have the lowest. It highlights that the concrete used in the floor and foundation significantly contributes to the building's WLEC. Therefore, one effective strategy for reducing the building’s EC is to focus on minimizing the carbon impact of the concrete.



A) Entire building view

B) Cross-section view

Figure 5.9: EC distribution using the colour coding system in the educational building

5.2 Hotel Building

5.2.1 Comparison of WLEC Assessment Using Type IV and Type I Approaches in the hotel Building

Tables 5.5 and 5.6 present a comparison of the WLEC assessment results obtained using the Type I and Type IV methods, highlighting slight variations across different building components and life cycle stages (A1-A3, A4, A5w, C2, C3-C4, and B4). Overall, the Type IV method consistently shows marginally higher values than the Type I method. However, these differences are generally minimal, demonstrating a strong alignment between the two methods in their overall assessment outcomes.

For most components, increases in the WLEC values are observed under the Type IV method. Examples include the ceiling and floor components. For the ceiling, there are increases in stages A4, A5w, C2, C3-C4 and B4, with the most significant increase being in C3-C4 (from 28,225.98 to 28,429.29). Similarly, the floor exhibits an increase in all stages. Smaller increases are also observed in the door component, particularly in B4, where the value rises from 100,804.33 to 101,557.20. On the other hand, some components show minimal or negligible changes. For example, the roof remains largely consistent across most stages, with only a slight reduction in A5w (from 425,290.31 to 425,095.71) and a minor increase in C3-C4 (from 21,376.95 to 21,421.47).

The structural column, stair, wall and structural foundation also show minimal variation. The window component exhibits a mixed trend, with a slight increase in A5w (from 2,420.69 to 2,429.21) but decreases in other stages.

Table 5.5: WLEC Assessment Results Utilizing Type I Method (kgCO$_2$e)

	A1-A3	A4	A5w	C2	C3-C4	B4
Ceiling	730,085.91	18,508.99	23,315.59	4,142.73	28,225.98	1,608,558.39
Door	68,137.54	1,352.94	1,413.40	431.19	6,303.79	100,804.33
Floor	1,251,512.02	28,264.16	81,354.14	28,264.16	22,050.87	-
Roof	2,636,145.30	12,940.43	425,290.31	12,663.22	21,376.95	556,798.53
Stair	11,077.52	255.24	622.62	255.24	156.07	-
Structural column	8,251.34	190.12	463.64	190.12	116.25	-
Structural foundation	143,804.93	3,313.41	8,080.26	3,313.41	2,026.07	-
Wall	643,019.88	76,004.23	62,487.71	13,428.03	54,748.41	-
Window	92,088.06	211.91	2,420.69	213.01	520.03	95,796.78

Table 5.6: WLEC Assessment Results Utilizing Type IV Method ($kgCO_2e$)

	A1-A3	A4	A5w	C2	C3-C4	B4
Ceiling	730,034.24	18,642.39	23,454.56	4,170.35	28,429.29	1,608,934.62
Door	68,294.92	1,354.51	1,418.12	432.33	6,309.35	101,557.20
Floor	1,257,310.82	28,397.63	81,582.08	28,397.64	22,132.47	-
Roof	2,636,146.23	12,940.44	425,095.71	12,663.23	21,421.47	556,798.53
Stair	11,090.39	255.25	618.81	255.25	156.08	-
Structural column	8,272.68	190.06	461.60	190.06	116.22	-
Structural foundation	143,917.04	3,315.76	8,030.30	3,315.76	2,027.51	-
Wall	643,024.30	76,062.30	62,454.56	13,436.58	54,745.87	-
Window	92,025.39	211.76	2,429.21	211.76	516.97	95,046.11

5.2.2 Accuracy Comparison at different modules in the hotel building

Figure 5.10 illustrates a comparative analysis of the accuracy of an integrated EC assessment method versus the traditional approach across various building components. The results demonstrate that the integrated method consistently achieves higher or comparable accuracy levels compared to the traditional approach, with values more than 98% across all components and life cycle stages. Notably, components such as foundations and columns exhibit consistently high accuracy, while elements like doors and windows show slight variations in certain stages but still perform well overall.

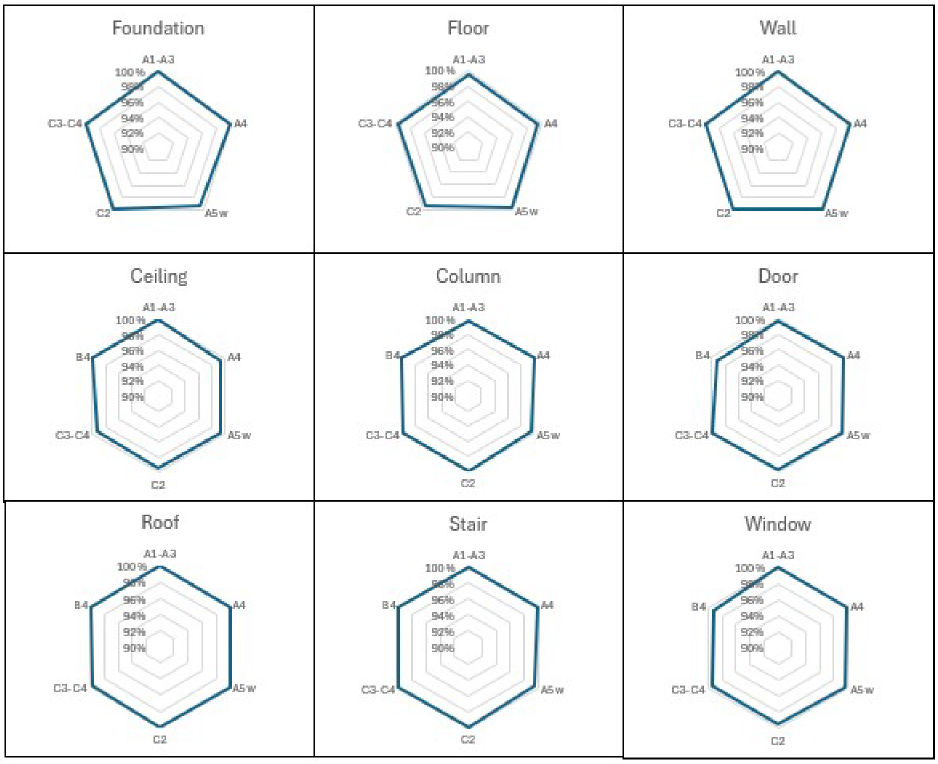


Figure 5.10: Comparison of the accuracy between the automated EC assessment method and the manual method in the hotel building

5.2.3 Material-Oriented Accuracy Comparison in the hotel building

Table 5.7 and 5.8 evaluates and compares the EC emissions of various construction materials in the hotel building across life cycle stages as calculated by two methods: Type I and Type IV integrated assessment methods.

Table 5.7: Comparison of EC Between Type I and Type IV Integration Methods Across Different Life Cycle Stages of the Hotel building (kgCO_2e)

Category	**Material**	**Traditional**						**Integrated**					
		Comments	**A4**	**A5w**	**C2**	**C3-C4**	**B4**	**Comments**	**A4**	**A5w**	**C2**	**C3-C4**	**B4**
Foundation	**Concrete, Cast in Situ**	143,804.93	3,313.41	8,080.26	3,313.41	2,026.07	-	143,917.04	3,315.76	8,030.30	3,315.76	2,027.51	-
Floor	**Concrete, Cast in Situ**	969,796.75	22,345.08	54,507.88	22,345.08	13,663.52	-	975,476.22	22,476.20	54,811.13	22,476.20	13,743.68	-
	Screed	73,792.65	2,535.13	7,395.82	2,535.13	6,189.06	-	73,792.65	2,535.13	7,399.52	2,535.13	6,189.06	-
	Polyurethane Foam	64,117.69	70.54	11,370.17	70.54	172.22	-	64,124.91	70.54	11,341.13	70.54	172.23	-
Wall	**Brick**	290,993.96	64,376.05	25,039.98	10,729.34	26,193.70	-	291,275.87	64,438.42	25,131.08	10,739.74	26,219.07	-
	Plasterboard	87,978.63	7,599.47	4,572.73	1,266.58	12,029.76	-	88,040.65	7,603.15	4,575.76	1,267.19	12,035.59	-
	Aluminium	183.23	3.16	5.82	0.53	1.29	-	183.23	3.16	5.83	0.53	1.29	-
	PVC	72,877.28	125.18	741.75	125.18	305.61	-	72,877.28	125.18	734.33	125.18	305.61	-
	Rock Wool	165,656.06	787.61	29,850.72	787.61	1,922.79	-	165,370.46	786.25	29,719.79	786.25	1,919.48	-
	Timber, Softwood	25,330.71	3,112.75	2,276.71	518.79	14,295.25	-	25,276.80	3,106.13	2,287.77	517.69	14,264.83	-
Ceiling	**Plasterboard**	22,509.78	15,400.44	2,702.22	2,566.74	24,378.48	135,115.32	22,432.89	15,520.63	2,711.03	2,589.80	24,575.51	135,659.74
	Fiberglass Batt	77,700.61	1,838.91	14,222.51	306.36	747.92	189,632.64	77,700.63	1,852.07	14,339.55	310.86	754.06	189,907.91
	Aluminium profile	629,875.51	1,269.63	6,390.85	1,269.63	3,099.58	1,283,810.43	629,900.72	1,269.69	6,403.99	1,269.69	3,099.72	1,283,366.97
Column	**Concrete, Cast in Situ**	8,251.34	190.12	463.64	190.12	116.25	-	8,272.68	190.06	461.60	190.06	116.22	-
Door	**Aluminium Profile**	23,810.16	36.08	239.70	36.08	88.08	23,678.06	23,809.97	36.78	239.73	36.78	89.79	24,139.90
	Glass, Glazing	6,303.26	20.65	338.93	20.65	50.41	13,463.09	6,425.18	21.05	345.49	21.05	51.38	13,723.51
	Timber, MDF	29,772.78	1,106.09	371.12	184.35	6,049.05	63,663.18	29,787.08	1,106.62	371.30	184.44	6,051.96	63,693.78

Table 5.8: Comparison of EC Between Type I and Type IV Integration Methods Across Different Life Cycle Stages of the Hotel building ($kgCO_2e$)

Roof	**Timber, Glulam**	10,955.94	113.92	2,823.57	113.92	4,816.45	-	10,955.93	113.93	2,827.65	113.93	4,860.97	-
	Tiles	8,643.94	95.89	788.68	95.89	234.11	-	8,643.94	95.89	799.27	95.89	234.11	-
	Plasterboard	1,613.00	138.46	83.74	23.08	219.18	-	1,613.00	138.46	83.74	23.08	219.18	-
	Timber, Softwood	1,580.28	194.19	142.03	32.37	891.82	-	1,580.28	194.19	143.03	32.37	891.82	-
	Polystyrene, Expanded	5,780.73	22.78	179.26	22.78	9.27	-	5,780.73	22.78	178.25	22.78	9.27	-
	Concrete, Cast in Situ	355,909.56	8,200.51	20,648.98	8,200.51	5,014.43	-	355,910.30	8,200.51	20,661.39	8,200.51	5,014.43	-
	Polyethylene (High Density)	7,141.48	19.70	1,275.70	19.70	48.10	-	7,141.48	19.70	1,272.30	19.70	48.10	-
	Extruded Polystyrene	2,238,216.44	3,484.94	397,710.73	3,484.94	8,507.84	-	2,238,216.62	3,484.94	397,496.85	3,484.94	8,507.84	-
	Asphalt Shingle	6,303.94	670.03	1,637.60	670.03	1,635.75	556,798.53	6,303.94	670.03	1,633.24	670.03	1,635.75	556,798.53
Stair	**Concrete, Cast in Situ**	11,077.52	255.24	622.62	255.24	156.07	-	11,090.39	255.25	618.81	255.25	156.08	-
Window	**Glass**	34,373.31	111.49	1,830.34	112.60	274.88	36,708.83	34,373.31	112.60	1,848.29	112.60	274.88	36,708.78
	PVC	56,868.93	98.86	581.83	98.86	241.35	58,578.40	56,806.26	97.58	572.40	97.58	238.22	57,817.78
	Aluminium	845.82	1.55	8.53	1.55	3.79	509.55	845.82	1.58	8.53	1.58	3.87	519.55

Table 5.9: Comparative Percentage Differences Between Type I and Type IV Integration Methods Across Various Life Cycle Stages of the Hotel building

Category	**Material**	**Difference**					
		Comments	**A4**	**A5w**	**C2**	**C3-C4**	**B4**
Foundation	**Concrete, Cast in Situ**	-0.08%	-0.07%	0.62%	-0.07%	-0.07%	0.00%
Floor	**Concrete, Cast in Situ**	-0.59%	-0.59%	-0.56%	-0.59%	-0.59%	N/A
	Screed	0.00%	0.00%	-0.05%	0.00%	0.00%	N/A
	Polyurethane Foam	-0.01%	0.00%	0.26%	0.00%	-0.01%	N/A
Wall	**Brick**	-0.10%	-0.10%	-0.36%	-0.10%	-0.10%	0.00%
	Plaster	-0.07%	-0.05%	-0.07%	-0.05%	-0.05%	0.00%
	Aluminium	0.00%	0.00%	-0.23%	0.00%	0.00%	0.00%
	PVC	0.00%	0.00%	1.00%	0.00%	0.00%	0.00%
	Rock Wool	0.17%	0.17%	0.44%	0.17%	0.17%	0.00%
	Timber, Softwood	0.21%	0.21%	-0.49%	0.21%	0.21%	0.00%
Ceiling	**Plasterboard**	0.34%	-0.78%	-0.33%	-0.90%	-0.81%	-0.40%
	Fiberglass Batt	0.00%	-0.72%	-0.82%	-1.47%	-0.82%	-0.15%
	Aluminium profile	0.00%	0.00%	-0.21%	0.00%	0.00%	0.03%
Column	**Concrete, Cast in Situ**	-0.26%	0.03%	0.44%	0.03%	0.03%	0.00%
Door	**Aluminium Profile**	0.00%	-1.95%	-0.01%	-1.95%	-1.95%	-1.95%
	Glass, Glazing	-1.93%	-1.93%	-1.93%	-1.93%	-1.93%	-1.93%
	Timber, MDF	-0.05%	-0.05%	-0.05%	-0.05%	-0.05%	-0.05%
Roof	**Timber, Glulam**	0.00%	-0.01%	-0.14%	0.00%	-0.92%	0.00%
	Tiles	0.00%	0.00%	-1.34%	0.00%	0.00%	0.00%
	Plasterboard	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Timber, Softwood	0.00%	0.00%	-0.70%	0.00%	0.00%	0.00%
	Polystyrene, Expanded	0.00%	0.00%	0.57%	0.00%	0.00%	0.00%
	Concrete, Cast in Situ	0.00%	0.00%	-0.06%	0.00%	0.00%	0.00%
	Polyethylene (High Density)	0.00%	0.00%	0.27%	0.00%	0.00%	0.00%
	Extruded Polystyrene	0.00%	0.00%	0.05%	0.00%	0.00%	0.00%
	Asphalt Shingle	0.00%	0.00%	0.27%	0.00%	0.00%	0.00%
Stair	**Concrete, Cast in Situ**	-0.12%	0.00%	0.61%	0.00%	-0.01%	0.00%
Window	**Glass**	0.00%	-0.99%	-0.98%	0.00%	0.00%	0.00%
	PVC	0.11%	1.30%	1.62%	1.30%	1.30%	1.30%
	Aluminium	0.00%	-1.96%	-0.02%	-1.96%	-1.96%	-1.96%

Figure 5.11 focuses on the discrepancies observed between Type I and Type IV methods for calculating EC during the A1-A3 lifecycle stages for the hotel building. These discrepancies, expressed as percentage differences, are minimal overall, with most variations within ±2%, highlighting close alignment between the two methods.

For foundation materials, cast in situ concrete shows slight discrepancies, with values as low as -0.08% and -0.59% in floor category for cast in situ concrete indicating a minor overestimation in the Type IV calculations. Other floor materials such as screed and polyurethane foam show negligible deviations, with the largest being -0.010%. Wall components reveal small positive differences for rock wool (0.17%) and softwood (0.21%), while materials like brick and plasterboard show minor negative differences of -0.1% and -0.07%, respectively.

In the ceiling category, plasterboard has a positive discrepancy of 0.34%, while fiberglass batt and aluminium profile demonstrate no significant variation (0.00%). Columns and roof components also show negligible differences, with cast in situ concrete (-0.26%) being the only notable deviations. For doors, glass glazing exhibits the largest negative discrepancy (-1.93%), highlighting a potential overestimation in the Type IV method.

Components like PVC and aluminium in windows show minimal deviations, with differences such as 0.11% and 0.00%, indicating a strong alignment between the two calculation approaches.

Figure 5.12 illustrates the discrepancies between Type I and Type IV methods during the A4 lifecycle stage for the hotel building. For foundation materials, cast in situ concrete shows minimal discrepancies, with value of -0.07%.

In the floor category, materials such as screed and polyurethane foam show no difference, and cast in situ concrete show negligible difference, with value of -0.59%. This consistency indicates strong alignment between Type I and Type IV methods for these materials in the A4 stage. Similarly, wall materials like brick and plasterboard display very minor negative deviations, with

-0.1% and -0.05%, respectively. However, rock wool and softwood show small positive discrepancies of 0.17% and 0.21%, indicating slight underestimation in the Type IV calculations.

Ceiling materials, such as fiberglass batt and plasterboard, show deviations of -0.72% and -0.78%. These negative values suggest slight overestimation of Type IV approach. For doors, aluminium profiles and glass, glazing exhibit negative discrepancy of -1.95% and -1.93%, two of the highest deviations in the dataset, indicating an overestimation by the Type IV method.

Roof and stairs materials exhibit negligible discrepancies, with most values at or near 0.00%, indicating excellent alignment between the two methods. However, windows, particularly PVC and aluminium, exhibit discrepancies of 1.30% (positive) and -1.96% (negative), respectively.

Figure 5.13 highlights the discrepancies between Type I and Type IV methods for A5w for the hotel building.

For foundation materials, cast in situ concrete shows a positive discrepancy of 0.62%. In the floor category, cast in situ concrete and screed show negative discrepancies of -0.56% and -0.05%, while polyurethane foam exhibits a positive deviation of 0.26%.

Wall components show varying results, with PVC displaying the largest positive discrepancy within this category, at 1.00%. In contrast, brick, plasterboard and aluminium exhibit small negative deviations of -0.36%, -0.07% and -0.23%, respectively, reflecting slight overestimations. These discrepancies remain minor but consistent across the materials.

For ceiling materials, fiberglass batt, plasterboard and aluminium profile demonstrate negative discrepancies of -0.82%, -0.33% and -0.21%, respectively. Columns reveal a positive variation of 0.44%. However, doors reveal a negative discrepancy for Glass, glazing at -1.93%. Aluminium profile and MDF, however, show negligible variation, with discrepancies of -0.01% and -0.05%, demonstrating close agreement between the methods for this component.

Roof components exhibit moderate discrepancies. For example, Tiles and expanded polystyrene have deviations ranging from -1.34% to +0.57%, indicating good alignment between the Type I and Type IV methods.

Finally, for stair and window materials, PVC windows show the largest positive discrepancy across all components at 1.62%, indicating significant underestimation of EC by the Type IV approach. Conversely, glass exhibits a small negative deviation of -0.98%, reflecting a slight overestimation.

Figure 5.14 compares the accuracy of the Type IV EC assessment method with the Type I approach for life cycle stage C2. The results indicate that most materials and components exhibit minimal deviations, with values close to zero, demonstrating strong alignment between the two methods. For foundation, floor, wall, column, stair and roof components, materials such as cast in situ concrete, screed, polyurethane foam, brick, plasterboard, Glulam, and polystyrene show negligible or no deviations, confirming the reliability of the Type IV method in these areas. However, discrepancies are observed in specific materials, such as fiberglass batt in ceiling (-1.47%) and aluminium in windows (-1.96%) as well as aluminium profile and glass, glazing in doors (-1.95% and -1.93%). On the other hand, materials like PVC in windows (+1.30%) and softwood in walls (+0.21%) show positive deviations.

Figure 5.15 compares the accuracy of the Type IV EC assessment method with the Type I approach for life cycle stages C3-C4 across various building materials and components. The findings indicate that the Type IV method aligns closely with the Type I approach for most materials, particularly in the foundation, wall, roof, and stair components, where deviations are minimal or negligible. For example, cast in situ concrete, screed, polyurethane foam, brick, plasterboard, and timber exhibit deviations close to zero. However, discrepancies are observed in certain components, such as glass, glazing (-1.93%) and aluminium profile (-1.95%) in doors, as well as aluminium (-1.96%) in windows. PVC in windows exhibits a positive deviation (+1.30%).

Figure 5.16 compares the accuracy of the Type IV EC assessment method with the Type I approach for life cycle stage B4. The results indicate that the Type IV method aligns perfectly with the Type I approach (0.00% deviation) for most materials, including those used in foundation, floor, wall, roof, and stair components. However, minor discrepancies are observed for plasterboard (-0.4%) and fiberglass batt (-0.15%) in ceilings. More significant deviations are evident in aluminium profiles (-1.95%) and glass glazing (-1.93%) in door components, as well as aluminium in windows (-1.96). Additionally, PVC in windows exhibits a positive deviation of +1.30%.

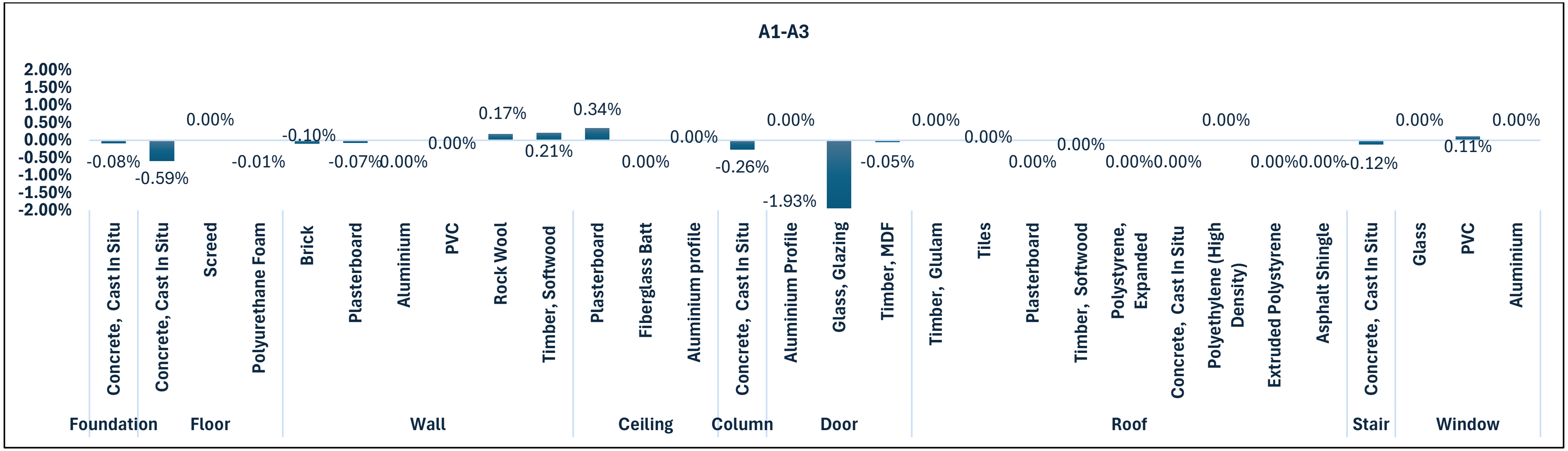


Figure 5.11: Percentage Variation Between the Two Methods for Building Components in the hotel Building During the A1-A3 Life Cycle Stage

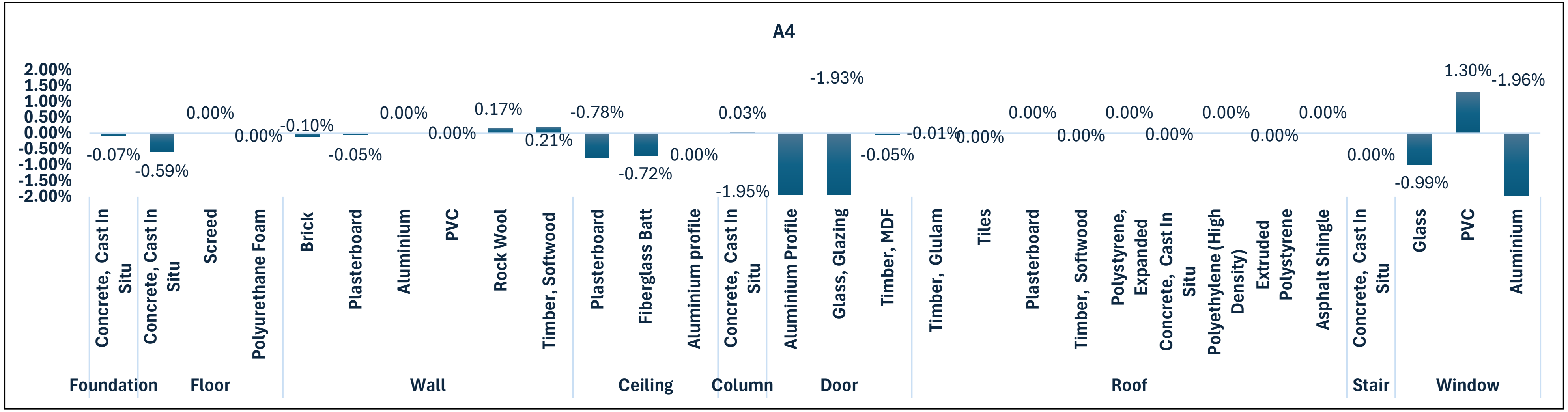


Figure 5.12: Percentage Variation Between the Two Methods for Building Components in the hotel Building During the A4 Life Cycle Stage

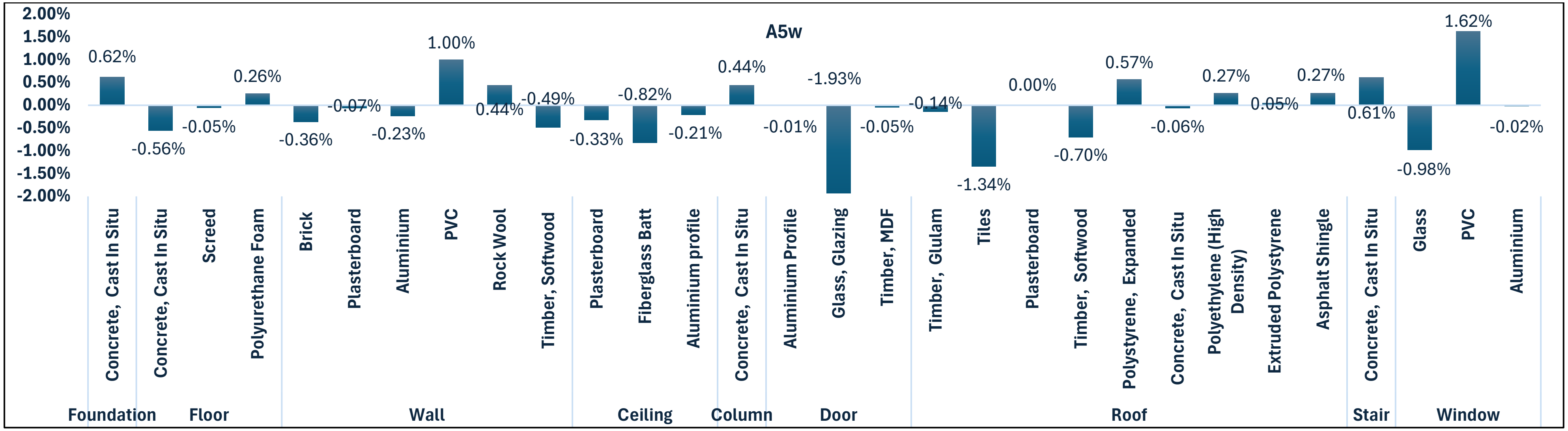


Figure 5.13: Percentage Variation Between the Two Methods for Building Components in the hotel Building During the A5w Life Cycle Stage

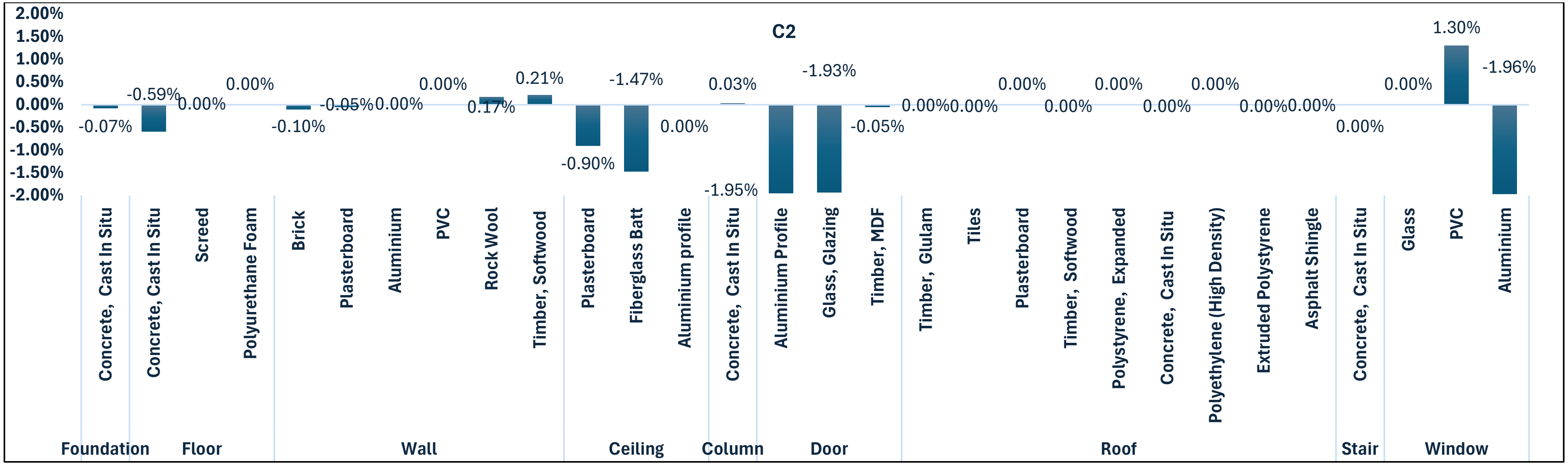


Figure 5.14: Percentage Variation Between the Two Methods for Building Components in the hotel Building During C2 Life Cycle Stage

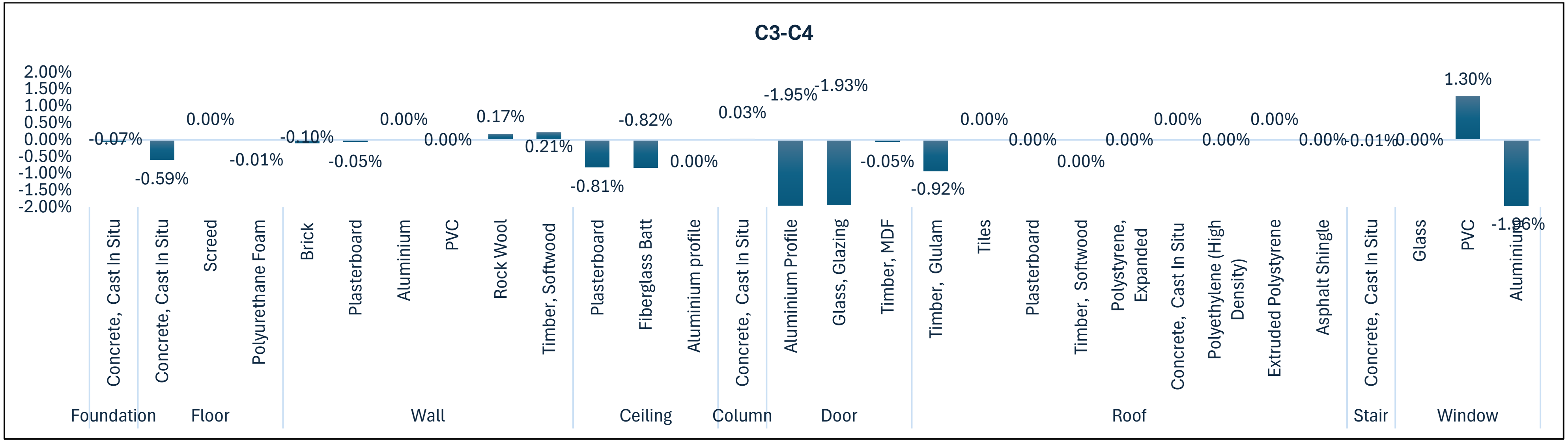


Figure 5.15: Percentage Variation Between the Two Methods for Building Components in the hotel Building During C3-C4 Life Cycle Stage

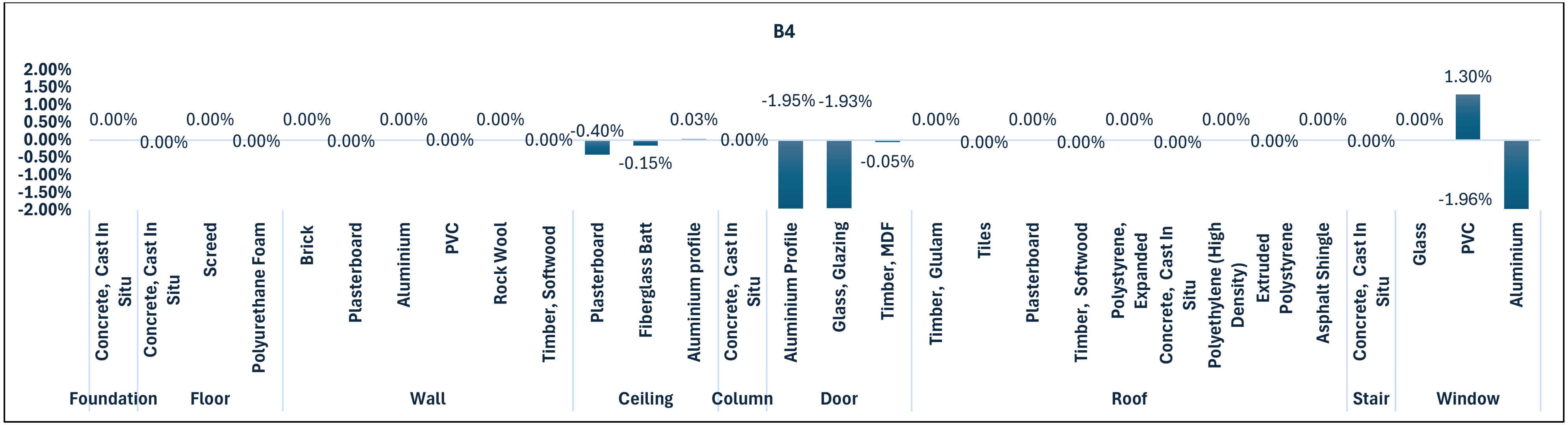


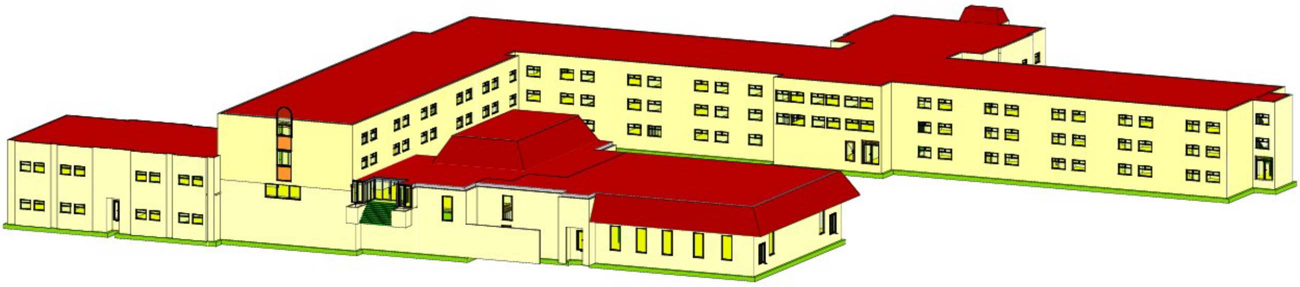
Figure 5.16: Percentage Variation Between the Two Methods for Building Components in the hotel Building During the B4 Life Cycle Stage

5.2.4 Visualization through a color-coded system in the hotel building

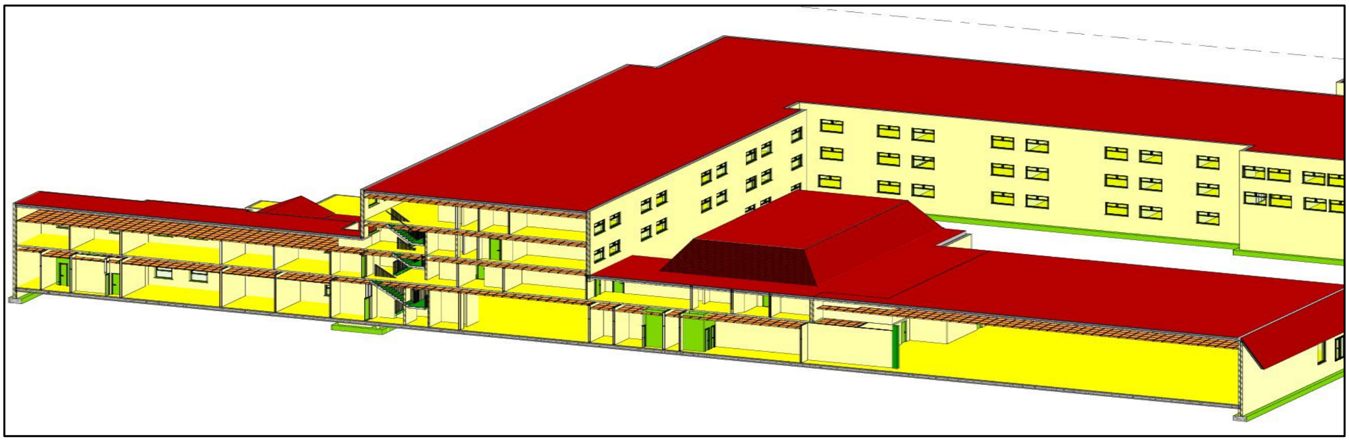
Figure 5.17 provides a visual representation of the EC of building components using a color-coded system that ranges from the minimum value of 9,230.62 $kgCO_2e$ to the maximum value of 3,665,065.61 $kgCO_2e$. Figure 5.18 (A) shows the exterior view of the building, where the roof is prominently coloured in red, signifying the highest levels of EC. The walls are depicted in light yellow, indicating a lower EC compared to the roof, while the foundation elements at the base are highlighted in green, representing the lowest EC values. Figure 5.18 (B) provides a sectional view of the building, offering a detailed look at the internal distribution of EC. The green colour visible at the column components shows minimal EC. The interior walls are color-coded, with the light shades of yellow representing moderate EC levels. Floors shaded in darker yellow indicate a higher EC potential. Meanwhile, the orange-coloured ceiling stand out as a significant contributors to the building's EC. The elevated EC levels in both the roof and ceiling are primarily attributed to the frequent material replacements required over the building's lifespan.

Minimum Value	9,230.62
MIN+1/9(Max-Min)	415,434.50
MIN+2/9(Max-Min)	821,638.39
MIN+3/9(Max-Min)	1,227,842.28
MIN+4/9(Max-Min)	1,634,046.17
MIN+5/9(Max-Min)	2,040,250.06
MIN+6/9(Max-Min)	2,446,453.95
MIN+7/9(Max-Min)	2,852,657.84
MIN+8/9(Max-Min)	3,258,861.72
Maximum Value	3,665,065.61

Figure 5.17: Color-coded system for visualizing EC distribution in the hotel building



A) Entire building view



B) Cross-section view

Figure 5.18: EC distribution using the colour coding system in the educational building

5.2.5 Time discrepancy between the two methods

Figure 5.19 highlights the significant time disparity between the manual and automated methods for conducting EC assessments across various building components. The manual method is highly time-consuming, especially for components such as walls, which take up to 220 hours and represent the majority of the total time required. In contrast, the automated method drastically reduces the time needed for every building component, as indicated by the much shorter bar. This illustrates the substantial efficiency gains offered by the automated approach, enabling quicker assessments without compromising accuracy, as demonstrated in earlier comparisons. The chart underscores the potential time savings of automating the EC assessment process.

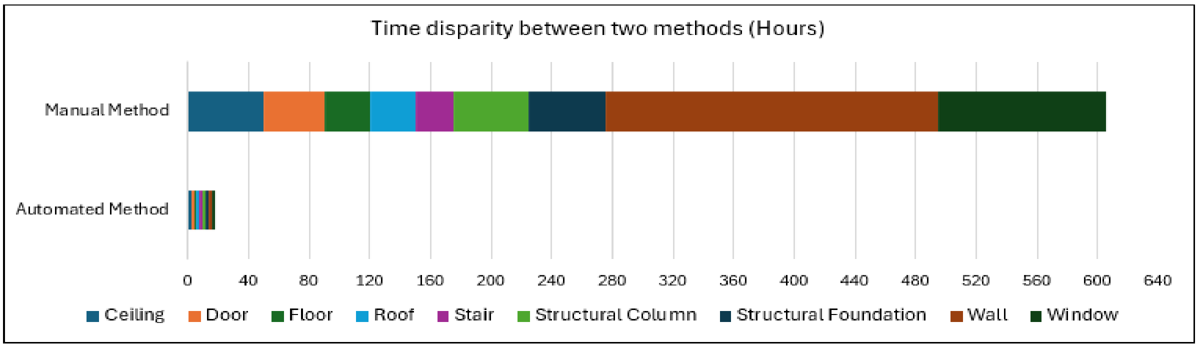


Figure 5.19: Time Difference Between Manual and Automated Methods

5.3 Summary

This chapter emphasizes the essential role of integrating BIM and LCA to automate EC assessments in the construction industry, using The London College and Hilton Hotel as case studies to demonstrate this approach. The developed process, which combines Revit, Dynamo, and Python scripting, greatly enhances both the accuracy and efficiency of EC calculations, covering the full life cycle of buildings. The results indicate that the automated method achieved over 98% accuracy compared to the manual approach while significantly reducing assessment time by more than 90%. The automated process enables real-time updates and allows for the identification of carbon "hot spots" during the design phase, promoting more sustainable material choices. For example, EC assessments for key building components, such as walls and structural foundations, were completed in 2 hours using the automated method, a drastic improvement compared to traditional manual calculations that can take much longer. Additionally, the integration of a color-coded visualization system significantly enhances decision-making by enabling designers to quickly interpret which components or stages contribute the most to the WLEC. This visual tool allows designers to identify and address carbon-intensive areas effectively, thus optimizing material choices and reducing emissions.

Chapter 6 : Embodied carbon reduction strategies

The construction industry plays a significant role in contributing to EC emissions, underscoring the need for swift and effective measures to reduce its environmental impact. As mentioned in the second chapter, various strategies exist for mitigating EC emissions within the construction industry including whole building reduction, one-for-one material substitution, and specification.

This chapter explores a comprehensive analysis of diverse approaches aimed at minimizing carbon emissions, with the objective of assessing their potential impact on achieving carbon savings in the building construction.

6.1 Application of green roofing system in hotel building

Implementing green roofs on top of buildings serves as an effective and sustainable strategy aimed at mitigating carbon emissions within urban environments. These environmentally friendly rooftops play a crucial role in achieving a dual reduction in a building's overall carbon footprint. Firstly, the vegetation present on green roofs actively sequesters CO_2 from the atmosphere, thereby contributing to a significant decrease in EC. Secondly, by acting as a natural insulator for the roof, green roofs enhance the building's energy efficiency by reducing the need for excessive heating and cooling. As a result, this improved thermal performance leads to a reduction in OC emissions. In this section, the environmental advantages resulting from the integration of green roofs at Hilton Watford are closely examined, in contrast to traditional roofing systems. The analysis extends to a thorough evaluation, covering both EC and OC considerations. The intentional choice of Hilton Watford as the case study is supported by its expansive rooftop, exceptionally suited for the effective implementation of green roofs. This strategic selection enables us to explore deeply the diverse environmental benefits associated with green roofing, adapted specifically to the unique characteristics of Hilton Watford.

6.1.1 Details of the Green Roof System

Within the framework of the highlighted case study, an innovative, lightweight, and low-thickness extensive greening system has been integrated, designed with a high capacity for water retention. This system is composed of a combination of four distinct layers, as illustrated in Figure 6.1. A comprehensive breakdown of the specific details and characteristics of each individual layer is provided in Table 6.1.

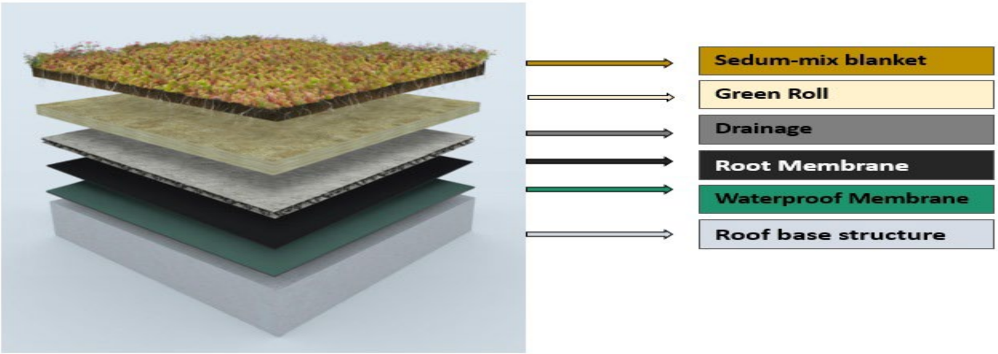


Figure 6.1: An extensive green roofing system comprises various layers superimposed upon a conventional roof structure

Table 6.1: Different layers of green roofing system

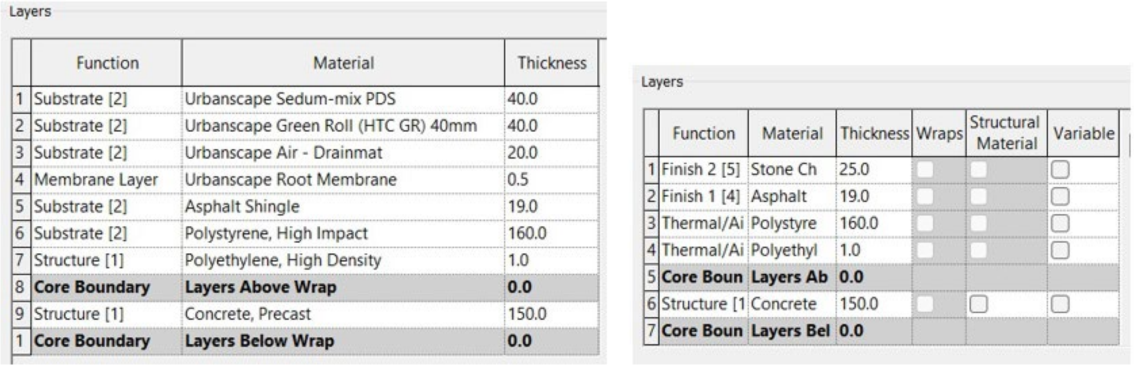
Layer of green roof	Details of components
Sedum-mix blanket	12 species of Sedum plants
Green Roll	Needle-punched, binder-free rock mineral wool
Drainage	Interwoven polypropylene filaments and nonwoven filter fabric
Root Membrane	LD Polyethylene

Starting at the top, there is a top layer of Sedum vegetation in the form of pre-cultivated rolls, consisting of 12 distinct species of Sedum plants. Next, a Green Roll growing medium, comprised of needle-punched, binder-free rock mineral wool, not only facilitates robust root growth for the sedum but also excels in retaining water. Drainmat introduces a cutting-edge drainage solution, ensuring exceptional water drainage capabilities. This advanced drainage layer comprises a three-dimensional, lightweight, and flexible composite materials. Its core is composed of interwoven polypropylene filaments, delivering a remarkable drainage capacity.

This core is further complemented on both sides with a nonwoven filter fabric. Drainmat stands as a high-performance CE-marked drainage system crafted entirely from 100% recyclable polypropylene. Finally, Root Membrane is a black LD Polyethylene regenerate which is used to prevent the roots penetrating in green roofs (Knauf Insulation, 2022).

Prior to the installation of the green roof, the base roof has to be tested and checked to see if there are any leakages, to prevent any inconveniences later in the process. Additionally, after the project is completed, it is strongly advisable to have regular maintenance (twice a year) on the green roof. In such a way, this means that the base roof will also be taken care of. Maintenance of the green roof means checking for any visual deformations, adding substrate where needed, replanting sedums with sedum cuttings where they are missing, fertilising, watering the roof, and inspecting the outlets.

In the initial stage of the process, the green roof of the building was modelled using Revit. This was done to accurately determine and extract the precise quantity of materials that have been incorporated into the construction of the green roof (Figure 6.3). Additionally, Figure 6.2 serves as a visual representation, clearly illustrating the different layers present in both conventional roofing systems and green roofing systems within the Revit environment. Furthermore, a detailed and comprehensive breakdown of the specific materials used in the green roof for the case study is presented in Table 6.2.



Layers

	Function	Material	Thickness
1	Substrate [2]	Urbanscape Sedum-mix PDS	40.0
2	Substrate [2]	Urbanscape Green Roll (HTC GR) 40mm	40.0
3	Substrate [2]	Urbanscape Air - Drainmat	20.0
4	Membrane Layer	Urbanscape Root Membrane	0.5
5	Substrate [2]	Asphalt Shingle	19.0
6	Substrate [2]	Polystyrene, High Impact	160.0
7	Structure [1]	Polyethylene, High Density	1.0
8	**Core Boundary**	**Layers Above Wrap**	**0.0**
9	Structure [1]	Concrete, Precast	150.0
1	**Core Boundary**	**Layers Below Wrap**	**0.0**

Layers

	Function	Material	Thickness	Wraps	Structural Material	Variable
1	Finish 2 [5]	Stone Ch	25.0	☐	☐	☐
2	Finish 1 [4]	Asphalt	19.0	☐	☐	☐
3	Thermal/Ai	Polystyre	160.0	☐	☐	☐
4	Thermal/Ai	Polyethyl	1.0	☐	☐	☐
5	**Core Boun**	**Layers Ab**	**0.0**			
6	Structure [1	Concrete	150.0	☐	☐	☐
7	**Core Boun**	**Layers Bel**	**0.0**			

Figure 6.2: Characteristic details of both conventional and green roofs in Revit

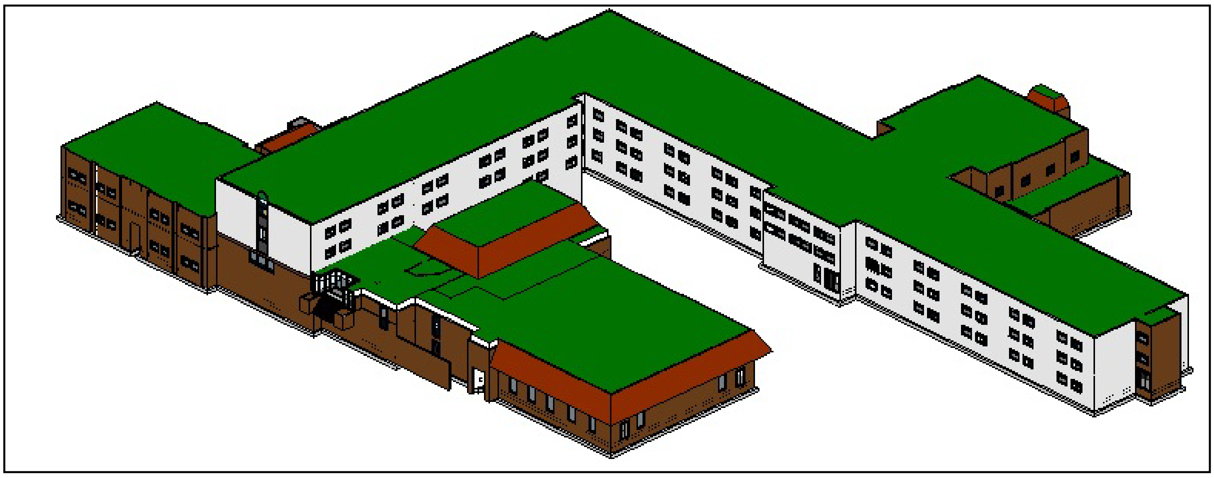


Figure 6.3: 3D model of Hilton Watford with green roofing system

Table 6.2: Green roof materials in the hotel building

Building Element	Structural Element	Component	Volume (m3)	Weight (kg)
Superstructure	Green Roof	Sedum-mix PDS	158.76	126,274.29
		Air-Drainmat	99.25	104,243.02
		Green Roll (HTC GR)	158.76	17,807.91
		Root Membrane	3.9	3,666

6.1.2 Carbon emission Analysis of Green Roof

6.1.2.1 Embodied Carbon

In the of this study, an EPD was utilized as a tool to evaluate and quantify the EC emissions that are specifically associated with the process of implementing a green roof system. The total surface area of the roof, which is entirely free from any installed equipment or structural obstructions and is deemed suitable for the installation and integration of a green roof, has been measured to be 3,438.51m^2.

Table 6.3 presents a detailed and comprehensive breakdown of the ECFs that are associated with each distinct phase within the entire lifecycle of the green roof. These values have been determined through the application of an EPD. However, it is important to note that this particular EPD does not take into account the EC emissions that are specifically related to the roofing membrane, and these emissions are calculated separately.

Table 6.3: Environmental impact of green roofs at different stages of its life cycle

Parameter	Environmental Impact						
	A1-A3	A4	A5	C1	C2	C3	C4
GWP-total ($kgCO_2e/m^2$)	3.68	1.5	1.13	0	0.16	67.9	0

The green roof, when installed over the base roof, should extend the lifespan of the underlying structure, irrespective of the base roof's original longevity (Rasul and Arutla, 2020). This extension is attributed to the green roof's ability to shield the base roof from damaging UV light and mitigate extreme temperature fluctuations (heat and cold) by providing an additional protective layer. As outlined in (Oberndorfer et al., 2007), this can potentially add 20 years to the base roof's lifespan. Given Hilton's confirmation of a 30-year lifespan for their conventional roof, the incorporation of a green roof elevates its overall longevity to 50 years.

Table 6.4 illustrates the amount of carbon that has been released over the 50-year lifespan of the green roof. The sedum layer significantly contributes to the GWP impacts during its production. This sedum layer emits 3.68 $kgCO_2e/m^2$ during the production stage. Considering the green roof's area in this structure, the total emissions during the production phase amount to 12,653.70 $kgCO_2e$. In addition to production emissions, transportation contributes 5,157.76 $kgCO_2e$, and the construction installation process contributes 3,885.51 $kgCO_2e$. End-of-life stage is responsible for the biggest share of carbon emissions. A lot of research does not consider the end-of-life as there are no specific methods for their analysis. In this study, EPDs were used, as they provide the most reliable data on carbon emissions at the end-of-life of the green roof. According to the EPD, the green roof is responsible for substantial amount of carbon emissions, approximately 233,474.56 $kgCO_2e$ during C3. This shows that the carbon stored by the sedum layer over its 50-year lifespan will be released when the materials are composted. Furthermore, the transportation of waste materials during this process results in an additional 550.16 $kgCO_2e$. According to the EPD, green roof is responsible for 255,721.69 $kgCO_2e$. In addition, root membrane of green roof is responsible for 8,117.87 $kgCO_2e$. summary, when all these emissions are combined, the green roofing system releases a total of 263,839.56 $kgCO_2e$ as EC.

In contrast, the layer of sedum plants absorbs 211,468.12 $kgCO_2e$ during the use stage of green roof. The information provided in this section clearly illustrates a substantial disparity of 52,371.44 $kgCO_2e$ between the quantity of carbon emissions released and the quantity sequestered.

Table 6.4: EC emissions during different stages of the green roof's life

Embodied carbon ($kgCO_2e$)						**Total**
A1-A3	**A4**	**A5**	**C2**	**C3**	**C4**	
12,653.70	5,157.76	3,885.51	550.16	233,474.56	-	255,721.69

6.1.2.2 Operational Carbon

In this study, OC emissions are also accounted for to provide a more comprehensive understanding of the environmental advantages associated with implementing green roofs. Therefore, the 3D dimensional model was transmitted to Insight, a cloud-based tool for performance analysis and simulation, where energy analysis of the building was performed (Figure 6.4). Insight serves as an invaluable adjunct to BIM software, particularly Revit, for comprehensive performance analysis and simulation of building designs. Insight is designed to provide data-driven and evidence-based insights into various aspects of a building's performance.

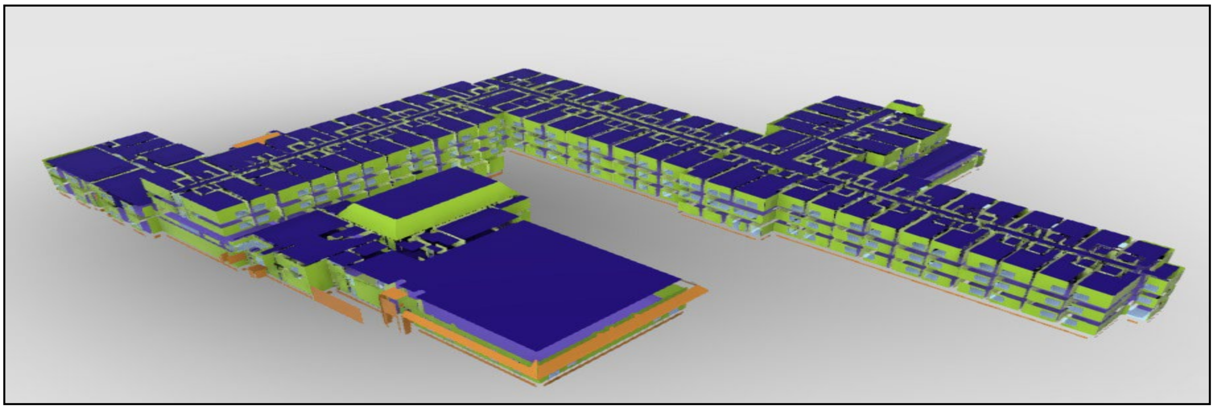


Figure 6.4: Schematic of the modelled building in Insight

For analysing OC, whole building energy analysis is performed using Insight, which captures the holistic interactions within the building and its systems through a comprehensive dynamic thermal energy simulation, utilizing DOE 2.2 and EnergyPlus.

Assigning the most appropriate weather data based on the modeling's purpose and the specific location of the case study is a critical step in the energy analysis. In this context, we've incorporated the nearest weather station to the case study into the model. Weather stations are from Autodesk's climate server, which provides data for the whole world at a 14 km grid.

Hotel buildings typically consume a substantial amount of energy due to their continuous operation, which necessitates constant heating, cooling, and hot water provision. Therefore, a 24/7 facility operating schedule is selected to meet these demands.

The energy performance of the building is significantly influenced by its Heating, Ventilation, and Air Conditioning (HVAC) system. Following discussions with an engineer at Hilton Watford, it was determined that "Central VAV, HW Heat, Chiller 5.96 CP, Boilers 84.5 eff" is the suitable choice for the HVAC system, given the use of natural gas as a heating fuel and the need for air conditioning to maintain the building's environment.

In the next phase, an evaluation is conducted to contrast the energy efficiency of the building featuring the original conventional roof with that of one incorporating a green roof. This undertaking is aimed at quantifying the extent to which the energy performance of the building may be diminished through the implementation of a green roof as an insulating component.

Table 6.5 presents the data pertaining to Energy Use Intensity (EUI) in the building across various R-values. EUI expresses energy consumption per unit of floor area. Lower EUI values indicate higher energy efficiency, while higher values suggest greater energy consumption relative to the building size. The modelled total EUI for the building with a conventional roof is 237 kWh/m²/yr. According to data provided by Hilton, the average total EUI over a five-year period is 215 kWh/m²/yr. The variation between these two figures is approximately 10.25%, which falls within an acceptable range of deviation, as supported by previous research (Amirkhani, 2022; Salem, 2020). Furthermore, Table 6.5 distinguishes between two scenarios, denoting them as BIM (Initial) and BIM (Final), where the former signifies the utilization of a conventional roof, and the latter denotes the implementation of a green roof. The findings indicate that the disparity in energy efficiency between the two scenarios is relatively low, approximately amounting to 3.3 kWh/m²/yr. This can be attributed to the effective insulation of the roofing system in the building.

Table 6.5: Energy efficiency of different roof construction

Roof Construction Name	R-Value ((hft^{2}°F/BTU))	Annual EUI (kWh/m^{2}/yr)
Uninsulated	1.33	279
R10	11.75	237
BIM (Initial)	12.47	236.4
R15	15.61	234
R19	16.39	234
BIM (Final)	19.77	233.1
10.25-inch SIP	37.71	229
R38	42.57	229
R60	66.23	227

Figure 6.5 illustrates that the building consumes the most energy when the roof lacks effective insulation, falling within the range from uninsulated to R10. Green roofs can greatly reduce EUI in this case. When the roofing system possesses insulation levels between R10 and R60, there is a relatively lower and more consistent EUI, with minor fluctuations. Applying green roofs in this range does not lead to a significant alteration in energy efficiency patterns.

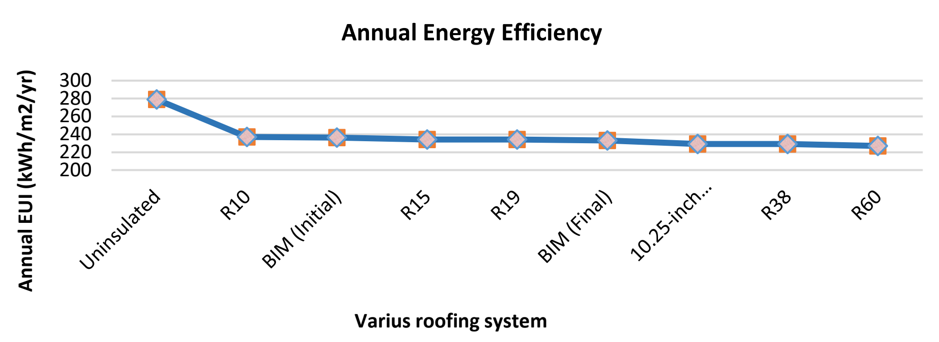


Figure 6.5: Energy efficiency patterns with various roofing systems

Table 6.6 presents a comparative analysis of energy consumption between traditional roofs and green roofs, considering various insulation thicknesses. It is evident that, depending on the level of insulation, EUI for conventional roofs can rise significantly from 236.44 kWh/m^2/yr to 279 kWh/m^2/yr. Furthermore, Figure 6.6 showcases the potential energy savings achievable by implementing green roofs as opposed to conventional roofing systems. According to Figure 6.6, the utilization of green roofs, results in a reduction in the EUI by 3.3 kWh/m^2/yr. Furthermore, the analysis reveals that green roofs exhibit a more substantial beneficial effect on roofs with suboptimal insulation when compared to the specific case study under examination. Figure 6.7 also demonstrates that energy savings rise with decreasing insulation thickness. In other words, green roofs work better on roofs with less insulation.

Table 6.6: Comparing the energy efficiency and savings of conventional and green roofs with varying insulation thickness

Thickness (mm)	**R-Value ((hft^2°F/BTU))**		**Annual EUI (kWh/m^2)**	
	Conventional Roof	**Green Roof**	**Conventional Roof**	**Green Roof**
160	12.45	19.77	236.44	233.18
140	11.02	18.34	239.71	233.53

120	9.60	16.92	245.23	233.86
100	8.18	15.50	254.02	234.19
80	6.76	14.08	256.41	235.27
60	5.34	12.66	261.97	236.35
40	3.92	11.25	267.63	237.17
20	2.50	9.83	273.30	238.26
Uninsulated	1.11	8.41	279	239.34

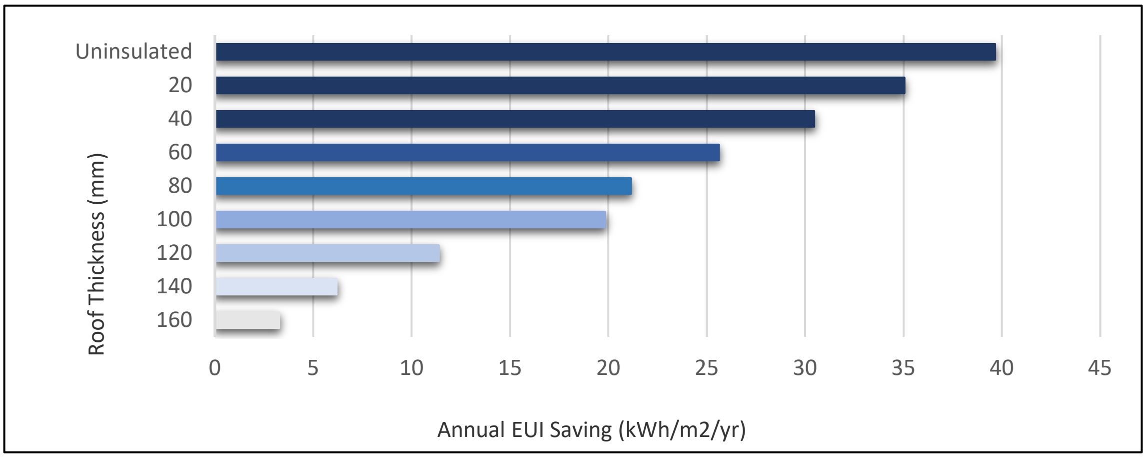


Figure 6.6: Annual energy savings associated with green roof usage

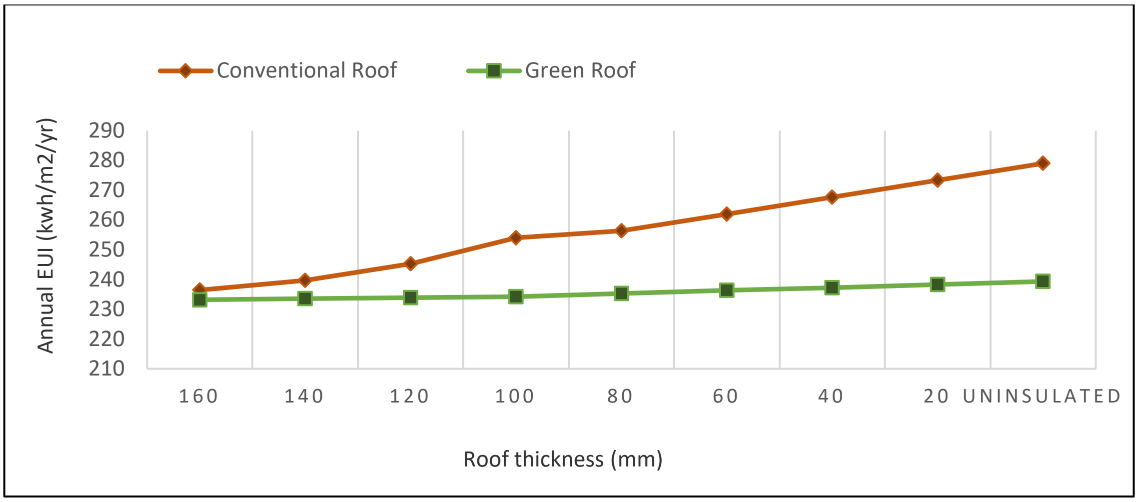


Figure 6.7: Energy efficiency for conventional vs green roofs with varying levels of insulation

Table 6.7 presents data illustrating the reduction in OC emissions achieved through the implementation of a green roof on the building. Table 6.7 reveals that while the adoption of green roofs imposes an EC burden of 52,371.44 kgCO$_2$e on the environment, it concurrently leads to a substantial saving of 112,130.31 kgCO$_2$e in OC emissions throughout the entire life cycle of the building. This data illustrates that the implementation of green roofs effectively mitigates the carbon emissions produced, resulting in a reduction of 59,758.87 kgCO$_2$e in the case study. Table 6.7 highlights the substantial impact of green roofs on reducing carbon emissions, particularly in scenarios with less effective insulation. The values in Table 6.7 showcase the correlation between insulation thickness and the resulting carbon emissions reduction in the case study. As the insulation thickness decreases, the EUI saving, energy consumption saving, and carbon emissions saving become more pronounced. For instance, with an insulation thickness of 160mm, the carbon emissions saving is 112,130.31 kgCO$_2$e. As the insulation thickness decreases, the savings increase, reaching a maximum of 1,363,587.28 kgCO$_2$e in the uninsulated scenario. This indicates that green roofs exhibit more substantial benefits in terms of carbon emissions reduction when the building has suboptimal insulation.

Table 6.7: OC emissions savings associated with green roof usage

Insulation Thickness (mm)	EUI Saving (kWh/m^2/yr)	Energy consumption Saving (kWh)	Carbon emissions Saving (kgCO$_2$e)
160	3.26	560,651.56	112,130.31
140	6.19	1,063,427.62	212,685.52
120	11.38	1,955,903.70	391,180.74
100	19.83	3,410,014.98	682,003.00
80	21.14	3,634,645.34	726,929.07
60	25.61	4,403,624.82	880,724.96
40	30.46	5,236,921.56	1,047,384.31
20	35.05	6,025,569.30	1,205,113.86
Uninsulated	39.66	6,817,936.40	1,363,587.28

This research investigated the carbon emissions released and sequestered by green roofs over their lifecycle. The results suggest that although installing green roofs can decrease carbon emissions, the reduction might not be substantial when compared to the total carbon emissions of a building. Notably, the environmental benefits of green roofs become more evident in buildings with insufficient insulation. Therefore, green roofs can be regarded as an effective strategy for reducing carbon in structures in cases with suboptimal insulation.

6.1.3 Cost of the green roof

In this project, the cost of implementing green roofs is a crucial aspect to evaluate. It's essential to assess whether the financial investment in green roofs is justified. Table 6.8 provides precise and reliable data on the prices of various components of the green roof, sourced directly from manufacturers. This information plays a vital role in the financial considerations for the project. According to Table 6.8, the cost of implementing a green roof for the project is £114,158.52. Maintenance is a crucial factor in determining the viability of green roof installations. The level of maintenance required depends on the type of green roof. For an extensive green roof, maintenance primarily involves biannual inspections (in spring and autumn) to remove weeds, check drainage systems, and apply fertilizers if necessary. Occasional replanting may be required to maintain vegetation coverage, while drainage outlets must be kept clear to prevent water buildup, and the roof membrane should be inspected for potential damage.

According to Calculattor.com (2024), the average annual maintenance cost for a green roof range from £0.10 to £1.00 per square foot after the first five years. Since extensive green roofs are designed for lower maintenance compared to intensive green roofs (Flavin, 2021), the minimum cost estimate has been applied in this case study. Consequently, the total maintenance cost considered in this research is £832,765.72. Thus, the combined installation and maintenance cost of the green roof amounts to £946,924.24. In comparison, according to Compass International INC (2016), the average hotel construction cost in London is £2,343.94 per square meter, bringing the total estimated construction cost of the case study building to £25,481,122. Since the green roof accounts for only 3.71% of the total building cost, its financial impact is negligible. Therefore, from a financial perspective, incorporating a green roof is a cost-effective and viable decision.

Table 6.8: Cost of the green roof installation

Product Name	Unit	Quantity	Price GBT/Unit	Total GBT
Urbanscape GR Premium Air	m^2	3438.51	31.6	108,656.91
URBANSCAPE Drainmat PVT				
URBANSCAPE Green Roll D11 3000x1000x40				
URBANSCAPE Sedum-Mix Blanket				
URBANSCAPE Root Membrane FLW500 6M	m^2	3438.51	1.6	5,501.61
Total Price				**114,158.52**

When assessing the expenses linked to green roofs, it is crucial to take into account their lasting financial benefits, particularly in terms of energy savings over time. Table 6.9 illustrates the cost savings realized throughout the lifespan of the building when employing a green roofing system. Analysis of Table 6.9, based on Hilton Watford's provided data, reveals an average electricity cost of £0.13 per kWh and an average fuel cost of £0.04 per kWh over 5 years for the hotel building. Considering the annual electricity savings of 276,308.05 kWh and annual fuel savings of 284,343.51 kWh, the adoption of a green roof at Hilton Watford could lead to substantial energy cost savings, totalling £48,509.90. This underscores the dual impact of a green roof, providing not only environmental benefits but also substantial long-term financial advantages.

Table 6.9: Reducing operational costs with green roofs

Electricity Cost (£) (Average 5 years)	164,443.40
Electricity Consumption (kWh) (Average 5 years)	1,254,714
Electricity Cost per kWh (£/kWh) (Average 5 years)	0.13
Electricity Saving per kWh (kWh)	276,308.05
Fuel Cost (£) (Average 5 years)	55,839.90
Fuel Consumption (kWh) (Average 5 years)	1,291,203
Fuel Cost per kWh (£/kWh)	0.04
Fuel saving per kWh (kWh)	284,343.51

Cost Saving (£)	48,509.90

It is also noteworthy to mention that, apart from the contributions of green roofs to carbon sequestration and energy conservation, green roofs yield additional advantages. Some noteworthy aspects include the reduction of Urban Heat Island Effect (UHI), rainwater management, extended roof life and noise reduction.

It's worth highlighting that green roofs can be effectively combined with Photovoltaic (PV) panels. Initially, there was a concern regarding the potential shading impact caused by PV panels when integrated with green roofs, specifically on the vegetation. However, it has been observed that the shading, instead of being harmful, actually aids in the growth of the vegetation (Kolk and Den Berg, 2019).

According to (van der Kolk *et al.,* 2020), increased shading can promote Sedum species richness and diversity by reducing drought stress. Shading can be achieved by a stepped building architecture and by placing structures on the roof itself, such as solar panels on standards.

6.2 Utilizing materials with lower carbon intensity

According to (Sandanayake *et al.,* 2017), top categories for reducing EC are Concrete, Rebar, Insulation and Glazing. In this approach, the high carbon-intensive materials highlighted in the preceding chapter will be substituted with materials of lower carbon intensity, and the resulting carbon savings will be presented. In this chapter, carbon-intensive materials across the various case studies will be examined to explore opportunities for their substitution with less carbon-intensive alternatives. Ultimately, the impact of employing these alternatives on the overall EC of the building will be analysed.

6.2.1 Residential Building

In Chapter 4, it was clearly demonstrated that, among all the materials utilized in residential building construction, concrete exhibits the highest EC. The specific building under discussion has been constructed using reinforced concrete (RC) with a strength grade of RC20/25. When examining the individual components involved in concrete production, cement emerges as a particularly significant contributor, accounting for approximately 7% of total GHG emissions. This percentage is anticipated to rise further in correlation with ongoing and continuous development. Cement remains the most widely utilized material in the construction industry on a global scale and stands out as the material with the highest EC within concrete (Anderson and Moncaster, 2020).

Fly Ash and Ground Granulated Blast Furnace Slag (GGBS) have been specifically chosen as partial replacements for cement in order to assess and evaluate their overall impact on reducing EC. There are numerous benefits associated with incorporating Fly Ash as a partial substitute for cement in concrete mixtures. Due to its significant environmental advantages, as well as its cost-effectiveness, Fly Ash which is a by-product generated from coal-fired power plants is widely regarded as a more sustainable and eco-friendlier alternative to traditional cement.

When used as a partial replacement for cement, Fly Ash can increase the workability and durability of concrete, reduce the heat of hydration, and reduce the amount of cement required for building construction. This can result in financial savings as well as environmental benefits, as cement manufacturing contributes significantly to GHG emissions.

Additionally, GGBS can be used as a partial cement substitute. According to (Rana and Rughooputh, 2014), partial substitution of GGBS for cement enhances the workability of the mixture. With increasing GGBS content, the compressive and tensile fracture strengths increase.

Various potential scenarios for reducing EC in the concrete materials used in the case study have been thoroughly examined. These scenarios specifically involve the use of Fly Ash and GGBS as replacement materials for cement. More precisely, the analysis considers Fly Ash replacements at levels of 15%, 30%, and 40%, along with GGBS replacements at proportions of 25% and 50%. As presented in Figure 6.9, the mixture consisting of an equal split of 50% cement and 50% GGBS demonstrates the most significant EC reduction, achieving a substantial decrease of 67.87% in comparison to other evaluated compositions. This makes it the most effective alternative among the various options analysed in this study. Following closely, the 40% Fly Ash replacement exhibits the next highest level of EC reduction, reaching a notable percentage of 58.45%. The replacement scenarios involving 25% GGBS and 30% Fly Ash produce very similar results, leading to EC reductions of 55.41% and 53%, respectively. Among all the examined replacement levels, the lowest observed reduction in EC is associated with the 15% Fly Ash substitution.

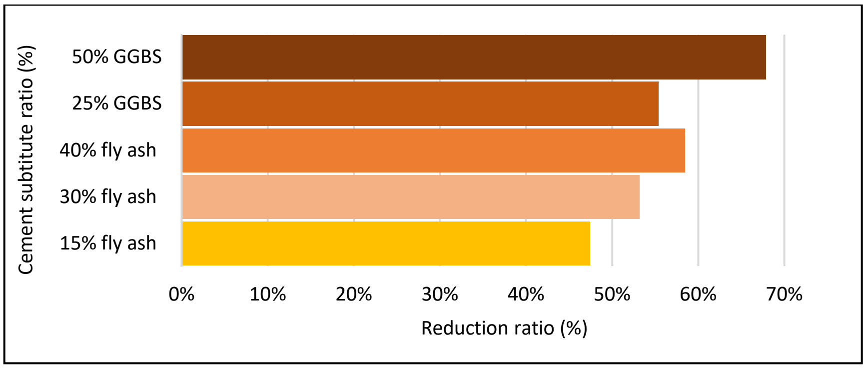


Figure 6.8: Minimizing EC emissions in the residential building with GGBS and Fly Ash as Cement Substitution

Metal materials, especially rebar is among the primary contributors to EC. In the UK, reinforcement can be manufactured using 98% recycled scrap metal (BAR, 2019). In the case studies, a recycled content of 97.9% was assumed for rebar, indicating that this material is already at its lowest carbon emission. Therefore, they cannot be less carbon-intensive than they currently are. However, utilising galvanized steel with 90% recycled content can reduce its EC emissions by 50.5%.

Producing high quality aluminium extrusions with substantial recycled content has been proven feasible. According to Hydro, the recycled content of aluminium can be more than 75%. Therefore, aluminium with 80% recycled content is regarded for assessing its potential reduction in EC. The result showed 64.84% reduction in EC of the material.

Moreover, Bricks rank third in terms of EC production, following concrete and insulation materials. The standard brick format used in the case study is a rectangular cuboid with a declared size of 215x100x65mm; 3 slotted perforations and 2 voids to the rear pass through the bed face of the brick. The brick consists of limestone aggregates with Portland cements with various proportions of oxide pigment. There are three types of this form of brick: white bricks, light-coloured bricks, and strong-coloured bricks. In the case study, strong-coloured brick is utilised.

Brick contributes to 15% of the total EC emissions, and one effective method to mitigate this impact is by incorporating reclaimed brick. Reclaimed brick is considered a sustainable building material since it reduces the demand for new brick production and minimizes waste by repurposing materials that would otherwise be discarded. Utilising reclaimed brick materials in this project significantly reduces the EC of brick by 95.91%.

According to BEWI (2019), Expanded Polystyrene (EPS) has the capability to be manufactured entirely from 100 percent recycled materials. Consequently, the utilization of EPS that is composed entirely of recycled materials provides an additional approach for reducing the EC of a building. This method has the potential to contribute to a reduction in EC by as much as 13.43%.

Based on the information provided in Figure 6.10, the incorporation of materials with lower carbon intensity, such as less carbon-intensive concrete, reclaimed brick, as well as the use of recycled galvanized steel, aluminium, and EPS, leads to a reduction in the total EC of the building. The specific reductions observed are 12.91% for less carbon-intensive concrete, 6.37% for reclaimed brick, 1.41% for recycled galvanized steel, 1.11% for aluminium, and 0.73% for EPS, respectively.

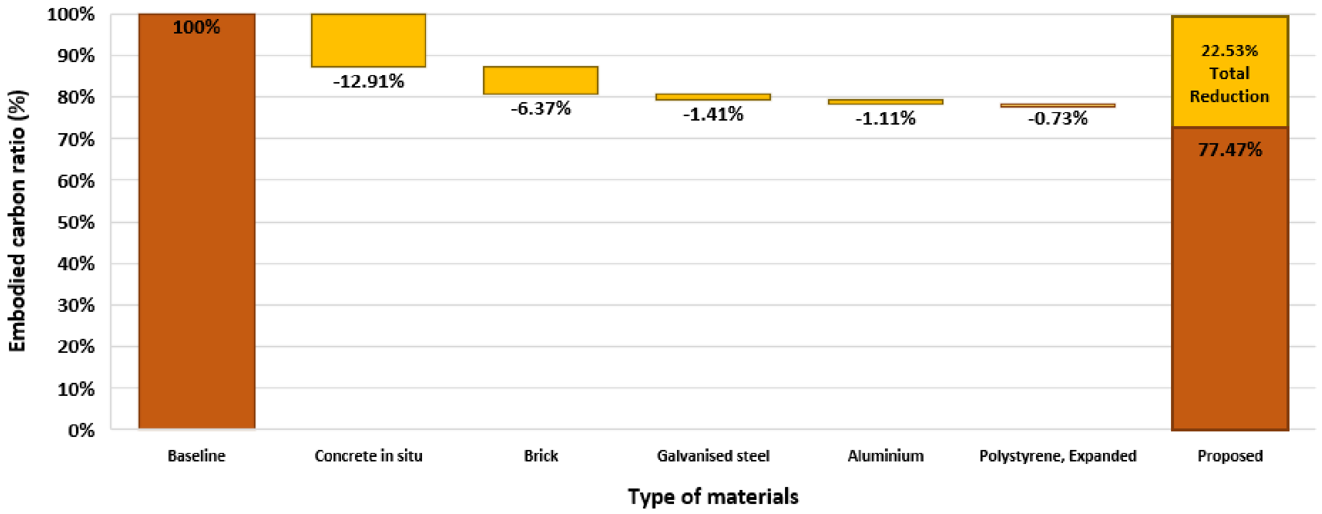


Figure 6.9: Total EC reduction in the residential building through using low carbon materials

6.2.2 College Building

As previously discussed, the substitution of cement with less carbon-intensive materials in the concrete mixture presents the most effective means of achieving substantial reductions in EC. As shown in Figure 6.11, using a mixture of 50% cement and 50% GGBS significantly reduces EC by 64.55% compared to alternative compositions. However, the use of this cement replacement mixture in the residential building resulted in a higher EC reduction. This is primarily due to the difference in concrete strength grades between the two structures; the residential building employs RC 20/25 grade concrete, whereas the college building utilizes a higher strength grade of RC 32/40.

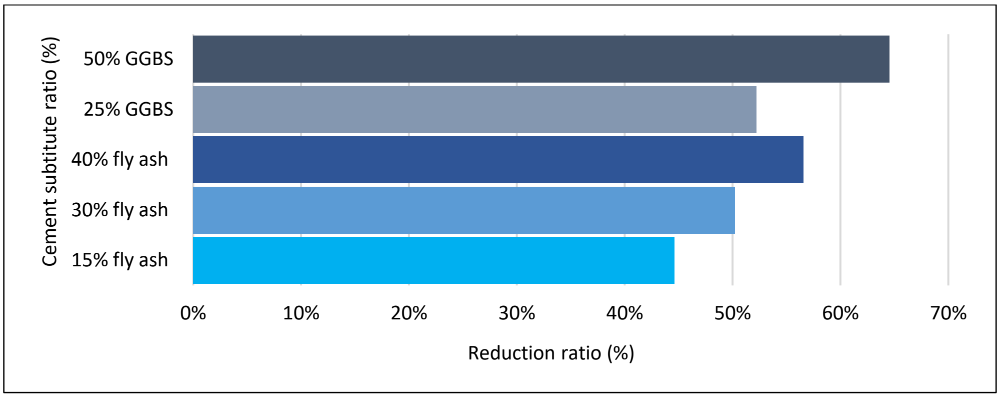


Figure 6.10: Minimizing EC emissions in the college building with GGBS and Fly Ash as Cement Substitution

Figure 6.12 provides a clear representation of the way in which the reduction of EC in materials influences the overall total EC emissions of the building. The figure effectively demonstrates that there is a decrease of approximately 35.17% in the total EC emissions. More specifically, the substitution of cement with GGBS plays a significant role in this reduction, leading to a notable decrease of around 27.84% in the total EC.

In this building, concrete materials rank first in terms of EC emissions and mitigating its environmental footprint can effectively decrease the overall ECF of the building. In addition, incorporating aluminium with 80% recycled content can result in a 5.2% reduction in the building's total EC.

Minimizing the EC by utilizing reclaimed brick can be a favourable option in building design. Reclaimed brick reduces the total EC by 2.05%.

Moreover, using recycled EPS insulation results in a 0.08% reduction of EC.

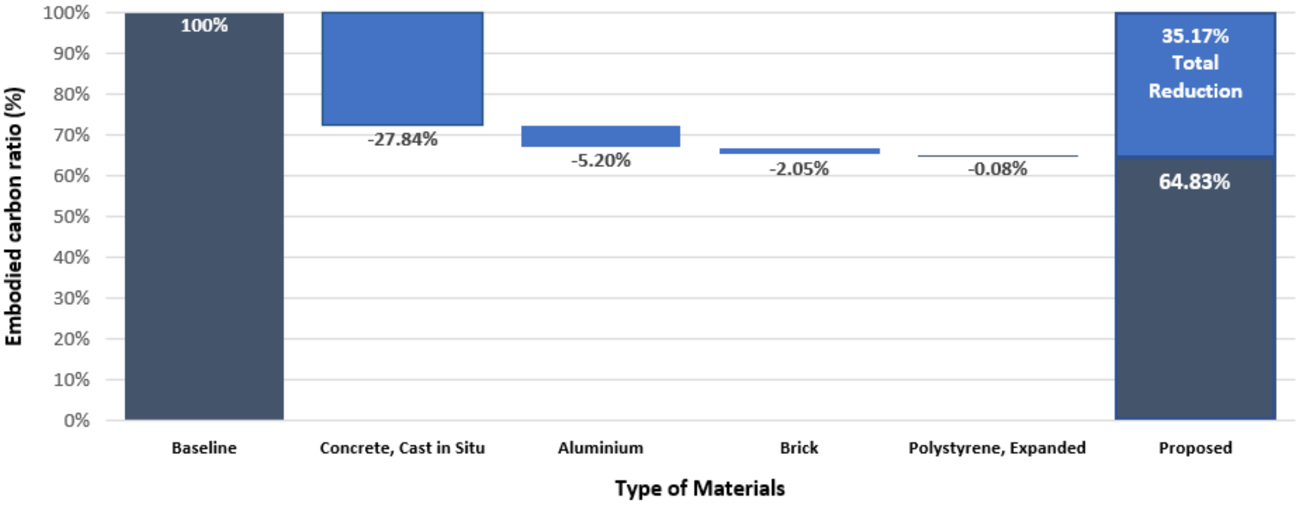


Figure 6.11: Total EC reduction in the college building through using low carbon materials

6.2.3 Hotel Building

In the hotel building, similar to residential and college structures, utilizing a mix of 50% GGBS and 50% cement achieves the most significant reduction in EC, reaching an impressive 61.49%

decrease. In contrast, a minimal 15% substitution with fly ash leads to a smaller reduction (Figure 6.13).

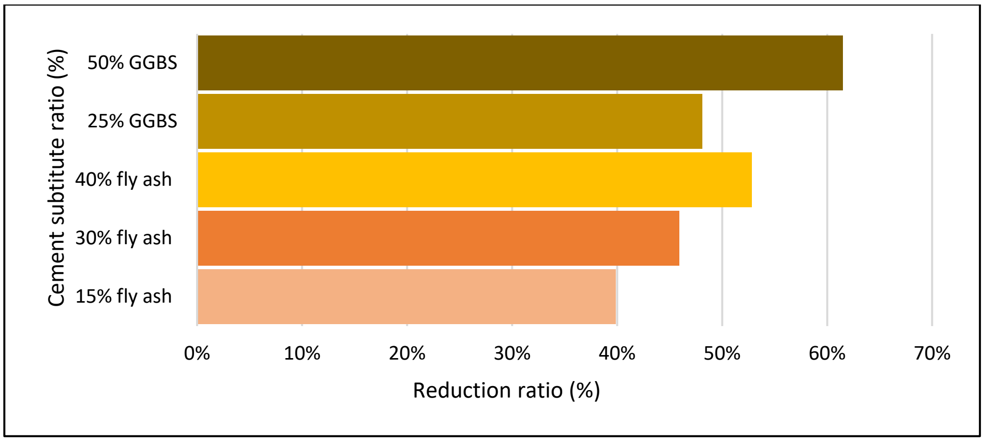


Figure 6.12: Minimizing EC emissions in the hotel building with GGBS and Fly Ash as Cement Substitution

Considering that concrete materials constitute only 26% of the total EC within the building, decreasing their EC could lead to an overall reduction of 10.02% in the building's total EC.

Similarly, choosing reclaimed brick can result in a 3.05% reduction in EC. Furthermore, utilising recycled aluminium and EPS can reduce the total EC by 4.64% and 0.01%, respectively.

In total, these EC reduction strategies result in a significant 17.72% reduction in total EC (Figure 6.14).

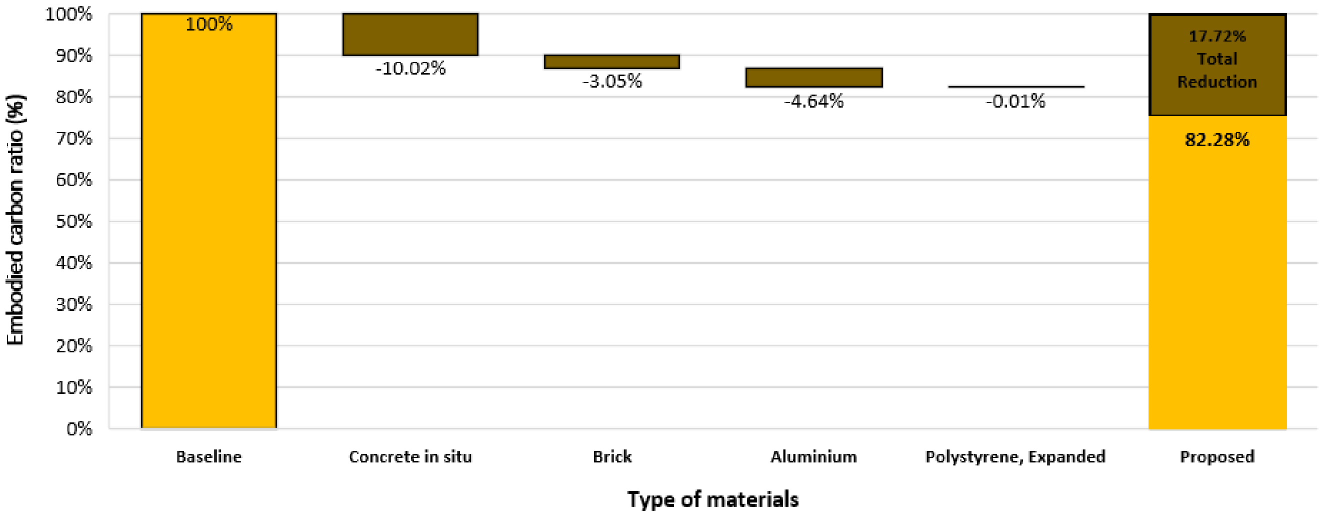


Figure 6.13: Total EC reduction in the hotel building through using low carbon materials

6.3 Embodied carbon benchmarking

The World Green Building Councils, including the UKGBC, are actively encouraging the construction industry to work towards achieving a 40% reduction in EC by 2030. This has encouraged a number of organisations, including professional bodies, advisory groups and local government, to introduce a series of staged aspirational targets in support of the Green Building Council ambitions (Hannah, 2022).

EC targets introduced by LETI are summarised in the following section.

6.3.1 LETI embodied carbon targets

LETI update their EC targets during 2021, seeking to ensure greater alignment with the RIBA 2025 and 2030 targets. LETI guidance also provides a breakdown of the EC target, providing an overall target and a separate target for ‘Upfront Carbon’ which cover Modules A1–A5 (Hannah, 2022).

LETI assume a current average for EC as 1400kgCO$_2$e/m^2 and an EC to practical completion average as 950kgCO$_2$e/m^2. Design targets for 2020 and 2030 have been introduced for office, education, retail and residential buildings (Hannah, 2022). Figure 2.4 shows LETI design targets for 2020 and 2030.

The EC reduction strategies outlined in this research can serve as valuable guidelines for architects during the initial stages of building design. By implementing these strategies, architects can proactively select less carbon-intensive materials, contributing to the creation of more environmentally sustainable buildings from the outset.

In this study, the aim is to evaluate the alignment of the EC reduction strategies with LETI design targets. It should be noted that, while a specific category for hotel buildings is not included by LETI, the analysis is focused on residential and college buildings for comparison purposes.

Table 6.10 displays the A1-A5 EC of the residential building before and after implementation of EC reduction measures. The “primary value” indicates the EC before reduction, while the “secondary value” indicates the corresponding figures after reduction.

Table 6.10: A1-A5 EC of the residential building before and after implementation of reduction strategies

Area	**m^2**	145.86
Primary value	**$kgCO_2e$**	70,925.50
Primary value	**$kgCO_2e/m^2$**	486.26
Secondary value	**$kgCO_2e$**	51,354.26
Secondary value	**$kgCO_2e/m^2$**	352.08

The primary EC during A1-A5 construction phases is 486.26 $kgCO_2e/m^2$, placing the building within the 'C' rating according to LETI's design target for residential buildings. However, by implementing an EC reduction approach, the building's EC can be significantly reduced to 352.08 $kgCO_2e/m^2$, elevating its rating to 'B'. This achievement aligns with the LETI 2020 Design Target, indicating substantial progress in meeting sustainability goals.

Table 6.11 showcases the A1-A5 EC of the college building both before and after the implementation of measures aimed at reducing EC.

Table 6.11: A1-A5 EC of the college building before and after implementation of reduction strategies

Area	**m^2**	2,500
Primary value	**$kgCO_2e$**	1,281,702.08
Primary value	**$kgCO_2e/m^2$**	512.68
Secondary value	**$kgCO_2e$**	717,839.41
Secondary value	**$kgCO_2e/m^2$**	287.14

The initial EC for the college building stands at 512.68 $kgCO_2e/m^2$, categorizing it with a "D" rating as per the LETI design target for educational buildings. Following the implementation of EC reduction strategies, this figure decreases to 287.14 $kgCO_2e/m^2$, elevating its rating to an

"A" level. This achievement aligns with the LETI 2030 Design Target, indicating substantial progress in meeting sustainability goals.

6.4 Summary

Chapter 6 explores strategies aimed at reducing EC emissions in the construction industry. It highlights the significance of addressing EC emissions and explores various approaches for mitigating them. The first approach is the application of green roofing systems in hotel buildings as a sustainable strategy to reduce carbon emissions. The analysis includes the environmental benefits of green roofs, details of the green roof system implemented at Hilton Watford, carbon emission analysis throughout the lifecycle of the green roof, energy efficiency comparisons between conventional and green roofs, cost considerations, and additional advantages of green roofs like reducing the Urban Heat Island Effect and rainwater management. The findings underscore the potential of green roofs to mitigate carbon emissions and operational costs while providing environmental benefits beyond carbon reduction.

This chapter also analysis the effects of substituting high carbon-intensive materials with lower carbon intensity alternatives. It examines various case studies, including residential, college, and hotel buildings, to analyse the impact of employing these alternatives on the overall EC of the buildings.

In the residential building case study, concrete is identified as the material with the highest EC, particularly due to cement's significant contribution to global GHG emissions. The chapter discusses the use of Fly Ash and GGBS as partial replacements for cement in concrete production, highlighting their environmental benefits and cost-effectiveness. Various scenarios for EC reduction in concrete materials are analysed, with the most effective choice being a mixture comprising 50% cement and 50% GGBS, resulting in a 67.87% reduction in EC.

Additionally, the chapter addresses the EC of metal materials. Utilizing galvanized steel with 90% recycled content can reduce its EC emissions by 50.5%. The chapter also discusses the potential reduction in EC by incorporating high-quality aluminium with substantial recycled content and reclaimed bricks in building construction.

Similar strategies are discussed in the case studies of college and hotel buildings, with a focus on substituting cement with lower carbon-intensive materials and incorporating recycled materials in construction. The chapter concludes with a discussion on the alignment of EC reduction strategies with targets set by organizations like the UKGBC and LETI, showcasing the potential for substantial reductions in EC and the importance of incorporating such strategies in building design to achieve sustainability goals.

Chapter 7 : Conclusion and Future Work

7.1 Summary of the work

Building construction and operations account for 39% of GHG emissions. This thesis has addressed the urgent need to mitigate GHG emissions, with a particular focus on EC in buildings, driven by the escalating awareness of climate change and the imperative to reduce carbon emissions in the UK. By focusing on residential, educational, and hotel buildings, the research aimed to comprehensively assess and mitigate EC using LCA across the building lifecycle to achieve net-zero carbon buildings.

The analysis conducted in this thesis provided valuable insights into the accuracy of EC databases, with enhanced database emerging as the most reliable sources. Significant variations in EC were observed within concrete materials, emphasizing the importance of considering individual components rather than treating concrete as a singular material. The identification of concrete as materials with the highest contribution to EC underscored the need for targeted reduction strategies, particularly during the early stages of the building's lifecycle.

In addition, this thesis explored the integration of BIM and LCA to automate WLEC assessments in buildings, using the London College and Hilton Hotel Building as case studies. The study demonstrated that the automated approach achieves over 98% accuracy compared to manual calculations while reducing assessment time by more than 90%. A color-coded visualization system effectively identified carbon-intensive materials. Minor discrepancies (<2%) between automated and manual calculations confirmed the reliability and efficiency of the automated approach.

Furthermore, the thesis explored strategies for reducing EC emissions in the construction industry, including the application of green roofing systems and the substitution of high carbon-intensive materials with lower carbon intensity alternatives. Case studies highlighted the potential for significant EC reductions through the use of alternative materials, aligning with targets set by organizations like LETI.

The research questions outlined in chapter 1 have all been addressed through different chapters. Below is the brief summary of the main findings with regards to the research questions.

1. **What is the discrepancy in EC between treating building materials as singular entities and analysing them based on their individual component parts?**

The discrepancy in EC between treating building materials as singular entities and analysing them based on their individual component parts is significant, as demonstrated in the thesis. When materials like concrete are assessed as singular units, their EC values tend to be overestimated. For instance, in one scenario, the EC of "Concrete, Cast in Situ (C20/25)" was found to be 30.29% higher when treated as a single entity rather than being broken down into its individual components. This discrepancy increases with higher-strength materials, as seen in "Concrete, Cast in Situ (C40/50)", where the overestimation reached 84.97%. This issue is also evident for reinforced concrete, where the EC was underestimated by 36.13% in residential buildings and 22.67% in college buildings when treated as a singular material. Similarly, materials such as AAC exhibited an overestimation of 24.9%, while screed showed an underestimation of 13.8%. The primary factor contributing to this discrepancy is the absence of precise material specifications.

2. **Which element and life cycle stage of buildings have the greatest impact on reducing EC?**

   The production phase (Module A) has the highest impact on EC, as it includes the extraction, processing, and transportation of raw materials. Concrete, particularly reinforced concrete, is one of the most significant contributors to EC due to the high carbon footprint of cement production. Cement alone accounts for approximately 1.5% of GHG emissions. However, replacing cement with supplementary materials such as Fly Ash and GGBS can significantly reduce EC. A 50% cement-GGBS mixture has been shown to lower the EC of concrete by 60% to 70%, making it the most effective material substitution strategy. When considering WLEC emissions, adopting a 50% cement and 50% GGBS mixture as an EC reduction strategy results in substantial carbon savings across different building types, with reductions of 12.91% in the residential building, 27.84% in the college building, and 10.02% in the hotel building.

3. **What effect will building's maintenance, repair and replacement have on EC?**

This research has conducted an in-depth analysis of the EC generated during Module B, addressing a gap in previous studies where this phase has been largely overlooked. The maintenance, repair, and replacement of building components significantly contribute to a structure's overall EC emissions throughout its lifecycle. Regular maintenance (Module B2) plays a crucial role in preserving building performance, preventing material deterioration, and ensuring operational efficiency. However, maintenance activities also generate EC through cleaning processes, material consumption, and waste generation. According to the London Plan

Guidance for WLC Assessments, maintenance-related emissions are estimated at approximately 10 $kgCO_2e/m^2$ GIA to ensure consistent evaluations.

Repair activities (Module B3) account for unplanned damage beyond routine maintenance and contribute to EC through material replacements, transportation, and installation. Given the limited availability of repair-related EC data, estimates suggest that its impact is approximately 25% of maintenance-related emissions. Replacement activities (Module B4) represent the most significant EC contributor within the use phase, as they involve producing, transporting, and installing new materials while disposing of old components. By considering the lifespan of materials in the case studies and the number of replacements required throughout a building's lifecycle, the EC impact of Module B4 has been quantified.

The findings highlight the substantial share of EC associated with Module B compared to other life cycle stages, particularly in the hotel building, where EC from Module B is 38.33% of Module A. Notably, EC emissions peak at 25- and 50-years post-construction, primarily due to the replacement of high-EC materials such as suspended ceilings, which have a lifespan of approximately 25 years and require two replacements during the RSP. In addition, in the college and residential buildings, Module B accounts for the second-highest EC emissions, representing 23.69% and 18.38% of Module A's EC, respectively. In both cases, EC from Module B exceeds that of Module C, underscoring the importance of considering this stage when evaluating WLEC emissions.

4. What is the variation in results between traditional and automated EC assessments?

The variation in results between traditional and automated EC assessments is minimal in terms of accuracy. The study compared manual EC calculations with an automated approach that integrates BIM and LCA using Dynamo and Python scripting. The results showed that the automated method achieved over 98% alignment with the traditional approach, with discrepancies consistently below 2%, confirming its reliability.

The most notable variations between the two methods were observed in specific building components. In the educational building, discrepancies were highest for ceilings during A5w (0.77%) and C2 (0.74%), columns during A5w (1.72%), and foundations during A5w (0.69%). In the hotel building, the largest differences were found in windows during B4 (0.78%), doors during B4 (0.75%), and ceilings during A4, C2, and C3-C4 (ranging from 0.67% to 0.72%). The observed variations typically within 2% are likely due to differences in the decimal precision of the material quantities used in the calculations. To minimise this, a standardised level of precision and rounding could be applied across both methods.

5. **How much automating the EC assessment speed up the analysis?**

Automating EC assessment significantly speeds up the analysis process. The research found that the automated method, integrating BIM with LCA using Dynamo and Python scripting, reduced assessment time from over 200 hours in manual calculations to just minutes. This drastic improvement in efficiency makes EC assessment more practical and scalable for industry adoption, enabling quicker decision-making and streamlined sustainability assessments across building projects.

7.2 Limitation of the work

While this study provides a comprehensive view of EC assessment and reduction strategies, certain limitations must be acknowledged. The feasibility of material substitution strategies depends on the market availability of low-carbon materials, particularly, which is critical to the effectiveness of EC reduction efforts.

Another limitation is the reliance on formulas suggested by RICS for estimating EC in Module C, as end-of-life strategies for some construction materials in the UK remain undocumented. There is a limited end-of-life strategy of materials available, which may affect the accuracy of EC estimations in this phase. Additionally, expanding EC data for recycled-content materials would provide more opportunities for optimizing EC reduction.

Additionally, economic factors such as cost fluctuations in sustainable materials and financial incentives for low-carbon construction could impact the practicality and large-scale adoption of the proposed strategies. Future research could further explore these evolving factors to enhance the effectiveness and applicability of EC reduction approaches.

7.3 Future work

Future research could focus on improving the feasibility and implementation of EC reduction strategies by addressing key limitations identified in this study. One area is the market availability of low-carbon materials, such as GGBS and recycled aluminium. Future studies could investigate regional and global supply chain challenges, explore strategies to enhance the production capacity of these materials, and assess how industry adoption can be increased to support large-scale implementation.

Another important area for further research is improving the accuracy of EC estimations in Module C (end-of-life stage). While this study has gathered information on end-of-life strategies for some key materials, the data remains incomplete for some construction materials in the UK. As a result, the research still relies on RICS formulas to estimate EC in this phase. Future work could focus on expanding real-world data collection on material disposal, recycling, and reuse pathways to develop more precise and representative EC calculations.

Future research could also assess the impact of cost fluctuations in sustainable materials and the role of government incentives, carbon taxation, and financial policies in encouraging the use of low-carbon construction methods. By developing economic models and policy recommendations, researchers can help ensure that EC reduction strategies remain both financially viable and scalable.

Future research could also explore how AI can improve material selection to reduce EC in buildings. AI can help identify low-carbon materials more efficiently by analysing large databases and suggesting sustainable alternatives based on EC emission, cost, and availability. Additionally, AI-powered tools could provide real-time recommendations for choosing materials that balance sustainability and performance. Future work could focus on integrating AI into design and construction processes, allowing for smarter material choices that minimize EC while maintaining quality.

7.4 Policy Recommendations

The findings of this study emphasise the critical need for governmental actions to minimize EC emissions in the UK building sector. Given that buildings account for around 39% of energy-related carbon emissions, it is critical to design a legislative framework that supports sustainable construction practices while remaining consistent with the UK's net-zero 2050 target. Based on the findings of this research, the following policy recommendations are proposed:

- **Mandatory WLEC Assessments**: All new buildings must undergo WLEC assessments to ensure EC emissions are accounted for at every stage of the building’s lifecycle. These assessments should be embedded within building regulations and planning approvals, making designers to create buildings with minimized EC at all phases of their lifespan.
- **Standardized EC Calculation Methods**: A national EC database should be introduced to provide a uniform and transparent WLEC assessment, reducing discrepancies in assessment results.
- **Encouraging Low-Carbon Materials**: As demonstrated in this research, incorporating low-carbon materials, such as sustainable concrete, can significantly reduce WLEC in buildings. Offering tax incentives and subsidies for the use of these materials in both

public and private construction projects would be an effective policy measure to promote sustainability and drive widespread adoption.

- **Recycling and Reuse Requirements**: Given the reduction in WLEC achieved using recycled and reused materials, policies should mandate a minimum percentage of recycled content in all new constructions and major renovations. This requirement will drive circular economy practices, which aim to keep materials and products in use through reuse, recycling, and regeneration. This approach helps minimize resource depletion and contributes to achieving net-zero carbon goals.
- **BIM-LCA integration for EC Tracking**: Given the high accuracy of automated BIM-LCA integration in WLEC assessments compared to manual methods, along with the substantial time savings it offers, it is recommended to mandate BIM-LCA integration in buildings. This will enable real-time EC tracking throughout the design and construction phases, ensuring more efficient and precise EC management.

7.5 Research findings in a list

The research questions were all answered and a brief summary of them was provided in Section 7.1. Below is the list of research findings for a quick reference:

- A key finding of this study was the significant discrepancy between the BEIS and Enhanced databases, primarily due to the limited level of detail in the BEIS dataset. Its use of broad, generic values fails to account for variations in material specifications, resulting in less accurate EC assessments compared to the more comprehensive Enhanced database.
- The difference in EC assessment results between the traditional and automated methods was mainly due to differences in the decimal precision of the material quantities used in the calculations. The automated method, using more precise and structured data, produced more accurate and consistent outcomes.

- The variation in EC values for concrete materials ranged from -36.13% to 60.54%, depending on material type and reinforcement. This discrepancy was primarily due to the absence of precise material specifications in the assessment data.
- Module A has the largest share of EC, significantly surpassing the other two modules. Following Module A, Module B ranks as the second highest, while Module C exhibits the lowest proportion of EC.
- Module B's EC during building's maintenance, repair, and replacement phases is 18.38%, 23.69%, and 38.33% of Module A's EC for residential, educational, and hotel buildings, respectively.
- Timber materials exhibit higher C3-C4 emissions compared to other materials, due to the energy consumed during the incineration and recycling processes.
- Timber materials resulted in significant EC savings beyond the LCA boundary (Module D), ranging from 16.18% to 50.42% of their original emissions. These savings are attributed to the recycling of timber materials, as well as the displacement of fossil fuels through energy recovery during incineration.
- Metal materials also demonstrated substantial EC savings beyond the LCA boundary, with reductions ranging from 8.05% to 18.85% of their original emissions. These savings are primarily due to the high recyclability of metals, which enables them to be reused in future production cycles, thereby offsetting the need for virgin material and reducing associated emissions.
- The integration of BIM and LCA enabled automated WLEC assessments for the London College and Hotel buildings, demonstrating below 2% difference compared to manual calculations, primarily due to decimal differences in the material quantity data used.
- BIM-LCA automation reduced assessment time by over 90%, significantly improving efficiency by eliminating manual data entry and calculations through automated extraction and processing of material quantities.

- The use of a colour-coded system to visualise EC distribution ranging from green for low emissions to red for high proved effective in quickly identifying carbon-intensive building components, supporting faster decision-making and more informed material selection.
- The implementation of green roofing systems in hotel buildings proved to be an effective carbon mitigation strategy, reducing emissions by 59,758.87 kgCO_2e in the case study. In addition to lowering embodied and operational carbon, green roofs extended the lifespan of the base roof and improved energy efficiency, particularly in buildings with poor insulation. With a cost representing just 3.71% of the total building budget, the investment was found to be both environmentally and financially justified.
- Concrete materials in all three case studies had the most significant impact on reducing the buildings' WLEC emissions. The adoption of a 50% cement and 50% GGBS mixture as an EC reduction strategy substantially decreased carbon emissions, with reductions of 12.91% in the residential building, 27.84% in the college building, and 10.02% in the hotel building. Using recycled metal materials also contributed to EC reductions, 2.52% in the residential building, 5.2% in the college building, and 4.64% in the hotel building. The utilisation of reclaimed bricks resulted in further reductions of 6.37%, 2.05%, and 3.05% in the residential, college, and hotel buildings, respectively. Additionally, EPS insulation made from 100% recycled materials provided minor reductions in EC emissions, 0.73% in the residential building, 0.08% in the college, and 0.01% in the hotel building.

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