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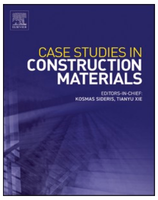

Case study

Materials and service lives alterations impacts on reducing the whole life embodied carbon of buildings: A case study of a student accommodation development in Ireland

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ABSTRACT

To meet the growing demand for student accommodations and fulfil climate change targets, it is essential to establish a methodology for evaluating and reducing their whole-life embodied carbon (WLEC) emissions. The study aims to develop a robust methodology for assessing and reducing the WLEC emissions of a new student accommodation development in Ireland as a replicable case study for other countries. The developed method is based on EN 15978 building whole life cycle standard and EU Level(s) framework. The reduction methodology based on hotspot analysis identifies the most impactful life cycle modules and materials. WLEC assessments were performed on an actual project with two base case scenarios: blockwork (BW) walls for the tender stage and precast walls (PC) for the as-built stage. The WLEC emissions were 749 $kgCO_2e/m^2$ for the BW and 838 $kgCO_2e/m^2$ for the PC. The production stage modules (A1-A3) and the replacement module (B4) were the primary contributors, with 56 % and 34 %, respectively. The proposed WLEC reduction methodology altered the concrete and the rebar with lower EC alternatives available in the Irish market. It modified the service life of seven building elements to align with the manufacturer's standards. Consequently, the WBEC emissions were reduced by 27 % and 33 % for the BW and PC scenarios. This methodology promotes low-EC and durable alternatives to replace conventional materials for the upcoming student accommodation projects in Ireland to achieve the Climate Action Plan EC reduction target by 2030.

1. Introduction

By 2030, greenhouse gas (GHG) emissions must be cut by 55 % from 1990 levels according to the European Climate Law's intermediate goal [1]. This goal aligns with the European Union's objective of achieving zero emissions by 2050 [2,3]. Worldwide buildings account for roughly 37 % of total GHG emissions [4]. Therefore, the world must prioritise the reduction of GHG emissions from the built environment. Approximately one-third of the buildings' GHG emissions are embodied carbon (EC) attributed to the

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extraction, manufacturing, transportation, installation, and disposal of materials [4]. Based on the Paris Agreement targets, by 2030, the Climate Action Plan aims to reduce the amount of EC emissions in buildings by 30 % [5,6]. Material substitution and fuel switching are some of the proposed strategies to accomplish this goal [6].

Currently, many countries have no specific legislation regulating the EC emissions of buildings [7]. In Ireland, the Royal Institute of the Architects of Ireland (RIAI) established an ambitious 2030 EC emissions target that aims for maximum EC emissions of 450 $kgCO_2e/m^2$ for residential buildings with a floor area above 133 m^2. Moreover, Röck et al. [8] developed an EC emissions benchmark for residential buildings in Europe, 400 $kgCO_2e/m^2$. A standardised EC emissions evaluation and reduction methodology must be designed to encourage the countries to have legislation that regulates the EC emissions of their different building typologies.

Life Cycle Assessment (LCA) is a robust tool for evaluating the EC emissions of buildings [9]. Different building LCA approaches were developed; however, there was inconsistency in the system boundary [10]. Birgisdottir et al. [10] collected over 80 building LCA case studies and found that the majority included the production stage modules (A1-A3) and the replacement module (B4). Around 50 % included waste processing and disposal modules (C3-C4), and 44 % included the reuse, recycling and disposal module (D). Around 25 % included the modules of the construction stage (A4-A5), 20 % included deconstruction, demolition and transport modules (C1-C2), however a small percentage included use and maintenance modules (B1-B2).

The same inconsistency is in Ireland, Fig. 1 shows evaluations obtained from previous studies regarding the EC emissions of residential buildings in Ireland [11]. The results were compared to the RIAI domestic EC benchmark and targets. The figure shows the lack of consistency in the system boundaries, which poses a significant challenge to the comparability of these results. Moreover, the studies had varying levels of completeness in terms of the assessed building elements.

The lack of uniformity in LCA boundary or scope emphasises the necessity of implementing a standardised LCA methodology to evaluate the whole-life embodied carbon (WLEC) emissions of the different residential building typologies in Ireland and achieve the reduction targets.

For reducing the WLEC emissions of buildings, several case studies demonstrated that substituting conventional materials with low-carbon materials can reduce emissions significantly. Kanavaris et al. [12] investigated potential reductions in the EC of concrete-framed residential buildings through improvements in materials use and specification. In a scenario involving replacing conventional concrete mixes and typical reinforcing steel "rebar" quantity with concrete mixes containing supplementary cementitious materials (SCMs) and reduced rebar, 40 % reductions of EC emissions were achieved compared to the baseline. Favier et al. (2018) [13] examined scenarios that can significantly reduce the EC of European concrete buildings. One of the scenarios involved the higher use of precast concrete to optimise the EC of the structure, which resulted in a reduction of up to 35 %. The study indicated (< 500 $kgCO_2e/m^2$) as a WLEC emissions limit for concrete buildings in Europe by 2030.

Service life extension and using more durable materials can also decrease the WLEC emissions of buildings. Rauf et al. [14] achieved a 29 % WLEC emissions reduction for a residential building by extending its life from 50 to 150 years [14]. Yokoyama et al. (2015) [15] investigated how extending the building life through a durable structure impacts the building's WLEC emissions. The results show that increasing the covering thickness of concrete for reinforcing steel increased the structure's durability and reduced the building WLEC emissions by up to 30 % [15].

Considering the growing global demand for constructing additional student accommodation developments by 2030 without a specific LCA standard or WLEC emissions reduction measures [16], a robust methodology to evaluate and reduce the WLEC emissions of this typology of buildings is crucial to achieving global climate commitments. Therefore, this study aims to develop a standard LCA methodology for assessing and reducing the EC of new student accommodation developments in Ireland as a replicable case study for

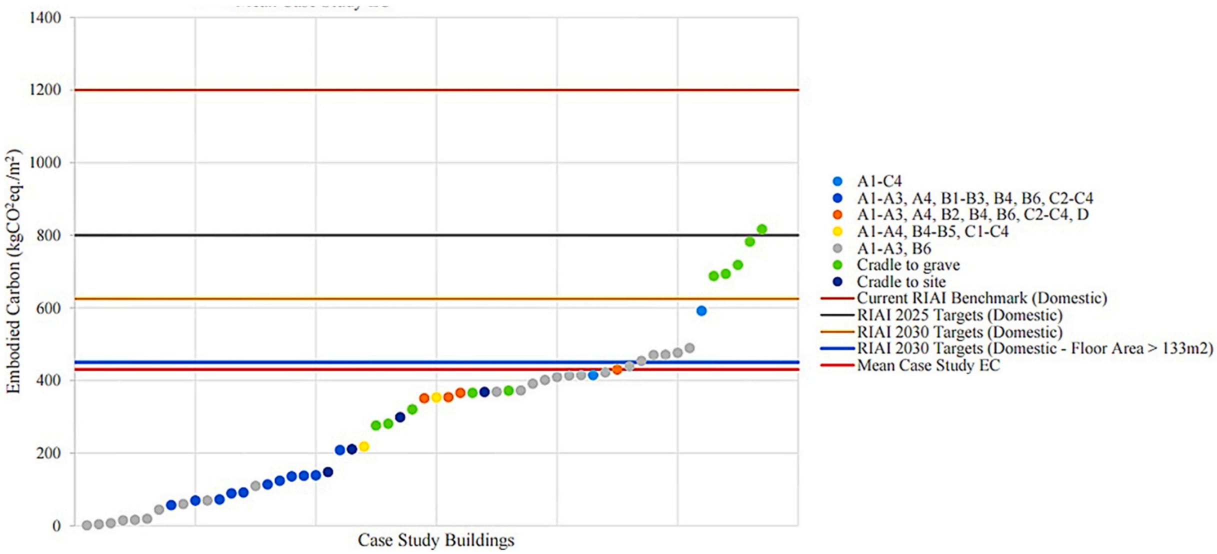

Fig. 1. Embodied carbon values of the residential buildings in Ireland compared to the RIAI domestic EC benchmark and targets [11].

other countries.

The required methodology should be clear and easy to apply based on the available materials, EC data, and assumptions on the national levels. For instance, the construction module (A5) data is challenging to measure accurately as it requires assuming wastage rates for all building materials and the emissions of the onsite construction processes [17]. Moreover, (B1-B3) modules had negligible impact on the WLEC of buildings according to previous studies [18–20], therefore they should be ignored. In addition, (B5 and D) modules consider the emissions for refurbishment and recycling stages, which are often unknown at the design stage of the building. Since student accommodation developments often are built with reinforced concrete structures and blockwork or precast walls, the proposed methodology should consider the EC emissions reduction measures involving concrete and rebar substitutions.

To achieve this aim, the study consisted of four sections; the first section describes the developed methodology for evaluating the WLEC emissions of student accommodation developments throughout a real case study in Ireland. The second section presents the developed method for reducing the WLEC emissions through what-if analyses. The third section discusses and compares the reduction scenarios with a previous case study in the UK and the national WLEC targets. Finally, the conclusion section outlines the key findings of the study.

2. LCA methodology

2.1. LCA standard and framework

The use of LCA is to monitor, report, and regulate the carbon emissions of buildings. Most importantly, LCA studies use an EN or ISO standard to manage their procedures. Several investigations (for instance, [21,22]) comply with the LCA methodology outlined in ISO 14040 [23] and 14044 [24]. Based on this approach, the LCA methodology has 4 phases: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation. The EN 15978:2011 standard provides a comprehensive overview of the whole life cycle of a building, from the extraction of raw materials to its eventual demolition, following a cradle-to-grave approach (Fig. 2). Emissions produced by a building occur at several points throughout its lifetime, including during production (A1–3), construction (A4 and A5), usage (B1–7), and finally, at the end of its life (C1–4). When calculating building LCAs, the EU Level(s) framework bases itself on EN15978. All European environmental performance rules fall under EN 15978 [25].

Level(s) is a European system that evaluates and communicates the sustainability of buildings [26]. Level(s) specifies indicators such as Global Warming Potential (GWP) of a life cycle, measured in CO_2e/m^2/year, and considerations for designing a structure that can be easily deconstructed, reused, and recycled. Level(s) enable researchers conducting LCA studies on buildings to establish a connection between the environmental impact of their facilities and the policy objectives set at the European Union (EU) level [1]. The EN 15978 standard serves as the primary benchmark for Level(s), and all EU countries that have LCA legislation have used this standard as the basis for their LCA calculation regulations [27]. Level(s) is a model that governments can utilise to enact LCA regulations in the construction of buildings.

2.2. LCA of the case study building

The Goldcrest Village student accommodation on the University of Galway campus in Ireland was analysed as a sample using the standardised LCA approach. Goldcrest Village comprises of 429 bed spaces organised into apartments with five or six bedrooms. These

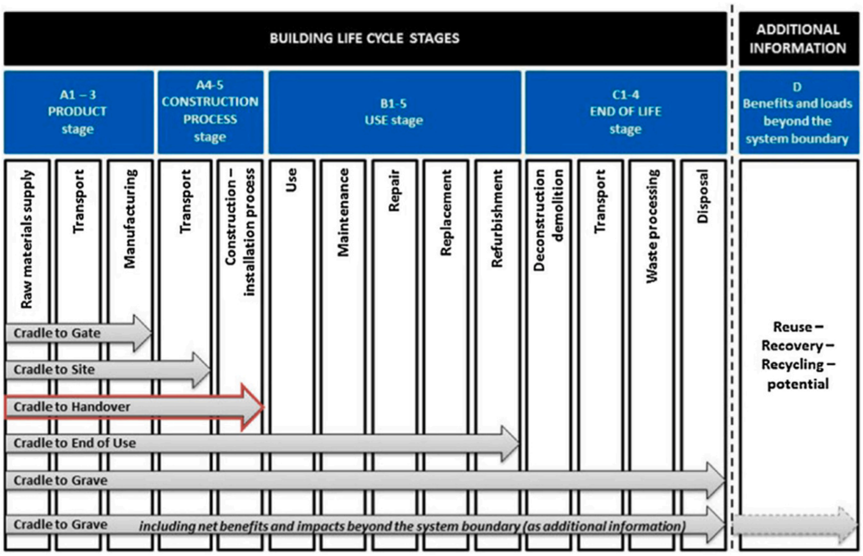

Fig. 2. EN 15978 Building LCA stages and system boundaries [10].

apartments feature shared cooking, dining, and living areas. The project, finalised in 2018, has four separate buildings, designated as blocks A to D. Block A is a block that has five floors, while blocks B, C, and D have four floors (Fig. 3). The combined gross floor space of the four blocks, shared facilities, and reception area is 12,801 m^2. According to the Level(s) User Manual 1.1, Goldcrest Village is in climate zone 4. The consultant electrical and mechanical engineers [28] provided data regarding building services. All bedrooms and living areas benefit from ample natural lighting and ventilation.

A preliminary LCA calculation was conducted utilising the bill of quantities (BOQ) generated during the tender phase. Initially, the structural elements of the building were designed to be concrete in substructure and superstructure, as well as load-bearing concrete blockwork. The initial design proposed for the project involved constructing load-bearing walls, mainly using blockwork and some partition walls. Additionally, metal studs and plasterboard partitions were planned for several internal partitions. The building's different blocks have comparable structural elements. However, the original plan specified that Block A would incorporate a metal standing seam façade system, while Blocks B-D would feature a brick cladding system. In the as-built design, the architectural composition of the building was modified from mostly using blockwork construction within situ beams and columns, as well as precast hollow core flooring, to a complete design of precast concrete. This will reduce the project time and cost since the precast requires lower labour costs and less on-site labour, and the installation will be quicker. These reasons led to a transition from blockwork to precast walls, including extra stud partitions in walls that do not bear any weight.

The literature study reveals a notable absence of uniformity in using LCA approaches to buildings in Ireland. This section outlines implementing a systematic LCA technique to analyse case study building. The LCA methodology adheres to the guidelines provided by ISO standards 14040 [23] and 14044 [24]. To begin with, the phase of defining the purpose and scope is explained. This encompasses the explicit delineation of the floor area utilised, the functional unit, the extent of the investigation, and a detailed portrayal of the building under examination. Additionally, the life cycle inventory (LCI) phase includes all the necessary input data for conducting the LCA, such as material quantities and environmental impact data for the (A1-A3) stage. Ultimately, the methods and information required for the remaining phases are delineated.

2.2.1. *Goal and scope definition*

Regarding the LCA of buildings, this phase determines the building's floor area and service lifespan. Additionally, it delineates the extent of building components and phases of the life cycle that should be incorporated into the analysis.

2.2.1.1. Floor area, service life, and functional unit. This study employs a standardised LCA technique based on the Level(s) framework [29]. The primary purpose of this study is to evaluate the whole-life embodied carbon (WLEC) of student accommodation developments. Adopting a functional unit precisely required defining the specific floor area to be utilised and the expected lifespan of the building. The study assumes a building service life of 50 years based on Level(s) standards. Level(s) refers to the standard functional unit, which measures the EC per square meter of the usable floor area (UFA). The UFA can be defined as an equivalent to the gross internal floor area (GIFA). Appendix A illustrates the method of calculating the UFA for a project [29]. Thus, the WLEC is measured in ($kgCO_2e/m^2$/50 years) for this methodology.

2.2.1.2. Scope of building elements. Appendix B displays the building elements from the Level(s) framework incorporated into the methodology. The current study utilises the building element list associated with the Level(s) framework. The LCA calculation did not consider elements present in the case study building, such as a piling foundation. The study eliminated the sanitary and fittings parts as they were considered beyond its scope. Due to the absence of suitable Mechanical, Electrical, and Plumbing (MEP) carbon data, the EC of the building services was determined based on the Chartered Institution of Building Services Engineers (CIBSE) TM65 estimates. These carbon impact estimates are based on the total weight in kg of the MEP elements [30].

2.2.1.3. System boundary. The complete system boundary encompasses all modules specified in EN15978, spanning from the

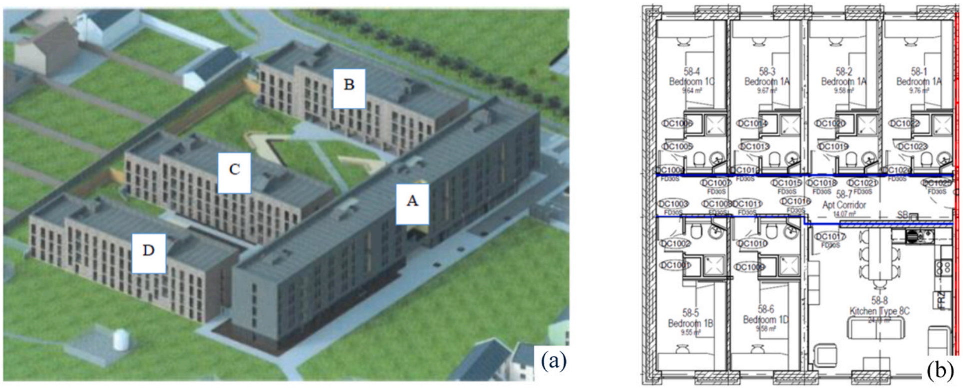

Fig. 3. Goldcrest Village student accommodation; (a) 3D render, (b) Typical six-bedroom apartment [11].

extraction of raw materials to the disposal of End-of-Life (EOL) waste and any additional benefits and burdens that extend beyond the system boundary. However, the methodology does not consider the construction process, module (A5), as it usually has a minimal effect on EC outcomes and is challenging to measure accurately [17]. Moreover, the Use (B1), Maintenance (B2), and Repair (B3) modules were ignored as their influence is negligible [18–20] in contrast to the Replacement module (B4), which is included in the calculations. The refurbishment module (B5) is not considered, as the (B4) module serves as a basic estimate of the material usage of a building during its lifespan [19]. The methodology focuses on evaluating the EC; therefore, it excluded the operational energy use (B6) and operational water use (B7) as they fall beyond the scope. Therefore, the boundary of this methodology includes (A1-A4, B4, and C1-C4) modules only.

2.2.2. *Life cycle inventory (LCI)*

As to the Level(s) user manual 1.2, determining a building's life cycle GWP emissions requires a BOQ for the building design, software, databases, and Environmental Product Declarations (EPDs) for the building materials. Gathering information about building supplies, fuel usage in applicable transportation modes, and EOL-related waste processing and disposal is the focus of the LCI phase. The BOQ, drawings, and BIM models are used to get the quantity data of building materials. The environmental data of materials were gathered from a variety of sources. To determine the EC of materials across their (A1-A3) life cycle stage, carbon factors (CF) were derived from EPDs and generic databases. Providing a clear and concise explanation of assumptions is essential in LCA to guarantee transparency and facilitate comparability. The methodology adopted several assumptions during the building life cycle stages. The Environmental Protection Agency (EPA), among other sources, offered information on the EC for different material types when discarded at their EOL stage [31], which are used to derive some EC assumptions. The following sections detail the assumptions considered at each life cycle stage.

2.2.2.1. Input data and assumptions. The BOQ, architectural and structural drawings, specifications, and BIM models were provided for the case study. The quantities of materials were extracted from the BOQ and entered an Excel spreadsheet. A conversion factor was then used to convert all numbers to kilograms. A closer look at the project specs, drawings, or the BOQ yielded the material specification. All materials (A1-A3) CFs were compiled after the quantities were converted from the BOQ to kilogrammes and entered the Excel sheet. Approximately 1400 rows of data on materials were generated in the Excel sheet to evaluate the EC of the elements in the scope.

2.2.2.2. Production stage (A1-A3) data. The EC of materials in the product stage were determined using (A1-A3) CFs. The criteria were obtained from product-specific EPDs and generic databases. To guarantee the use of accurate and pertinent data, EPDs were employed wherever they were accessible for particular products. If EPDs were not accessible, alternative databases such as the Irish Green Building Council (IGBC) National Inventory of Generic Construction Materials Data (NIGCMD) and the Inventory of Carbon and Energy (ICE version 4) databases were utilised [32,33]. Regarding products made from concrete in Ireland, there is a serious lack of EPDs. When a concrete product EPD was unavailable, the methodology of concrete mix design was used [34]. This applied to both in-situ, precast concrete and concrete blocks.

2.2.2.3. Concrete mix design methodology. Finding a method to determine the (A1-A3) CF for concrete elements was necessary when there were no EPDs for these items. Therefore, the ICE Cement, Mortar, and Concrete Model (version 1.2) [34] was used with the specific blend compositions specified in the project documentation and sourced from local providers to calculate the CF. The user can input a concrete mix design using the Excel spreadsheet model, select the constituent parts, and specify their quantities. Cement, aggregate, and various admixture EC intensities were used in the model, drawing the CF of the concrete element at the end.

Carbon emission variables for in-situ and precast concrete batching and processing, as well as generic transport distances, are included in the model. Modifications were made to the ICE model to incorporate aggregate and cement carbon emission coefficients from Irish EPDs and the IGBCs NIGCMD, making it more relevant to the Irish building industry. The (A1-A3) CFs were sourced from the CEM I (Ordinary Portland Cement) and CEM II/A-L (Ordinary Portland Cement and limestone) EPDs supplied by Irish Cement Manufacturers, and the Ground Granulated Blast Furnace Slag (GGBS) cement EPD from Ecocem, respectively, and were included into the calculator. An (A1-A3) CF was brought in from the NIGCMD for use with CEMII/A-V (Ordinary Portland Cement and fly ash). The average carbon component for the Irish aggregate was obtained from the IGBC website. The transportation distances were calculated by considering the precise locations of the production sites and the sources of the raw materials, which were acquired through discussions with nearby suppliers. Without knowing which provider to use, the ICE calculation used the mix designs' intrinsic transport assumptions derived from the BOQ or specification. Appendix C provides a concrete illustration of a carbon factor calculation for a specific type of concrete block. Appendix D illustrates the results of implementing the concrete mix design approach to various concrete products.

2.2.2.4. Construction transportation module (A4) data and assumptions. All products and materials are transported from the factory gate to the construction site as part of the (A4) life cycle module. This module used various numbers collected from the Product Category Rules (PCR) document maintained by EPD Ireland [35] and the Institution of Structural Engineers (IStructE) [36]. Appendix E displays the road and marine transportation distances obtained from EPD Ireland [35], from a manufacturing to a site in Ireland. Appendix F categorises construction materials into three groups: bulk material (Irish), other materials (Irish), and materials (non-Irish). This facilitates the assumption of material transportation to any place in Ireland, ensuring a consistent (A4) EC outcome for all case studies.

The IStructE EC guide [36] presents CFs for road and sea transportation modalities, which are displayed in Appendix G. The CF are expressed in the unit kgs of CO_2 equivalent per kg of material per km driven. The values in Appendix F are multiplied by the mass of the material to compute the A4 emissions of a material. The A4 module EC was computed using Eq. 1.

$$\mathrm{EC}\ (A4) = Weight \times Distance \times Transport\ (\mathrm{CF}) \tag{1}$$

Where the parameters are:

- EC of (A4) – EC of transport ($kgCO_2e$)
- Weight – material mass (kg)
- Distance – distance travelled (km) between the site of material manufacture and the construction site (Appendix E).
- Transport (CF) – relevant mode of transportation CF ($kgCO_2e/kg.km$) (Appendix F).

2.2.2.5. Replacement module (B4) assumptions. To calculate the EC for the (B4) module, assumptions about the replacement of various building elements during the building's 50-year service life must be made. Each time a replacement occurs, the EC for a specific building element will arise in the production, construction, and EOL stages. The material replacement module (B4) was estimated using default service lives from the Level(s) indication 1.2 user manual [37].

Eq. 2 illustrates the B4 EC calculation.

$$EC(B4) = (EC(A1-A3) + EC(A4) + EC\ (C2-C4)) \times Replacement\ Factor \tag{2}$$

Where the parameters are:

- EC (B4) – EC of replacement ($kgCO_2e$)
- EC (A1-A3) – cradle-to-gate EC of the listed building material ($kgCO_2e/FU$).
- EC (A4) – transport EC of the listed building material from the manufacturer to the site of use

- ($kgCO_2e/FU$).
- EC (C2-C4) – EOL EC of the listed building material, including the transportation from
- the site ($kgCO_2e/FU$).
- Replacement Factor – number of expected replacement cycles of a building material over the building service life. Calculated using Eq. 3.

The replacement factor was determined by utilising the projected lifespan of the building (50 years) and the anticipated lifespan of the building components.

$$Replacment\ Factor = (Building\ Service\ Life/Material\ Service\ Life) - 1 \tag{3}$$

Appendix G presents the recommended service life of building elements at different levels when service lives for individual products are unknown. The service lives were included in the LCA calculation as a factor for replacement. As in the appendix, it was anticipated that all painting and coating would completely change after 10 years. Therefore, a replacement factor of four was applied to account for a building's service life of 50 years.

2.2.2.6. End of life stage (C1-C4) assumptions. Some assumptions went into determining the amount of EC in the building's end-of-life stage. For module (C1), the methodology adopted the Royal Institution of Civil Engineers (RICS) carbon emissions factor developed for demolition after reviewing case studies in London [38]. The CF of the demolition is 3.4 $kgCO_2e/m^2$ of GIFA. For modules (C2, C3, and C4), a waste treatment scenario is presumed for each type of material, relying on EPA building and demolition waste statistics specific to Ireland [31]. The EPA statistics are utilised to ascertain the proportionate distribution of EOL treatment scenarios, as depicted in Appendix H. These statistics are combined with the data presented in Appendix I and Appendix J to compute the emissions related to the transportation, processing, and disposal of buildings via their EOL stage.

Eq. 4 represents the calculation of the EC for the C2 module.

$$EC\ C2 = Weight \times Distance \times Transport\ CF \tag{4}$$

Where the parameters are:

- EC C2 – EC of EOL transport ($kgCO_2e$)
- Weight – material mass (kg)
- Distance – distance travelled (km) from site of material use to EOL treatment (Appendix I)
- Transport EF - relevant mode of transportation CF ($kgCO_2e/kg.km$) (Appendix J)

  Appendix J provides CFs for waste disposal methods. The values represent the CO_2e emitted per kg of each material type. The criteria were extracted from the GHG Reporting Conversion criteria 2022 dataset [39], which is sourced from the Department for Energy Security and Net Zero of the United Kingdom (UK). Eq. 5 provides a method for computing the EC of the C3 and C4 modules.

$$EC(C3-C4) = \Sigma\ Weight \times (EOL\ Scenario \times \text{Waste Management}\ (CF)) \tag{5}$$

Where the parameters are:

- EC (C3-C4) – EC of waste processing and disposal scenarios ($kgCO_2e$)
- Weight – material mass (kg)
- EOL Scenario – percentage of the material functional unit allocated to the stated EOL

- treatment scenario in Appendix H.
- Waste Management CF – EC CF ($kgCO_2e$) per functional unit for the stated EOL

treatment scenario (Appendix J).

Table 1 summarizes the characteristics of the developed methodology, which can be modified to evaluate similar case studies in other countries. The modifications will replace the Irish data sources in the modules with equivalent national data according to the country where the case study is located.

2.2.3. WLEC assessment and interpretation

When more EC data is provided during the LCI phase, the LCA results can be better understood in terms of their GWP impact. For the interpretation phase, a hotspot analysis was performed on the LCI data to identify the most impactful life cycle stages and materials and their contribution to the building's WLEC. In addition, it helps to develop scenarios throughout "what-if analyses" that can greatly enhance the reduction of the WLEC.

2.2.3.1. The WLEC result of tender design (BW). In Fig. 4, the WLEC of the tender design (BW) is 749 $kgCO_2e/m^2$, and the EC during the (A1-A3) stage accounts for 56 % of the WLEC. The replacement module (B4) accounts for a substantial portion of the BW design WLEC, around 34 %, due to the Level(s) default element service lives. When combined, approximately 90 % of the building's WLEC comprises the (A1-A3) and (B4) modules. The (A4) module of product transportation accounts for 6 % of the building WLEC, which is relatively small. The EC of the (A4) module can be significantly influenced by the procurement decisions made during the construction process. Since the EOL stage (C1-C4) contribution is 4 % and the (C2) module has the highest quantity of EC within the EOL stage, accurate project-specific transport distances are needed to evaluate and reduce them in the future.

2.2.3.2. The WLEC result of as-built design (PC). In Fig. 4, the precast as-built design yielded a WLEC outcome of 839 $kgCO_2e/m^2$, surpassing that of the blockwork tender design. The EC induced by the life cycle modules (A1-A3) constitutes 55 % of the WLEC, while module (B4) makes a substantial contribution of 35 %. Similar to the BW design, the (A1-A3) and B4 life cycle modules collectively account for 90 % of the WLEC of the building. This indicates that these modules should be prioritised in the potential reduction scenarios. Module (A4) is responsible for 6 %, whereas the (C1-C4) modules are responsible for 4 % of the WLEC. The transportation of waste (C2) has the most significant contribution (66 %) to the EOL stage EC.

2.2.3.3. Materials hotspot analysis. After calculating the WLEC of the base case designs (BW and PC) using the developed LCA methodology and obtaining the results, a hotspot analysis is required to identify the materials with the most significant shares in the WLEC. Appendices K-P provide a detailed breakdown of the EC of the building materials in BW and PC designs during (A1-A3), A4, B4, and (C2-C4) modules. Fig. 5 shows both designs' (A1-A3) EC divided by material category. The "Other" category includes floor and wall tiles, tile adhesives, vinyl floor covering, entry matting, and similar products. The (A1-A3) stage is mostly dominated by concrete and steel, as these materials were used in substantial quantities in the foundations and superstructure, significantly impacting the building WLEC. Windows, external doors, and curtain walls are mostly made from aluminium and glass, making them considerable contributors to the WLEC. In module (B4), the concrete continues to be the primary contributor, as in Level(s), the interior walls, stairs, ground floor slab, and roof slab must be replaced every 30 years.

Table 1
The characteristics of the developed methodology.

Standard and Framework		ISO 14040/14044 & EN 15978:2011 & EU Level(s) framework
Goal		Whole-life Embodied Carbon assessment
Scope		Building elements in Level(s) framework
Functional Unit (lifespan)		$kgCO_2e/m^2$ (50 years)
Boundary	**A1-A3**	BOQ/drawings/BIM models to get materials quantities and specs – Generic databases/EPDs/Concrete Mix Design Methodology to get CF
	A4	PCR EPD Ireland & IStructE
	B4	Default service lives from the Level(s) indication 1.2 user manual
	C1	RICS carbon emissions factor for demolition
	C2-C4	EPA building and demolition waste statistics specific to Ireland (CFs) for waste disposal methods

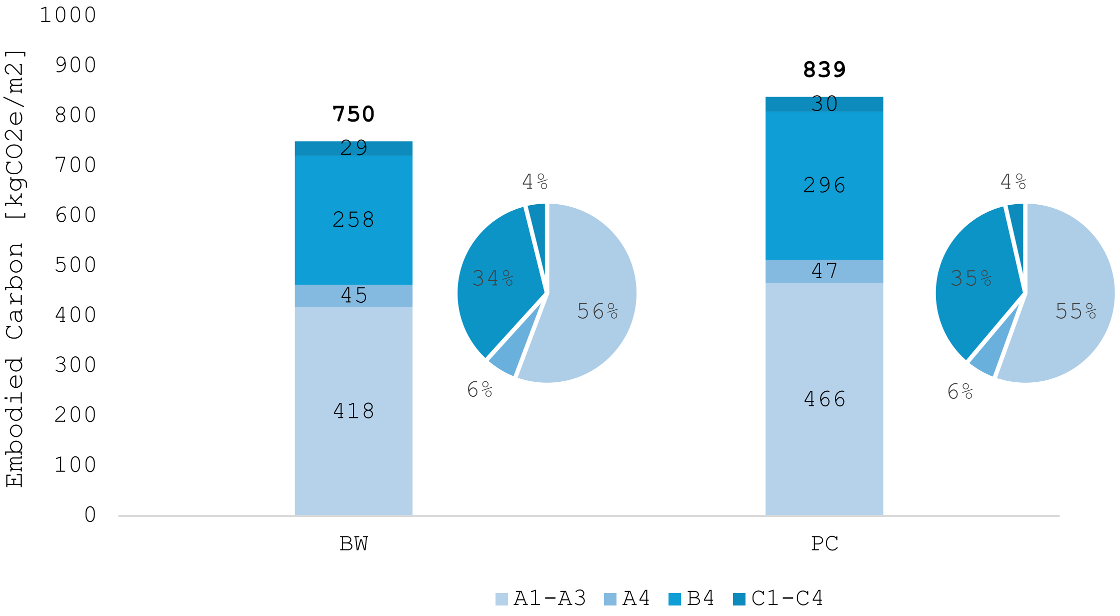

Fig. 4. WLEC and life cycle modules contributions for the tender (BW) and the as-built (PC).

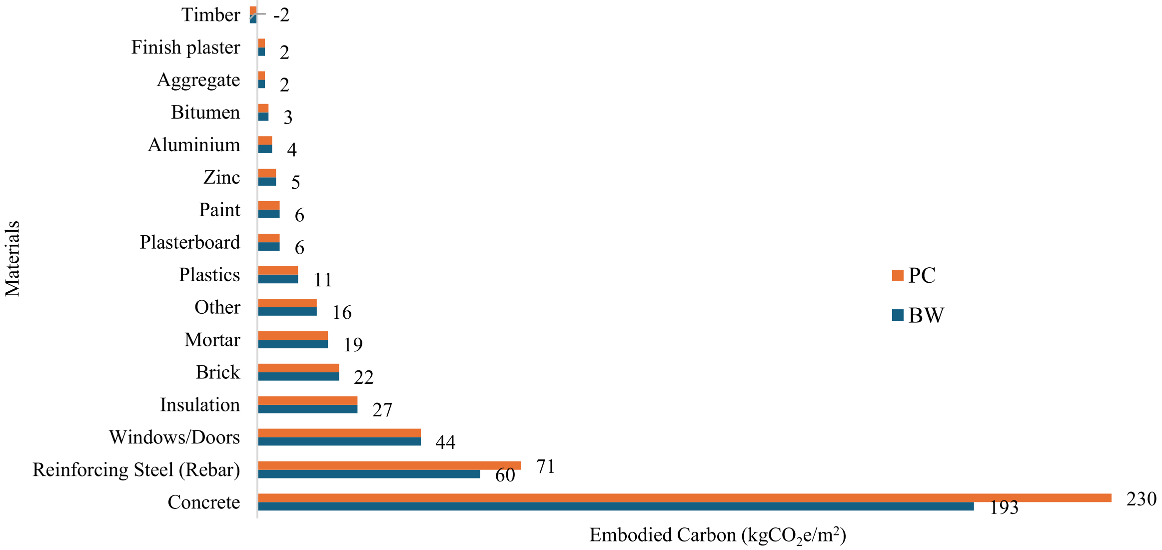

Fig. 5. (A1-A3) Embodied carbon contributions by the building materials for the BW and PC designs.

3. WLEC reduction methodology “what-if analyses”

3.1. *What-if analysis of the tender design*

Hotspot analysis was used to evaluate the assumptions for each life cycle module. At first, it was found that several building elements did not have suitable default Level(s) service lifetimes in the B4 replacement module. Certain construction elements had their service lifetimes adjusted after a thorough evaluation of those lifetimes. The project also included material substitution on some structural components to evaluate the possibility of EC reductions. Throughout the material replacement method, the authors focused on the carbon emissions for the production stage (A1-A3).

3.1.1. *Modifications to the service lives of building elements*

The second most crucial life cycle step that contributed to the building’s EC was the replacement module (B4). The study aims to assess the impact of using the actual higher values for the service lives of the building’s elements on the whole life EC of the building.

The service lives of materials in Level(s) were modified to align with the manufacturer's standards, resulting in fewer replacements during the use stage. The projected service lives of the building elements were determined by examining EPDs, technical data sheets, and manufacturers' warranties. If the actual service life of the building element exceeded 50 years, it would be aligned with the service life of the building, hence eliminating the need for replacements. Table 2 displays the building elements that underwent modifications to their service life.

During the building's use stage, it was determined that the façade elements would not be replaced unless a significant refurbishment was performed. These façade elements include the insulation, supplementary materials, and zinc façade for Block A and the brick cladding and shading systems for Blocks B, C, and D. They were given a 30-year service life within Level(s) assumptions. After reviewing their EPDs, with more certainty their service life will last for 50 years. Thus, there will be no mandatory replacement during the use stage.

Timber, steel, and in-situ concrete slabs were used to construct the building's roof. It was anticipated that these components would remain in good condition for the duration of the building's 50-year lifespan. However, the projected service life for the roof weatherproofing was less than 50 years due to the expected damage to the roofing and sealants. Thus, the roof weatherproofing service life had not been changed. Thistle bonding and skim coatings, mortar, plasterboard, mineral wool insulation, and metal stud framing were used in ceiling and wall finish. It was deemed improbable that these components would be substituted during the building's lifespan because of their durability, as indicated by their EPDs, which exceeded the building's lifespan.

3.1.2. Material substitution

According to the LCA results, the most harmful stages of the life cycle to the environment were (A1-A3). In the tender design, the key impactful elements are foundations, superstructure, exterior walls, and facades. Subsequently, research was conducted to identify Irish market materials that may be used as a low-carbon alternative without altering the building's structural design. The impact of more sustainable mix designs on the environment was evaluated by calculating the CFs for various blocks and concrete element mix designs. The authors communicated with a concrete provider in Ireland to collect the mix designs for ready-mix concrete and concrete blocks incorporating GGBS [40]. As stated in the BOQ, the mix design for C30/37 and C32/40 concrete was used in the tender stage design, with 50 % Ordinary Portland Cement (OPC) and 50 % GGBS made up the cement part of this mixture. Moreover, an EPD for the high-density concrete block was used. The authors communicated with the supplier to get mix designs for the ready-mix concrete products incorporating 65 % GGBS. The supplier provided the mix design of the 13 N low-carbon block, which is composed of a mixture of 50 % GGBS, 50 % CEMII/A-L cement, and Accelor8 [41]. Accelor8 is a hardening accelerating additive specifically for use with GGBS cement in precast concrete products. With the mix designs provided in the BOQ and the 65 % GGBS mixes, a CF was calculated for the in-situ C30/37 and C32/40 concrete. The chemical compositions of the 13 N low-carbon building blocks were determined. The typical rebar factor in Ireland was used for the concrete elements. The EPD of XCarb rebar exhibited a significant carbon reduction over the (A1-A3) phases. Table 3 illustrates the (A1-A3) CFs of the original and the alternative low-carbon materials.

3.2. What-if analysis of the as-built design

The as-built design included solid and precast concrete for the load-bearing walls, while the non-load-bearing walls were plasterboard with metal studs. The floor and roof constructions comprised precast hollow core slabs and a few in-situ slabs. The carbon data for the precast wall systems were sourced from the manufacturer. This included the different precast components and their individual formula and durability categories. Furthermore, schedules and reinforcement drawings were taken from a similar project. Based on correspondence with the design engineer, it was presumed that the quantity of rebar in the solid precast walls was the same as that in the twin walls.

An in-depth analysis differentiating between exterior and interior walls was applied using the BOQ and the Revit models for the as-built design to evaluate the EC of the exterior and interior walls. To further guarantee consistency with the as-constructed Revit models, the quantities obtained from Revit were cross-checked with the original BOQ to confirm that the ratio of outside to interior walls remained unchanged. The quantities of the exterior doors, windows, and curtain walls called from the CAD drawings. The carbon data of the supplied doors, windows, and curtain walls were provided by the specific product EPDs.

The same updated service lives and low-carbon alternative materials were used for the materials in the tender design. In addition, two more materials were substituted, including Precast concrete twin and solid walls C40/50 and Precast concrete twin wall in-situ infill C32/40. A mixture of 65 % GGBS and 35 % CEM II was used instead of the twin and solid wall mixtures. Table 4 displays the material replacement, including the original and the low-carbon alternative materials.

Table 2
Projected alterations to the lifespan of the elements in the tender design.

Building parts	Related building elements	Level(s) Service Life (yrs)	Altered Service Life (yrs)
Non-load bearing elements	Ground floor slab Internal walls, partitions, doors Stairs and ramps	30	50
Facades	External wall systems, cladding and shading devices		
Roof	Structure (Timber, steel, and in-situ concrete slabs)		
Fittings and furnishings	Ceiling and wall finish		

Table 3
(A1-A3) carbon factors for the original and the alternative low-carbon materials for the tender design.

Original Material	(A1-A3) CF[$kgCO_2e/kg$]	Alternative low-carbon Material	(A1-A3) CF[$kgCO_2e/kg$]
In-situ concrete (C30/37)	0.0639	In-situ concrete (C30/37) with (65 % GGBS)	0.0462
In-situ concrete (C32/40)	0.0660	In-situ concrete (C32/40) with (65 % GGBS)	0.0488
High density blockwork (13 N)	0.0725	13 N low-carbon block (50 % GGBS, 50 % CEMII/A-L cement, and Accelor8)	0.0505
Rebar	0.7370	XCarb rebar	0.3000

Table 5 presents the baselines and the generated modified scenarios. Blockwork (BW1) is the base case of the tender stage of the project. The (BW2) scenario involves the modified service lives of building elements. Scenario (BW3) involves the changes in the service lives of building elements and the substitution of materials. The PC scenarios refer to the building for its as-built precast concrete configuration where the primary alteration involved the substitution of blockwork with precast concrete walls. Precast (PC1) is the base case scenario for the as-built design. The (PC2) scenario utilises the modified service life of building elements. Scenario (PC3) incorporated modified service lifespans and material replacements.

4. Results of reduction and discussion

This section discusses and compares the scenarios' results to evaluate the proposed reduction methodology. The results were also compared with similar results for building typologies in previous studies. Moreover, the results were examined against RIAI's benchmark and objectives.

4.1. Evaluation of each scenario and the potential EC reduction

In Fig. 6, the WLEC outcomes for the 50-year lifespan of a building are expressed in $kgCO_2e/m^2$ for each scenario. BW3 scenario incorporated the lowest EC materials to get the most minimal WLEC with 544 $kgCO_2e/m^2$ compared to the other scenarios, which were more harmful to the environment. A reduction of 295 $kgCO_2e/m^2$ (35 %) exists between the most impactful scenario (PC1) and the BW3 scenario. Significant WLEC reductions occurred in BW2 and PC2 scenarios because the building element service lives were extended in the tender and as-built designs. There is a 22 % drop in the WLEC from BW1 to BW2 and a 23 % drop from PC1 to PC2. While there is a 27 % reduction between the BW1 and BW3 scenarios, the PC3 scenario is 33 % smaller than the PC1 scenario. Accordingly, the reduction methodology appears more effective in precast construction due to the significant reductions in concrete elements. In the tender design scenarios, there is a 7.5 % reduction between the BW2 and BW3 scenarios while just considering material substitution. In the as-built scenarios, the WLEC in PC3 was decreased by 13 % compared to the PC2 scenario. The more significant reduction in the precast design can be attributed to the exclusive utilisation of 100 % CEM II in the concrete mixture for precast elements. Integrating GGBS notably impacted reducing the EC in the precast concrete walls. However, the tender design scenario (BW3) only used 50 % GGBS in the blockwork, which limited the possible decrease in the WLEC due to the inability to add more GGBS to these mix designs.

The EC contribution of each life cycle stage for the analysed scenarios shows that the EC is consistently the highest at the production stage (A1-A3) regardless of the scenarios. In the (A1-A3) stage of the blockwork scenario, a decrease of 10 % was achieved in BW3 by using low-carbon carbon concrete, blocks, and rebar. In the precast scenario, a reduction of 18 % was achieved in the (A1-A3) stage of PC3. The literature review indicated that the earliest stage (A1-A5) of a building accounts for about 66 % of the EC during the life cycle. Approximately 62 % of the WLEC in the BW1 and PC2 scenarios came from the (A1-A4) modules, while 76–79 % of the EC in BW2, BW3, PC2, and PC3 came from the same modules. In the base case scenarios (BW1 and PC1) where the default element service lives mentioned in Levels were used, over one-third of the WLEC is attributable to the replacement module (B4). Consequently, when considering the phases with varying service life, the influence of B4 was lessened. B4 accounts for around 35 % of the WLEC in the BW1 and PC1 scenarios; however, it only accounts for about 16 % in the BW2 and PC2 scenarios.

The EC of the transportation to site (A4) and the end-of-life (EOL) (C1-C4) stage are consistent in the tender and the as-built

Table 4
Replacement of materials performed for as-built design analysis.

Original Material	(A1-A3) CF [$kgCO_2e/$ kg]	Alternative low-carbon Material	(A1-A3) CF [$kgCO_2e/$ kg]
In-situ concrete – C30/37	0.0639	In-situ concrete (C30/37) with (65 % GGBS)	0.0462
In-situ concrete – C32/40	0.0660	In-situ concrete (C32/40) with (65 % GGBS)	0.0488
High density blockwork (13 N)	0.0725	13 N low-carbon block (50 % GGBS, 50 % CEMII/A-L cement, and Accelor8)	0.0505
Rebar	0.7370	XCarb rebar	0.3000
Precast concrete twin and solid walls C40/50	0.140	Precast concrete twin and solid walls C40/50 with (65 % GGBS and 35 % CEM II)	0.073
Precast concrete twin wall in-situ infill C32/40	0.115	Precast concrete twin wall in-situ infill C32/40 with (65 % GGBS and 35 % CEM II)	0.054

Table 5
Summary of case study base cases and generated modified scenarios.

Stage	Goldcrest Village Scenario	Structural Materials	A1-A3 Carbon Factor Sources	B4 Stage Assumptions
Tender	BW1 (Tender base case) BW2 BW3	-Blockwork walls -In-situ concrete -Rebar	- Concrete blocks - In-situ concrete - Rebar - 50 % GGBS concrete blocks - 65 % GGBS in-situ concrete - Low-carbon rebar	Level(s) default service lives (30 years) Altered service lives (50 years) Altered service lives (50 years)
As built	PC1 (As-built base case) PC2 PC3	Precast walls, in situ concrete substructure	- Precast concrete - In-situ concrete - Rebar - 65 % GGBS precast concrete - 65 % GGBS in-situ concrete - Low-carbon rebar	Level(s) default service lives (30 years) Altered service lives (50 years) Altered service lives (50 years)

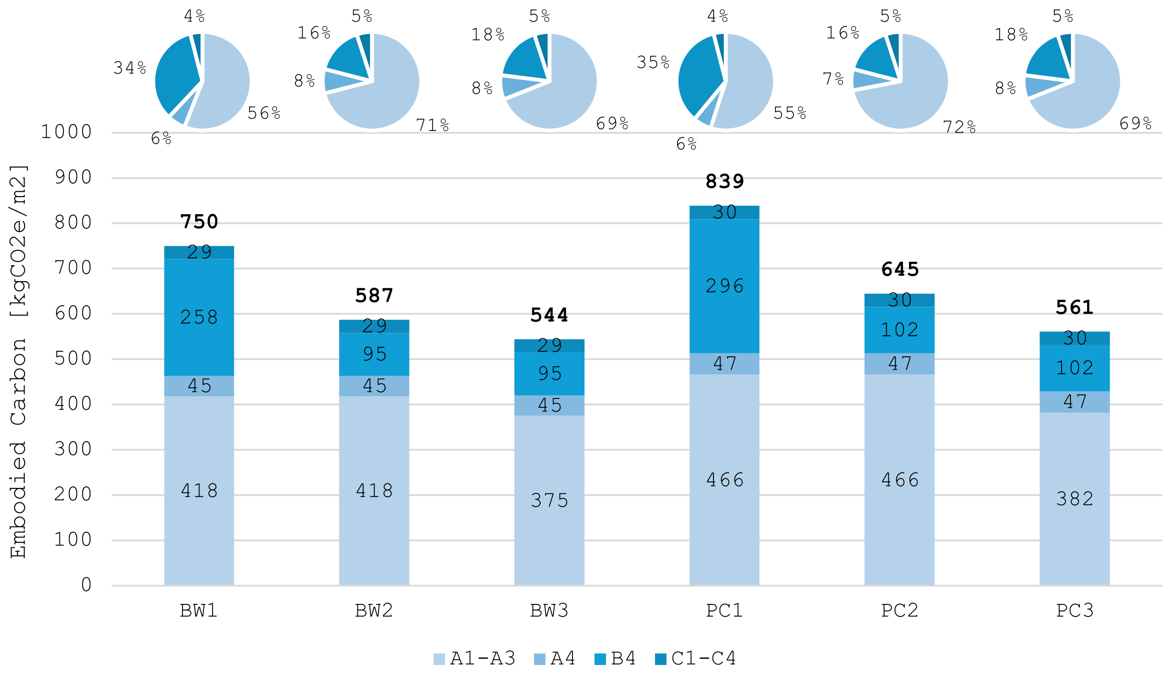

Fig. 6. WLEC and life cycle modules contributions for each scenario.

scenarios. In all scenarios, the WLEC contribution from the EOL stage stays below 6 %. These phases have a far more negligible environmental effect than the product and use phases. The quantities of materials could explain the small differences in the tender and the as-built scenarios, which differ slightly.

4.2. Comparison to a similar case study in the UK

The WLEC results were compared to a similar case study from the literature review in the UK. A 2250 m^2 student residential building consisted of 4 storeys above ground. The EC results of the two design options were 486 and 420 $kgCO_2e/m^2$ for the reinforced concrete (RC) and the blockwork (BW), respectively [42]. Fig. 7 compares the results of the Goldcrest Village scenarios to the UK case study design options. The primary methodological distinction between the UK study and the current study is that the UK study considered the A and C life cycle phases only. Including the (B4) module in the Goldcrest Village scenarios significantly increased the WLEC results. This is a probable explanation for the lower WLEC results observed in the UK study. Regarding the choice between RC and BW, the UK study shows a lower WLEC outcome for the RC option. This is because the RC used in the UK study is C25/30, which is not as harmful as the precast wall panels used in the Goldcrest Village. The RC option in the UK study was also made with blockwork wall partitions, which also had a lower EC compared to the solid precast walls utilised in the Goldcrest Village.

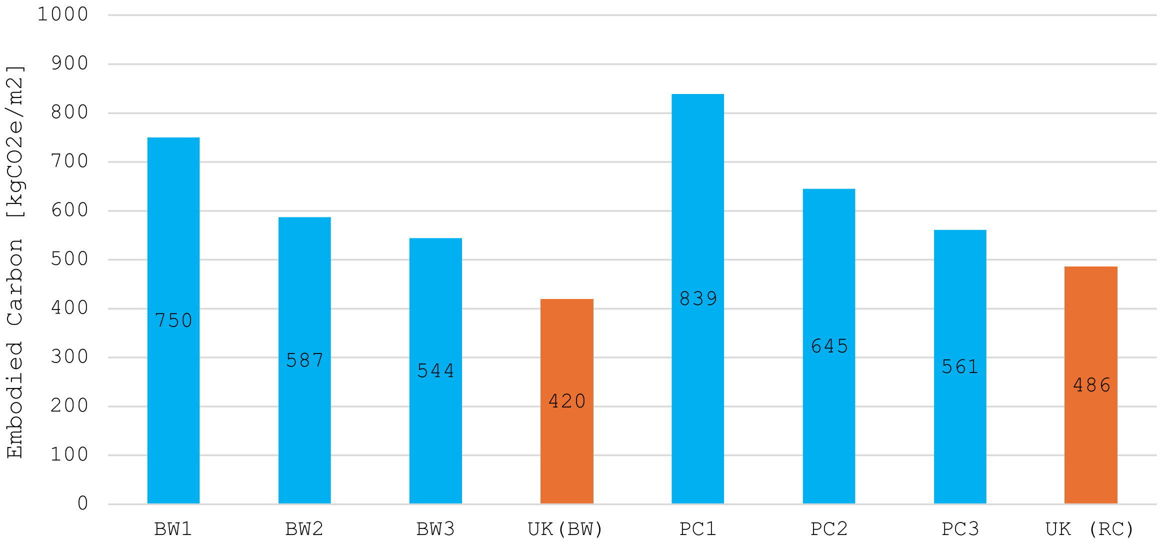

Fig. 7. Goldcrest Village scenarios WLEC results vs. those of the UK case study.

4.3. Examining RIAI's benchmark and objectives

While the literature review notes that Ireland does not yet have any EC regulations, the RIAI climate challenge paper lays out some general goals [43]. Fig. 8 presents a comparison between the RIAI benchmark and targets and the EC results obtained from this investigation. The findings of this study align with the results reported in the literature. Notably, all the values are well below the existing 1200 kgCO2e/m2 benchmark established by the RIAI document. The BW1, PC1, and PC2 scenarios exceed the RIAI 2030 domestic objective of 625 $kgCO_2e/m^2$, while PC1 also exceeds the 2025 domestic target of 800 $kgCO_2e/m^2$. All scenarios shown surpass the 2030 target of 450 $kgCO_2e/m^2$ for bigger houses with a floor area above 133 m^2, as specified for this evaluation. The precast concrete design, when constructed, exhibits the poorest performance across all specified targets. It is difficult for the construction sector to reduce EC while dealing with workforce constraints in the business.

5. Conclusions

This study aimed to enhance the current global efforts in reducing the EC emissions of buildings by developing a robust WLEC evaluation and reduction methodology for a high-demanded building typology and applying it to an Irish case study. The developed LCA methodology is replicable with limited modifications to assess similar projects in other countries.

To avoid the inconsistency in the previous methods, the developed methodology adopted nine LC modules (A1-A4, B4, and C1-C4) and the building elements scope from Level(s) framework to be calculated for a 50-year service life in the WLEC evaluation, which made the assessments easier, comparable, accurate, and comprehensive. Based on the quantities of building materials from the BOQ, their carbon factors from the EPDs or the ICE generic data, and specific assumptions for (A4, B4, and C1-C4) modules, the WLEC emissions were evaluated.

To apply the methodology on a real case study, a student accommodation development was selected for the evaluation. The results show that the WLEC of the precast concrete walls as-built design (PC1) exceeded the blockwork walls tender design (BW1) by 12 % due to the increase in the use of reinforced concrete. Moreover, the product stage (A1-A3) and the replacement module (B4) were the primary WLEC contributors, with around 56 % and 35 % in both scenarios.

To mitigate the WLEC emissions of this typology of buildings, altering concrete and rebar with lower carbon materials is mandatory. The alternative low-carbon materials (i.e. 50 % GGBS concrete blocks, 65 % GGBS in-situ concrete, low-carbon rebar, and 65 % GGBS precast concrete) were employed in an applicable methodology to reduce the WLEC emissions by replacing the conventional materials. The replacement resulted in a reduction of 10.4 % and 17.9 %, respectively, in the production stage (A1-A3), which aligns with the results of the previous studies [12] [13].

The modifications to the (B4) module substantially influenced the reduction of the WLEC of the case study. When the service lives of the non-load bearing elements, facades, roof structure, and ceiling and wall finish were extended from 30 to 50 years (as observed in the BW2 and PC2 scenarios), the WLEC contribution of the replacement (B4) module decreased from 258 $kgCO_2e/m^2$ (34 %) in BW1 base case to 95 $kgCO_2e/m^2$ (16 %) in BW2 scenario. Hence, prioritising the use of durable materials can reduce the WLEC emissions of the building, as also previously mentioned in Rauf et al. [14] and Yokoyama et al. [15] studies.

The WLEC emissions of the BW1 and PC1 base cases surpassed the domestic objective of 625 $kgCO_2e/m^2$ set by RIAI 2030. However, the developed methodology successfully reduced both design options to below the targeted limit in scenarios BW2, BW3, and PC3. This shows that modifications to materials and service lives are recommended to keep the WLEC within the targeted limits.

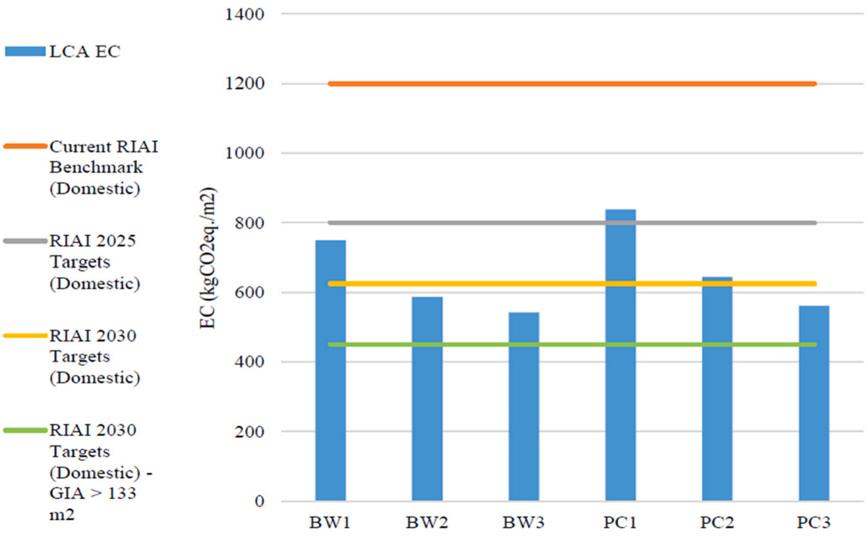

Fig. 8. RIAI's domestic EC aims and the outcomes of the EC.

The current default service life for building elements in the Level(s) may be a source of uncertainty for specialised components such as internal walls, partitions, and staircases. These elements are frequently constructed from concrete, with a significantly extended lifespan. A reassessment of the Level(s) service lives to be more accurate is necessary.

The development methodology has limitations in the reduction measures regarding the limited alternative low-carbon products in the Irish market. Moreover, reduction measures such as substitution with bio-based materials like timber cannot be included due to structural design considerations; however, they will relatively have high potential to reduce the WLEC emissions.

Presently, cement substitutes like GGBS are not widely employed in the manufacture of precast concrete. The primary reason is the prolonged setting time resulting from using GGBS. Moreover, the IStructE report in 2023 [44] mentioned that GGBS resources are limited and almost fully utilised globally. Therefore, increasing the use of GGBS is unlikely to be possible nowadays, and alternative options need to be developed. Excluding the GGBS leaves a significant opportunity for the researcher to study how the EC of precast concrete can be reduced. Conducting more research in this field would be an advantageous approach to decrease the EC of buildings.

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CRediT authorship contribution statement

Moran Paul: Writing – review & editing, Project administration. **Flynn Jack:** Methodology, Data curation. **Larkin Conor:** Methodology, Data curation. **Goggins Jamie:** Supervision, Funding acquisition, Conceptualization. **Elkhayat Youssef:** Writing – original draft, Visualization, Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jamie Goggins reports financial support was provided by The Sustainable Energy Authority of Ireland (SEAI). Jamie Goggins reports financial support was provided by Laudes Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cscm.2025.e04514.

Data availability

No data was used for the research described in the article.

References

[1] Nugent, Montano-Owen, Pallares, Richardson, and Rowland, EU Policy Whole Life Carbon Roadmap for Buildings, 2022.
[2] European Commission, Energy Performance Of Buildings Directive, (Online). 2023. ⟨https://energy.ec.europa.eu/topics/energy-efficiency/energyefficient⟩-buildings/energy-performance-buildings-directive_en. (Accessed 7 August 2023).
[3] European Commission, EU Emissions Trading System (EU ETS), (Online). 2023. ⟨https://climate.ec.europa.eu/eu-action/eu-emissions-tradingsystem⟩- eu-ets_en#a-cap-and-trade-system. (Accessed 7 August 2023).
[4] R. O'Hegarty, O. Kinnane, Whole Life Carbon Quantification of the Built Environment: Case Study Ireland, Elsevier, 2022 (Accessed 7 August 2023). https://www.sciencedirect.com/science/article/pii/S036013232200960X?casa_token=VyXth3WNZJEAAAAA:Zi9HVJ2vQ_YyXbzQLAhqTf9wTe4xFUp_6z5BPmcvMYHKHpIrFfVI5X0quJJXg78HhzvF-2SL.
[5] United Nations, The Paris Agreement, (Online) 2023. ⟨https://unfccc.int/process-and-meetings/the-paris-agreement/the-parisagreement?⟩ gclid=Cj0KCQiAofieBhDXARIsAHTTldppPnN8eNnOHOukY0- w8owPmxHRC5ydeKqsbw_biJLonqTMLJseXZEaAmvsEALw_wcB. (Accessed 7 August 2023).
[6] Department of the Environment, Climate Action Plan 2023,, (Online) 2023. ⟨https://www.gov.ie/en/publication/7bd8c-climate-action-plan⟩- 2023/. (Accessed 7 August 2023).
[7] R. O'Hegarty, S. Wall, and O. Kinnane, Whole Life Carbon in Construction and the Built Environment in Ireland, 2022.
[8] A. Duffy, Land use planning in Ireland-a life cycle energy analysis of recent residential development in the Greater Dublin area, Int. J. Life Cycle Assess. 14 (3) (May 2009) 268–277, https://doi.org/10.1007/S11367-009-0059-7.
[9] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: a critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416.
[10] T. Lützkendorf and M. Balouktsi, Basics, IEA-EBC Annex 57 Subtask 1 report-Actors and Concepts, Evaluation of Embodied Energy and CO2eq for Building Construction (Annex 57), International Energy Agency, Institute for Building Environment and Energy Conservation, Japan, 2016.
[11] C. Larkin, J. Flynn, Environmental Life Cycle Assessment of Buildings in Ireland, University of Galway, 2023.
[12] F. Kanavaris, G. Di Benedetto, A. Campbell, G. Gedge, S. Kaethner, Reducing the embodied carbon of concrete-framed buildings through improved design and specification: influence of building typologies, construction types and concrete mix, Structures 67 (Sep. 2024), https://doi.org/10.1016/j.istruc.2024.107005.
[13] A. Favier, C. De Wolf, K. Scrivener, G. Habert, ETH Library A sustainable future for the European Cement and Concrete Industry Technology assessment for full decarbonisation of the industry by 2050 (2018), https://doi.org/10.3929/ethz-b-000301843.
[14] A. Rauf, R.H. Crawford, Building service life and its effect on the life cycle embodied energy of buildings, Energy 79 (2015) 140–148, https://doi.org/10.1016/j.energy.2014.10.093.
[15] K. Yokoyama, M. Yamamoto, N. Yokoo, T. Oka, T. Sawachi, Study on impact of embodied energy and CO2 emissions for prolongation of building life time: case study in Japan, J. Civ. Eng. Archit. 9 (2015) 274–282.
[16] L. G. a. H. Department of Housing, A New Housing Plan for Ireland, (Online) 2021. (Accessed 7 August 2023). ⟨https://www.gov.ie/en/publication/ef5echousing- for-all-a-new-housing-plan-for-ireland/#view-the-plan⟩.
[17] H. Yan, Q. Shen, L.C.H. Fan, Y. Wang, L. Zhang, Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong, Build. Environ. 45 (4) (2010) 949–955.
[18] Y. Schwartz, R. Raslan, D. Mumovic, The life cycle carbon footprint of refurbished and new buildings – a systematic review of case studies, Renew. Sustain. Energy Rev. 81 (2018) 231–241, https://doi.org/10.1016/j.rser.2017.07.061.
[19] A. Takano, Comparison of life cycle assessment databases: a case study on building assessment, Build. Environ. 79 (2014) 20–30.
[20] A. Akbarnezhad, Z.S. Moussavi Nadoushani, A computational method for selection of optimal concrete recycling strategy, Mag. Concr. Res. 67 (11) (2015) 543–558.
[21] M. Norouzi, S. Colclough, L. Jiménez, J. Gavaldà, Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland, Energy Build. (2022). Accessed: Aug. 07, 2023. [Online]. Available: ⟨https://www.sciencedirect.com/science/article/pii/S0378778822001074⟩.
[22] J. Goggins, P. Moran, A. Armstrong, and M. Hajdukiewicz, Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland, Energy Build, (Online) 2016. ⟨https://www.sciencedirect.com/science/article/pii/S0378778816300160?casa_token=BQCEiMGFquMAAAAA:WZ5hZyEbxGSOA8loqykE5nrbswQNzyUaS_9k4iGo4UKBUIfURr33g3QJwQZUV6meEFmV5t1R⟩.
[23] National Standards Authority of Ireland, Environmental Management - Life Cycle Assessment - Principles and Framework I.S. EN ISO 14040:2006&A1:2020, 2020.
[24] National Standards Authority of Ireland, Environmental Management - Life Cycle Assessment - Requirements and Guidelines I.S. EN ISO 14044:2006&A1:2018&A2:2020, 2020.
[25] National Standards Authority of Ireland, Sustainability of cOnstruction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products I.S. EN 15804:2012+A2:2019&AC:2021., 2021.
[26] Irish Green Building Council, EPD Ireland, (Online) 2023. ⟨https://www.igbc.ie/epd-home/⟩.
[27] European Commission, How Does Level(s) Work? (Online) 2023. ⟨https://environment.ec.europa.eu/topics/circular-economy/levels/lets-meetlevels/⟩ how-does-levels-work_en. (Accessed 7 August 2023).
[28] J.T.C.C. Engineers, Goldcrest Village - NUIG Student Accommodation Substantial Completion, (Online) 2023. ⟨https://www.jvtierney.ie/goldcrestvillage⟩-nuig-student-accommodation-substantial-completion. (Accessed 8 August 2023).
[29] N. Dodd, S. Donatello, and M. Cordella, Level(s) – A cOmmon Eu Framework of Core Sustainability Indicators for Office and Residential Buildings, User Manual 2: Setting up a Project to Use the Level(s) Common Framework (Publication version 1.1), 2021.
[30] TM65 Embodied Carbon in Building Services: a Calculation Methodology, (Online), 2023. ⟨https://www.cibse.org/knowledge-research/knowledge-portal/embodied-carbon-in-building-services-a-calculation-methodology-tm65#:~:text=Other%20Details-,Embodied%20carbon%20in%20building%20services%3A%20A%20calculation%20methodology%20⟩(TM65),related%20to%20whole%20life%20carbon. (Accessed 6 August 2023).
[31] EPA, Construction & Demolition Waste Statistics for Ireland, (Online) 2022. (Accessed 8 August 2023). ⟨https://www.epa.ie/our-services/monitoring–assessment/waste/national-waste-statistics/construction–demolition/⟩.
[32] Cambridge Architectural Research (CAR) and Irish Green Building Council (IGBC), National Inventory of Generic Construction Materials Data (NIGCMD), 2022.

[33] C. Jones and G. Hammond, ICE (Inventory of Carbon and Energy) Version 4, , (Online) 2024. (Accessed 26 February 2025) ⟨https://circularecology.com/embodied-carbon-footprint-database.html⟩.

[34] C. Jones, ICE Database - Embodied Carbon Model of Cement, Mortar and Concrete V1.2, (Online) 2024. 2025. [Online]. (Accessed 26 February 2025) ⟨https://circularecology.com/embodied-carbon-footprint-database.html⟩.

[35] E.P.D. Ireland, Product Category Rules: Part A Implementation and Use of EN 15804:2012+A1:2013, EN 15804:2012+A2:2019 and CEN TR 16970:2016 in Ireland for the development of Environmental Product Declarations, 2022.

[36] O. John, O. Gibbons, W. Arnold, A Brief Guide to Calculating Embodied Carbon (2020).

[37] N. Dodd, S. Donatello, and M. C, Level(s) Indicator 1.2: Life Cycle Global Warming Potential (GWP) User Manual: Introductory Briefing, Instructions and Guidance (Publication version 1.1), 2021.

[38] S. Sturgis and A. Papakosta, RICS Professional Standards and Guidance, UK Whole Life Carbon Assessment for the Built Environment 1st4 Edition, November, 2017, 2017.

[39] E. I. S. Department for Energy Security and Net Zero and Department for Business, Greenhouse Gas Reporting: Conversion Factors 2022.

[40] M. Collins and C. Larkin, “Editor.,” 2023.

[41] Ecocem, Ecocem AccelR8, (Online) 2023. (Accessed8 August 2023). ⟨https://www.ecocemglobal.com/en-gb/products-projects/ecocem-accelr8/⟩.

[42] A.M. Moncaster, F. Pomponi, K.E. Symons, P.M. Guthrie, and A.A. Nezhad, Why Method Matters: Temporal, Spatial and Physical Variations in LCA and their Impact on Choice of Structural System, (Online) 2025. (Accessed 24 February 2025) ⟨https://www.sciencedirect.com/science/article/pii/S0378778818308946⟩.

[43] RIAI, RIAI 2030 Climate Challenge 2021, (Online) 2023. (Accessed 8 August 2023). ⟨https://www.riai.ie/discover-architecture/riai-publications/riai-2030-climatechallenge⟩.

[44] W. Arnold, P. Astel, T. Forman, M. Drewniok, The Efficient Use of GGBS in Reducing Global Emissions, Institution of Structural Engineers, United Kingdom, 2023.