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Developing a methodology with a tool for calculating and reducing the upfront carbon emissions of buildings: Ireland as a case study

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ABSTRACT

Upfront carbon emissions of buildings encompass all greenhouse gas emissions linked to building materials extraction, manufacturing, transportation, and installation processes. Many countries face barriers in calculating and reducing the upfront carbon emissions of buildings during the design stage due to unreliable materials embodied carbon (EC) data, inconsistent methods, and tool complexity. Therefore, the current study aims to develop a national adaptable methodology with a simple tool for calculating and reducing buildings' upfront carbon emissions based on a reliable regional EC dataset. To validate the developed methodology and tool, a group of architecture firms in Ireland used it to calculate and reduce the upfront carbon emissions of their projects. Fourteen buildings representing six typologies were evaluated, and on average, the results were 436 and 648 $kgCO_2e/m^2$ for residential and non-residential buildings, respectively. The calculation method and tool have been validated since the upfront carbon emissions values align with the averages of buildings in Europe. The reduction methodology was developed using the materials' substitution strategy to replace in-situ concrete, steel, insulation, and window frames with lower-EC alternatives. The substitutions reduced the upfront carbon emissions of the residential and non-residential case studies by 21% and 23.8% on average, achieving the Irish government's 2030 Climate Action Plan. The future development of the reduction methodology can go further by considering more key materials.

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Upfront carbon emissions; building LCA; carbon calculation tool; carbon reduction; material substitution

Introduction

The buildings and construction sector represent around a third of total energy system emissions, including buildings operations (26%) and embodied carbon (EC) emissions (7%) associated with building materials' extraction, manufacture, transportation, assembly, replacement, and disposal (University of North Carolina at Chapel Hill Champions, 2023). Reducing the EC of buildings is a pressing and crucial matter, as the current trend of buildings' EC emissions does not fit with the global net-zero carbon target by 2050 (Melton, 2023). For instance, Marianne Wiik (2025) developed whole-life carbon benchmark values for Norwegian buildings, and the greenhouse gas emission

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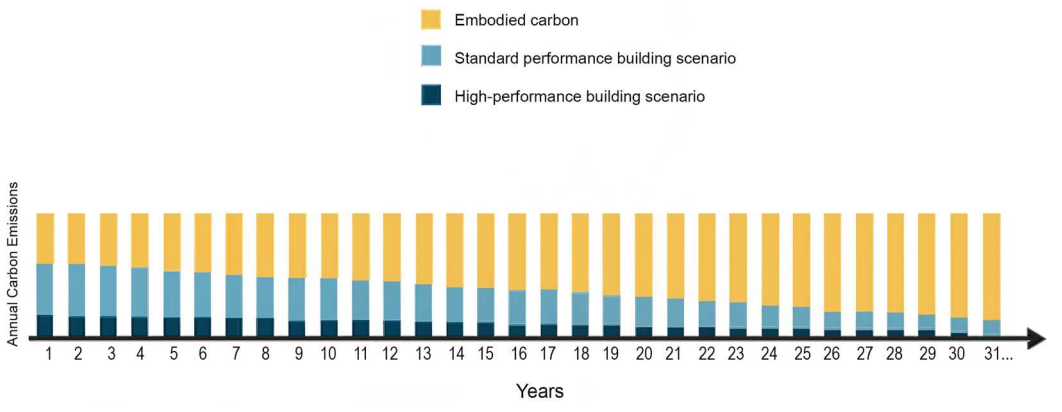

Figure 1. The following 30 year's scenarios projection shows that an action to reduce the embodied carbon of buildings is more important than operational carbon (Lewis, Huang, Carlisle, & Simonen, 2020).

results showed that the Nordic best practice projections are at least 50% more ambitious than current practice. Figure 1 shows that during the following 30-year period, the EC will grow proportionately and contribute more to building emissions (Melton, 2023). Architects and other built environment professionals must use the available solutions to speed up the adoption of low-EC buildings and apply extraordinary measures necessary to fulfil the aim of the Paris Climate Agreement and restrict global warming to 1.5°C (United Nations, 2023).

However, the existing EC calculating methods for buildings vary in terms of life cycle boundaries and scope and do not have a consistent life cycle inventory (LCI) dataset or assumptions (Anand & Amor, 2017; Skaar & Jørgensen, 2013). Moreover, they have a lack of support to add or change information in the LCI dataset, such as adding material EC data from a verified Environmental Product Declaration (EPD) (Cardellini, Mutel, Vial, & Muys, 2018). The existing EC calculation tools for buildings have regional limitations (Bueno & Fabricio, 2018), and complex modelling processes (Anand & Amor, 2017), and many of them are not free (Bueno & Fabricio, 2018). Furthermore, most available methods and tools lack reasoning and decision-support capabilities, such as exploring material substitution scenarios to evaluate alternative options that promote reducing a building's embodied carbon (Skaar & Jørgensen, 2013). Therefore, there is no internationally accepted method for calculating and reducing the EC of buildings consistently and comparably.

To fill this gap, the current study aims to develop a regional adaptable methodology with a simple tool to calculate the EC of buildings and support reduction decisions based on consistent LCI data gathered at the national level. Due to the consistency with the different countries that gathered their specific LCI data, the developed methodology focuses on calculating the EC for (A1–A5) stages 'upfront carbon emissions', which also represents the majority (more than 50%) of the building's whole-life embodied carbon (Craft et al., 2024; Wong, 2024).

After the following literature review section, the study comprises four major sections to achieve these objectives. Methodology of Calculation section develops and validates the upfront carbon emissions calculation methodology and the tool. Methodology of Reductions section develops an upfront carbon emission reduction methodology and applies the developed upfront carbon emissions reduction methodology to different building typologies. Discussion section discusses and concludes the outcomes.

Literature review

Embodied carbon calculation methods

Presently, three fundamental approaches exist for calculating the EC of buildings: process-based (Zhang, Yan, Hu, & Guo, 2019), input–output (I–O) (Leontief, 2018) and hybrid (Suh, 2004). Every

approach possesses distinct qualities and areas of applicability. The process-based approach is entirely viable if a comprehensive bill of quantities (BoQ) and the building components' carbon factors (CF) are available. Consequently, this strategy typically pertains to singular instances and product-specific process investigations.

Conversely, when the economic I–O tables of a national economic framework are accessible, the input-output approach can be employed. This method employs a top-down linear macroeconomic framework to elucidate the intricate inter-industry relationships concerning monetary transactions within an industrial structure (Lenzen, Murray, Korte, & Dey, 2003). In other words, all energy exchanges inside national economic frameworks are recognised and recorded. These can subsequently evaluate the energy inputs and outputs (Omar, Doh, Panuwatwanich, & Miller, 2014). Using I–O data enhances the credibility of the life cycle assessment (LCA) by augmenting the completeness and dependability of LCI in contrast to conventional inventory analysis (Crawford, 2008). The I–O technique assesses upstream emissions from buildings according to economic sectors (Dixit, 2017). This method is more suitable for calculating macro-EC emissions of buildings. Nonetheless, it fails to interpret a more intricate relationship between particular building elements (Mi et al., 2017; Minx et al., 2009).

Certain scholars employ a hybrid approach to calculating the EC of buildings more precisely (Acquaye, Duffy, & Basu, 2011; Druckman & Jackson, 2009; Lausselet, Crawford, & Brattebø, 2022). This approach integrates the benefits of the more precise process-based approach with the broader system boundaries of the I–O approach (Mattila, Pakarinen, & Sokka, 2010). Despite the enhanced accuracy of the hybrid approach, the procedure is sophisticated and time-consuming.

These approaches are universally recognised for various reasons in calculating the EC of buildings. Nonetheless, the process-based approach is more practical when the BoQ and materials carbon factors are available before the assessment (Röck, Hollberg, Habert, & Passer, 2018).

Material Flow Analysis (MFA) is unsuitable for calculating the EC of buildings due to not providing the detailed emissions data required for EC assessments. Therefore, EC calculations rely on LCA methodologies and EPDs to quantify GHG emissions across a building's life cycle. LEED and BREEAM certifications include criteria for only reducing EC through material selection, LCAs, and other strategies. They encourage the use of low-carbon materials, efficient design practices, and transparent reporting to meet sustainability goals.

Embodied carbon calculation tools

Numerous building EC calculation tools have been developed to calculate the EC of buildings, including Athena Impact Estimator, Tally, and One Click LCA (One Click LCA Ltd, 2025). While current tools can aid with EC calculations, they function as a black box, as end-users possess a limited understanding of the underlying facts and assumptions of the tool (Bueno & Fabricio, 2018). This may hinder a comprehensive interpretation of the results and hotspots (Al-Ghamdi & Bilec, 2017). Moreover, the results are inconsistent for the same project because each tool employs different databases or calculating methods. The commercial EC calculation tools are incredibly useful; however some tools are complex and require significant expertise to use effectively, which can be a barrier for small firms or new LCA software users (Anand & Amor, 2017). The commercial tools often use generalised data or assumptions which might not be compatible with the specific conditions of a project. Therefore, scholars tried to develop building LCA tools to overcome the limitations of commercial tools.

Domjan, Arkar, and Medved (2020) developed an Excel-based decision-supporting tool for nearly zero energy building renovations. Miyamoto, Allacker, and De Troyer (2019) developed a decision-support tool to combine LCA and life cycle cost during the initial design phase for residential buildings to minimise the duration needed for comparing design options. Duprez, Fouquet, Herreros, and Jusselme (2019) developed machine learning algorithms enabling designers to assess options utilising the trained models swiftly. The primary benefit of these non-commercial tools is their capacity to

integrate data from diverse external sources, which commercial solutions do not permit (Forth, Braun, & Borrmann, 2019). Consequently, it is advisable to build tailored tools to enhance the incorporation of EC calculations throughout the design phase of buildings.

Embodied carbon reduction methods

Many studies investigated various methods to reduce the EC of building materials. These methods can be generally divided into four categories (Akbarnezhad & Xiao, 2017; Pomponi & Moncaster, 2016): (1) Selecting low-carbon materials, (2) Material optimisation, (3) Material reuse and recycling, and (4) Sourcing local materials. Their advantages are reviewed as follows.

Selecting low-carbon materials

Architects are typically required to select from a restricted collection of materials for each element in the building (Alireza Ahmadian, Rashidi, Akbarnezhad, & Waller, 2017). The shortlisted materials are chosen based on technical and performance criteria and may exhibit significantly varied EC for the buildings (Hammond & Jones, 2006, 2008). The upfront carbon emissions of materials can differ markedly based on the nature of the raw material components, the geographical location of quarries, the transportation methods employed, the emissions during extraction and processing activities and relevant material installation techniques (Hammond & Jones, 2008). Numerous prior research (González & Navarro, 2006; Reddy, 2009; Reddy & Jagadish, 2003) have examined the significant impact of material selection on the EC of buildings. González and Navarro demonstrated that substituting conventional materials with low-EC alternatives resulted in approximately a 30% reduction in the whole building's EC emissions (González & Navarro, 2006).

Material optimisation

The total EC of a building is directly proportional to the amount of material utilised in its construction (Akbarnezhad & Nadoushani, 2014). Optimal design, preventing overdesign, can significantly reduce the overall material quantity and, consequently, the environmental impact of the building. Avoiding overdesign has been promoted for years as a fundamental tenet of engineering design to save costs, weight, and material consumption in structures (Yeo & Gabbai, 2011). For instance, the modular reinforced concrete construction approach can reduce EC emissions by 36% compared to the traditional methods (Jang, Ahn, & Buildings, 2022). Reducing material usage and the EC must be executed while ensuring the building fulfils all other technical and performance specifications (Yeo & Gabbai, 2011).

Material reuse and recycling

Demolition, landfilling, recycling, and reusing materials are common ways to deal with buildings that have ended their useful lives (Akbarnezhad, Ong, Zhang, et al. 2013; Xiao, Ma, & Ding, 2016). The cradle-to-grave EC of buildings can be lowered by considering carbon emission effects when choosing the end-of-life plan. Suppose the demolition and landfilling strategy is used. In that case, it not only wastes the EC that was used to turn the materials into an integrated structure, but it also adds to the carbon emissions released by the demolition of the building and the transportation of debris to remote landfills (Akbarnezhad & Moussavi Nadoushani, 2015). On the other hand, recycling is one of the oldest and most environmentally friendly ways to deal with building and demolition waste (Akbarnezhad, Ong, Tam, et al., 2013). Zhang et al. (2022) found that implementing recycling practices can lead to a substantial reduction of almost 50% in EC emissions from the Chinese building sector by 2060.

Sourcing local material

The review has highlighted the significant role of transportation as a contributor to the environmental cost of buildings (Yan, Shen, Fan, Wang, & Zhang, 2010). The primary determinants

influencing transport emissions are the volume of material to be transported, the cargo's dimensions, the transportation distance, and the mode of transport (Ahmadian, Akbarnezhad, Rashidi, & Waller, 2016). A material supply chain configuration can significantly influence transportation needs and the corresponding transport emissions (Alireza Ahmadian et al., 2017). The primary elements influencing material transport emissions, such as trip frequency, transportation mode, and travel distance needs, must be considered. According to Crishna, Banfill, and Goodsir (2011) (Crishna et al., 2011), local stones can reduce the EC of blocks by up to 84% compared to imported stones, depending on the type of stone and its country of origin.

In conclusion, the four materials' EC reduction methods have various advantages; however, selecting low-EC materials significantly reduces buildings' upfront carbon emissions.

Methodology of calculation

Standards and framework

There are international standards for LCAs; the general principles are set out in ISO 14040, and the more specific principles for buildings are set out in the EN 15978 standard (National Standards Authority of Ireland, 2011). In the current case study, the EC dataset of building materials was collected from the EU countries; thus, the proposed methodology adopted the EN 15978 standard and the EU Level(s) indicator 1.2 – Life cycle Global Warming Potential (GWP) as frameworks (Dodd et al., 2021aa). However, EN 15978 explains the principles; a specific question should be addressed: what building elements should be included in the inventory? The EU sustainable buildings framework Level(s) indicator 1.2 specifies the inventory of the building and its components (see Section 3.2). Moreover, Level(s) assures that the methodology will align with the EU requirements in the Green Deal Taxonomy (Fetting, 2020), the Energy Performance of Buildings Directive (EPBD) (European Commission, 2024), and the Corporate Sustainability Reporting Directive (CSRD) (Poulle, Kannan, Spitz, Kahn, & Sotiropoulou, 2024). If the methodology is applied in non-EU countries, the exact building elements included in the inventory must be defined initially.

Building physical scope

Building LCA methods often have limitations in scope, so explain the significant building elements not included in the assessment. Building materials data is usually not available until the design is nearing completion. Therefore, the completeness of an assessment has a significant impact on the building EC result. The physical scope is stated in the Level(s) Indicator 1.2 manual, as shown in Figure 3 (Dodd et al., 2021aa).

Boundaries, data sources, and assumptions

In building LCA studies, system boundaries define which processes and phases of a building's life cycle are included in the assessment. These boundaries are crucial because they determine what is considered and excluded, impacting the assessment's results and conclusions. The following are the upfront life cycle modules (A1–A5) included in the methodology to be assessed, along with the data sources and assumptions.

(A1–A3) materials supply, transport, and manufacturing

Producing life cycle carbon estimates of buildings at the end of the design stage, before material suppliers are identified, requires a set of carbon profiles for generic materials. To carry out consistent assessments, it is crucial to provide a consistent set of background data based on materials used in the state to reflect the overall emissions, and it should be used for all assessments in the state to ensure consistency.

In 2022, the Cambridge Architectural Research and Circular Ecology studies produced (A1-A3) carbon data. It was supplemented with EPDs from Cement Manufacturers in the EU and data from the UK Inventory of Carbon and Energy (ICE) database for other materials to provide one database of consistent carbon emission production figures for many materials used in the EU construction sector today. The dataset is now available online as a 'Generic Dataset' (IGBC, 2025). The 'Generic Dataset' is used for the current methodology to provide consistent results for all building-level upfront EC assessments. More accurate assessments can be done using EPD data where available and should be encouraged.

(A1–A3) MEP materials supply, transport, and manufacturing

Mechanical, electrical, and plumbing (MEP) building services are thought to substantially influence the building upfront EC because they are predominantly made from metals and plastics; however, no sufficient EC data is available from the manufacturers (Rodriguez, Huang, Lee, Simonen, & Ditto, 2020).

The Chartered Institution of Building Services Engineers (CIBSE) TM65 methodology for calculating the EC of building services estimates MEP's GWP impact based on the total mass of equipment (TM65 Embodied carbon in building services: A calculation methodology, 2021). Therefore, the current methodology adopted CIBSE TM65 MEP carbon intensity estimates. The benefit of following CIBSE TM65 is that the method aligns with the best practices in this area and is applicable globally.

(A4) transport to site

Transportation of materials from manufacturing plants to building sites is practically difficult to calculate as most materials do not take the shortest route and are transported via a storage and distribution network (Chen, Yang, Zhang, Jordan, & Huang, 2022). For this reason, applying default assumptions for journeys is more robust, saving the end-users time and effort for a part of the result. For the current methodology, it is assumed that all materials manufactured nationally will travel 200 km by road to site, except for bulk materials such as concrete, which will travel 100 km by road. All imported materials are also assumed to travel a further 1,000 km by sea. These assumptions are per the EPD Ireland Product Category Rules (PCR) for developing EPDs of specific materials (EPD Ireland, 2022). The IStructE embodied carbon guide (John, Gibbons, & Arnold, 2020) presents road and sea transportation emission factors (EF). The EF are expressed as the ratio of kilogrammes of CO_2 equivalent emitted to kilogrammes of material for each kilometre travelled. A4 emissions of building materials are calculated by multiplying these assumed travel distances by the EF in Table 1 by the weight of the material (see Equation 1).

$$EC(A4) = Weight \times Distance \times TransportEF \quad (1)$$

where EC (A4): embodied carbon of material transportation to site ($kgCO_2e$), Weight: material mass (kg), Distance: distance travelled (km) between site of material manufacture and construction site, Transport EF: relevant mode of transportation carbon EF ($kgCO_2e$/kg km).

(A5) construction installation process

In module A5, due to the challenge of calculating accurately the EC for all construction processes, the methodology considered calculating the EC of the on-site waste only. Moreover, the current methodology does not consider the emissions from site preparation processes or any energy usage during the construction process due to the limited data and resources. Although Level(s) provides an indicator (Indicator 2.2) for calculating on-site waste, few developers actively record and

Table 1. Emission factors for road and sea transport (John et al., 2020).

Transport method	Emissions factor [$kgCO_2e$/kg.km]	Source
Road	1.065E-4	HGV (all diesel) average laden
Sea	1.614E-5	Average cargo/container

manage this waste. Therefore, applying assumptions of waste rates for different materials as a percentage of each material when assessment occurs before starting the construction stage is more effective. Level(s) provides a set of percentage assumptions added to the materials BoQ (Dodd et al., 2021b). This method also accounts for the EC associated with manufacturing and delivering materials wasted during construction. If country-specific data were available, using it instead of any assumptions would be better.

In conclusion, Table 2 summarises the data sources and assumptions made in the required upfront life cycle modules (A1–A5) by the EN 15978 standard. The assumptions were encoded into the associated Excel-based carbon calculation tool, enabling the end-users to comprehensively input materials and MEP quantities to calculate the building's anticipated upfront EC emissions.

Upfront embodied carbon calculation

The current methodology uses the process-based calculation method since the detailed design stage has been completed and all material quantities and specifications have been defined. Fundamentally, the upfront EC calculation is quite simple: quantifying the materials quantities from the BoQ and multiplying each material quantity by its relevant carbon factor. Credible sources are used to determine the carbon factors (see Table 2). Figure 2 shows the relationships between the inventory data, carbon factor sources, and the modules in which each result is calculated. The proposed methodology utilises GWP, measured in $kgCO_2$ equivalents per square meter ($kgCO_2e/m^2$) to assess the upfront EC of a building. Therefore, using this metric entails precisely delineating the specific floor area to be utilised. Level(s) states the standard functional unit as the environmental impact per $1m^2$ of total useful floor area or the gross internal floor area. Appendix A displays a table from Level(s) that illustrates the proper method for calculating the useful floor area of a project (Dodd et al., 2021b).

The calculation tool tracks which building elements have data supplied against them and requires the end-user to indicate which elements are not included in the assessment. A 100% complete assessment should contain data on every element included in the scope or record that the element does not exist in the building. Therefore, a completeness tracker provides an overview of the assessment as it develops. The completeness tracker can be seen on the Report Template tab in the Excel-based tool (Appendix B).

The calculation tool is programmed with generic carbon factors (from the NGD), which can vary from one country to another depending on the manufacturing process and the energy sources involved. At the early design stage, the materials suppliers may not be known so that a generic estimate can be used. As a design develops and materials are specified, the background data on carbon factors can be sourced more accurately from Environmental Product Declarations (EPD). An EPD will offer a more accurate carbon factor for a material's (A1-A3) stages as it is a report of an LCA carried

Table 2. Data and assumptions applied to upfront (A-A5) life cycle modules in EN15978.

Module	Name	Data/assumptions	Data source
A1	Extraction of raw materials	– (A1-A3) GWP impact in the specific product EPD.	EPD International Library (EPD International, 2025), National EPD (EPD Ireland, 2025)
A2	Transportation to plant	– No EPD, then the national generic carbon factor is used.	Eco-Platform (ECO Platform, 2025), and National Generic Dataset (IGBC, 2025)
A3	Manufacturing	– CIBSE TM65 MEP carbon intensity estimates for MEP	
A4	Transportation to site	Assumed: – Bulk materials: 100 km road journey – Other materials: 200 km road journey – Imported materials: 1,000 km sea journey	National EPD
A5	Construction	Waste rates on site	Level(s) Manual

Figure 2. Upfront carbon emissions calculation methodology.

out on that specific material. Therefore, the calculation tool considers the data quality of the carbon factors applied to the production of each material by confidence scores defined in the RICS WLCA Professional Statement (Sturgis et al., 2023) (see Table 3).

The intention is to consider how well the carbon factor matches the product used in the project and, therefore, how confident the user should be about the data. For example, if the exact product used has a manufacturer-specific EPD, then using this EPD would score 40 out of 40 (100%), as it exactly represents the geography and technology used. If a collective EPD for an average product in the EU was used for this product instead, the score would be lower (62.5%) since the EPD covers a range of products, not the exact one used (Sturgis et al., 2023).

Carbon factors are labelled 'GWP' in the results table of an EPD. This GWP data can be used in the methodology, but it can be challenging to incorporate. The GWP is expressed as $kgCO_2e$ per Functional Unit (FU) rather than per kg mass, which is what the methodology uses. For instance, the FU may be a cubic metre of concrete or a square meter of plasterboard. Therefore, to convert the result in the EPD to $kgCO_2e$ per kg, a conversion factor must be applied – essentially, the mass weight of the FU expressed in kg. Dividing the GWP score by the number of kg will give the $kgCO_2e/kg$ value that can then be added to the EPD tab in the tool.

Generic data is used when an EPD is unavailable to be consistent across assessments and to avoid practitioners selecting data from EPDs of optimum products that may not be used. Generic data represents average values across a product category or industry, providing a standardised baseline for comparisons and assessments. This method is helpful in EC calculations, where the goal is to maintain objectivity and avoid bias. However, the confidence score will be low (52.5–57.5%); the authors recommend adding a safety margin when generic data is used to ensure the reality is not worse than the calculated value. Typically, safety margins might range from 5% to 20% of the calculated EC. The exact percentage used often depends on the specific industry, the quality of the data available, and the assessment goals. For example, industries with more standardised processes might use a smaller safety margin (5–10%), while those with higher variability might use a larger one (10–20%) (Muthu, 2024).

Table 3. Data sources and confidence scores (Sturgis et al., 2023).

Data source	Confidence score (%)
Product & manufacturer specific EPD	(40/40) 100%
Manufacturer-specific EPD	(35/40) 87.5%
National average EPD	(33/40) 82.5%
EU average product EPD	(25/40) 62.5%
NGD – Irish National Generic Dataset	(21-23/40) 52.5–57.5% depending on material

Validation

To validate the methodology, a User Acceptance Testing (UAT) through sharing the tool with 12 architecture firms in Ireland to conduct upfront EC assessment on their projects (Herrmann & Moltesen, 2015). Sharing the tool has resulted in continuous feedback and constant improvement throughout the project. The developed tool was employed to calculate the upfront EC of 14 case studies provided by architecture firms in Ireland representing six building typologies (Semi-detached Houses, Detached Houses, Apartments, Schools, Office Buildings, and Warehouses). The upfront EC calculations were conducted based on the materials BoQ for tender. Also, the building drawings and BIM models were used to quantify the quantity of materials, such as length, area, and volume. The materials were categorised based on Tier 1 and 2 scopes in Figure 3. All quantities were converted to mass in kilogrammes using a conversion factor. The material specification was obtained by examining either the BoQ or doing a more comprehensive analysis of the project drawings and specifications. After compiling the quantities, converting them from the BoQ quantity to kilogrammes, and inputting them into the tool with carbon factors for each material collected for (A1-A3) stages.

The results are plausible and consistent with the estimates. Table 4 shows the upfront EC results of the case studies with the same background data and assumptions. The preliminary evaluations of the case studies reveal that the resulting upfront EC average is 436 $kgCO_2e/m^2$ for residential buildings and 648 $kgCO_2e/m^2$ for non-residential buildings. These results validate the developed methodology and tool as they align with the 400 and 600 $kgCO_2e/m^2$ averages for residential and non-residential buildings in Röck et al. (2022) study (Röck et al., 2022). Figure 4 shows that the upfront EC averages for the evaluated typologies in the case studies.

Methodology of reductions

The developed tool enables the end-users to replace the most impactful materials with low-EC alternatives to reduce the upfront EC of buildings. However, the tool cannot comprehensively modify the building's design or structural system. Therefore, only a one-for-one material substitution strategy can be conducted manually by the end-users. Figure 5 shows a flowchart of the proposed material substitution methodology that guides the end-uses in reducing the EC of their buildings by selecting lower-EC materials. Four steps should be followed to complete the material substitution process:

1. Check the building's top five most EC contributing materials identified by the tool.
2. Search the tool's library for alternative materials with a lower carbon factor and similar/comparable material specifications, then replace the existing materials with the available alternatives.
3. If there are no alternatives in the library, search online for lower carbon materials with verified EPDs, add them to the library, and then replace the existing materials with the added alternatives. If no alternatives were available, then no substitution is required.

The authors conducted a hotspot analysis on the collected case studies to identify the most impactful materials in Ireland and model material substitution scenarios that guide the end-users during applying the reduction methodology on their buildings. The hot spot analysis has been conducted according to the following steps:

1. The calculation tool identified each case study's top five most upfront carbon emissions contributing materials.
2. Those materials were grouped into categories based on the material classification in the ICE database (Dodd et al., 2021b): (In-situ Concrete, Steel Products, Curtain Walls/Windows, Insulation, Stone/Brick, Concrete Block, Aluminium, Plasterboards, Precast Concrete, Cladding Panel, Cement, Solar Panels, and Timber).

	SCOPE Tier 1 building element	SCOPE Tier 2 building element
From Materials Tab	Foundations (substructure)	Piles
		Basements
		Retaining walls
	Load bearing structural frame	Frame (beams, columns and slabs)
		Upper floors
		External walls
		Balconies
	Non-load bearing elements	Ground floor slab
		Internal walls, partitions and doors
		Stairs and ramps
	Facades	External wall systems, cladding and shading devices
		Façade openings (including windows and external doors)
		External render
	Roof	RoofStructure
		Weatherproofing
	Parking facilities	Above ground and underground (within the curtilage of the buildin
	Fittings and furnishings	Sanitary fittings
		Cupboards, wardbrobes and worktops (where provided in reside
		Ceilings finish
		Wall finish
		Floor coverings and finishes
	Drainage systems	Drainage system
	Utilities	Connections and diversions
		Substations and equipment
	Landscaping	Paving and other hard surfacing
		Fencing, railings and walls
FROM MEP Tab (TM65)	In-built lighting system	Light fittings
		Control systems and sensors
	Energy system	Heating plant and distribution
		Cooling plant and distribution
		Electricity generation and distribution
	Ventilation system	Air handling units
		Ductwork and distribution
	Sanitary systems	Cold water distribution
		Hot water distribution
		Water treatment systems
		Drainage system
	Other systems	Lifts and escalators
		Firefighting installations
		Communication and security installations
		Telecoms and data installations

Figure 3. Physical scope of assessment as described in Level(s) Indicator 1.2 manual (Dodd et al., 2021b).

3. The average EC ($kgCO_2e/m^2$) for each category was calculated according to Equation 2:

$$EC\ average\ of\ a\ material\ category\ = \left(\frac{\sum EC\ per\ material\ category\ for\ case\ studies}{Number\ of\ case\ studies}\right) \quad (2)$$

Based on the resulting averages, the categories were prioritised descending (see Appendix C).

Table 4. List of case studies and their upfront carbon emissions results.

			Upfront carbon emissions ($kgCO_2e/m^2$)											
			Life cycle stages				Tier 1 building elements							
Typology	Case study	Useful floor area [m^2]	A1 – A5	A1 – A3	A4	A5	Sub	Sup	NLB	F&R	F&F	D&U	L&P	MEP
Semi-detached Houses	SEMI D – HOUSE 1	140	424	357	43	24	45	196	21	49	36	NDA	28	48
	SEMI D – HOUSE 2	2,012	478	399	49	30	126	275	46	28	2	NDA	NDA	NDA
Detached Houses	DETACHED HOUSE 1	206	461	395	40	2	NDA	242	2	100	21	50	27	19
	DETACHED HOUSE 2	267	355	328	11	17	NDA	179	37	82	27	NDA	11	20
	DETACHED HOUSE 3	382	456	416	25	14	23	154	55	140	25	1	3	55
Apartments	APARTMENT BLOCK 1	3,959	402	375	16	10	25	165	44	57	23	3	6	78
	APARTMENT BLOCK 2	635	478	439	28	12	27	245	13	62	58	NDA	3	69
School	PRIMARY SCHOOL	5,000	738	677	41	20	191	253	62	77	15	NDA	2	138
Office Buildings	OFFICES 1	5,601	532	482	36	13	125	129	19	74	42	1	85	56
	OFFICES 2	10,194	693	647	25	21	189	123	139	113	63	20	2	43
	OFFICES 3	26,470	806	776	14	16	2	484	178	NDA	39	NDA	NDA	103
	OFFICES 4	51,000	756	710	27	20	150	306	12	30	80	3	3	172
Warehouses	WAREHOUSE 1	2,882	464	390	52	22	NDA	346	5	74	NDA	NDA	29	10
	WAREHOUSE 2	8,123	546	517	15	14	39	381	14	2	41	1	NDA	70

NDA: No data available; Sub: Substructure; Sup: Superstructure; NLB: Non-load bearing elements; F&R: Facades & Roof; F&F: Fittings and furnishings; D&U: Drainage & Utilities; L&P: Landscaping & Parking; MEP: Mechanical, Electrical and Plumbing.

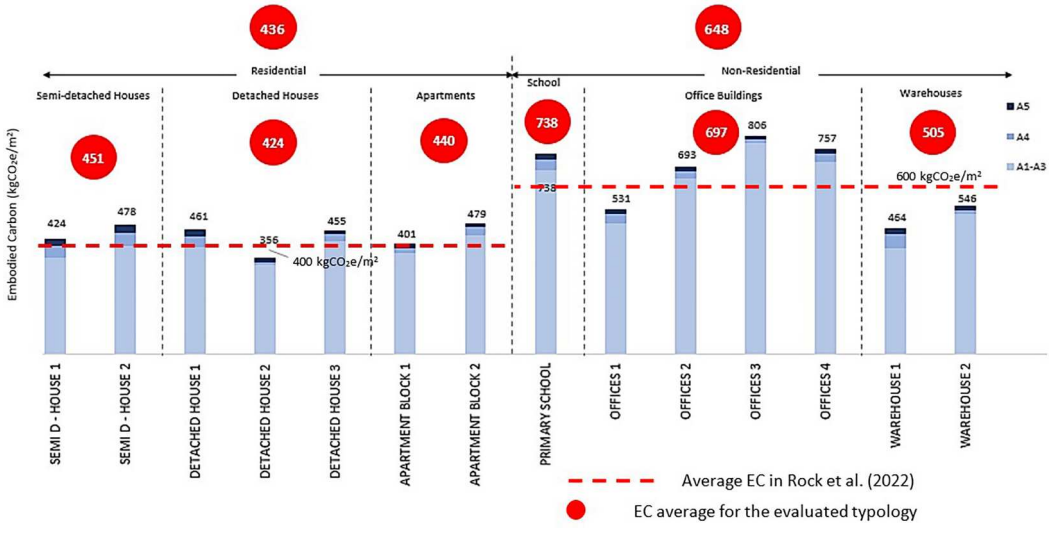

Figure 4. Case studies upfront carbon emissions evaluations and typologies averages against Röck et al. averages.

Figure 6 shows the share of material categories ascendingly in the total upfront carbon emissions of the case studies. The top four materials are In-situ concrete (33.1%), Steel Products (24.5%), Curtain Walls/Windows (10.9%), and Insulation (6.0%). Therefore, the reduction methodology prioritised substituting the top four categories of materials. In a future development stage, the substitution of more materials will be integrated.

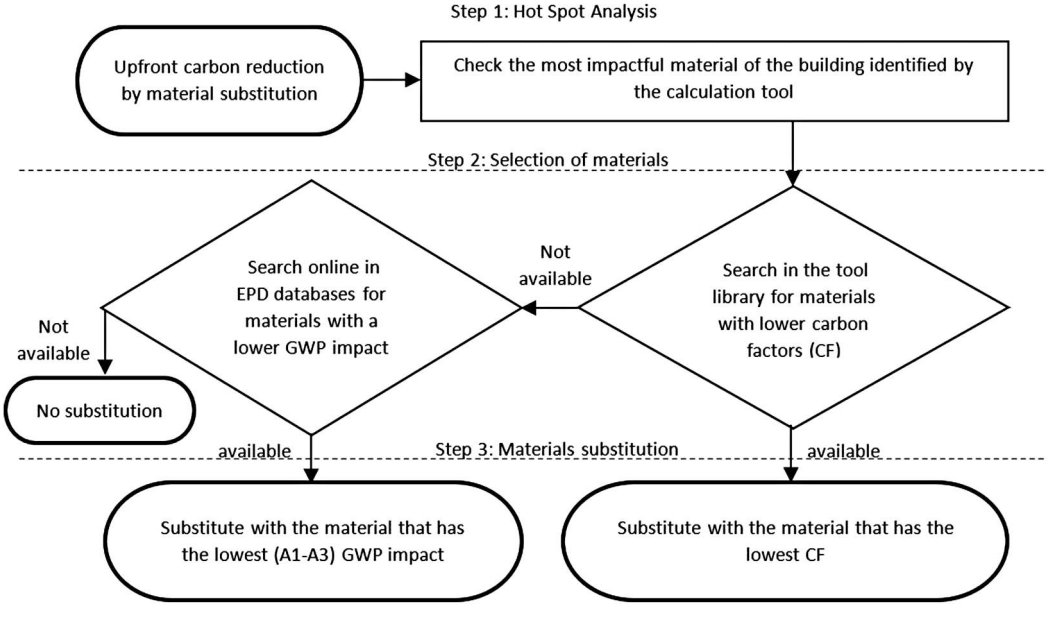

Figure 5. A flowchart of replacing the most impactful materials with lower carbon materials.

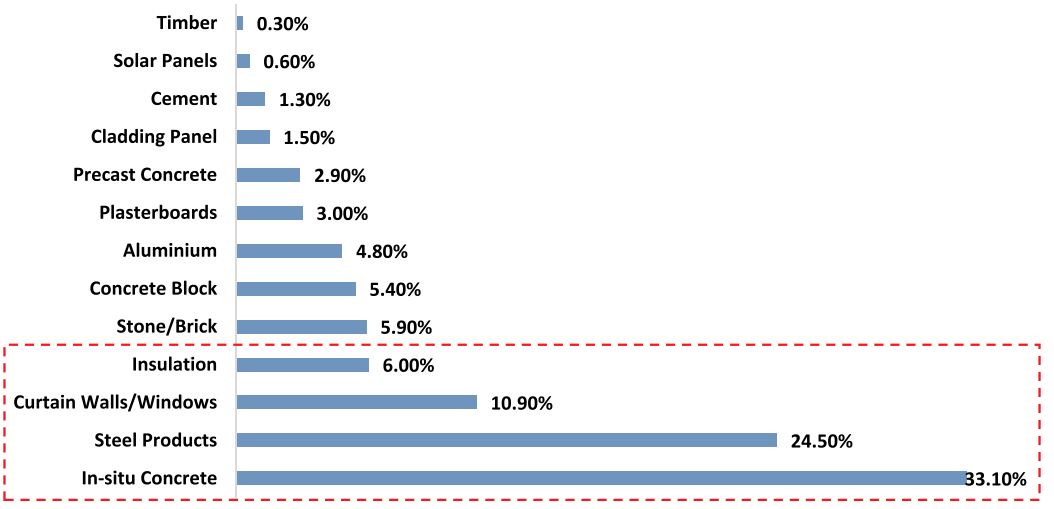

Figure 6. The share of material categories in the total upfront carbon emissions of the case studies.

Material substitution scenarios

In situ concrete substitution

Various studies showed that cement replacements, such as ground granulated blast-furnace slag (GGBS), can decrease the EC of concrete buildings. An LCA conducted on a retail facility in Ireland revealed an EC result of 592 $kgCO_2e/m^2$. In an optimum design scenario, the increase of GGBS content in concrete elements resulted in a reduction of 30% in the whole-building EC, reducing it to 415 $kgCO_2e/m^2$ (RIAI, 2023). Similarly, a study on an office building in Ireland revealed that the whole-building EC decreased by 30% when a mixture containing 50% GGBS was utilised instead of ordinary Portland cement (OPC) concrete (Goggins, Keane, & Kelly, 2010). From these studies, GGBS can reduce the EC in concrete buildings. Therefore, the In-situ concrete with (70% GGBS) alternative was chosen to substitute the existing one. Appendix D shows the existing materials, and the alternatives used in the case studies.

Steel elements substitution

Electric Arc Furnaces (EAFs) produce less than half as much CO_2 as basic oxygen furnaces (BOFs), and even less when the source energy is renewable (Embodied Carbon Quick Guide A Quick Reference Guide for Teams to Reduce their Project's Embodied Carbon, 2020). Zhang et al. (2022) found that implementing recycling practices and enhancing material production efficiency might lead to a roughly 50% reduction in EC emissions from the Chinese building sector by 2060. Hence, it is advisable to utilise salvaged or recycled materials whenever feasible to mitigate the emissions linked to the production of new materials. Gan et al. (Gan, Cheng, & Lo, 2019) said that incorporating 30-100% recycled scrap steel in reinforced concrete buildings could reduce EC emissions by 10-40%. Based on these results, a low-carbon steel alternative was selected from the EPD online library to replace the existing steel elements. Appendix E shows the three low-carbon steel substitutions conducted in this scenario.

Window frame substitution

Sinha and Kutnar (2012) compared the carbon footprints and thermal performance of three similar window frames in an area manufactured from aluminium, polyvinyl chloride (PVC), and timber. They found that the environmental performance of the timber window frame was superior to those of aluminium and PVC. Based on this result, timber window frames were chosen to replace aluminium

ones in the case studies. However, weatherproof sealants or preservatives are often recommended to enhance longevity and resistance to harsh conditions. In the material library of the calculation tool, two timber window frames were found, one with a double glass and the other with a triple glass. Appendix F shows the substitutions of the window frames.

Insulation substitution

Natural insulation materials in lieu of artificial ones with higher EC, such as Extruded polystyrene insulation (XPS), can reduce the upfront carbon emissions of a building by up to 16% (Esau, Jungclaus, Olgyay, & Olgyay, 2023). Therefore, cellulose and cork were selected from the calculation tool material library as natural insulation materials to replace the existing insulation materials in walls, attics, roofs, and floors. The properties of cork insulation sheets make them more suitable than cellulose for roofs and floors. A moisture barrier is necessary when using cork close to the ground or where there is a lot of moisture. Cellulose and cork insulations are warm materials with fantastic densities, making them the best thermally performing materials. Moreover, both insulations are durable, eco-friendly, made in Ireland, and registered with the Irish Agrément Board, NSAI (Cellulose insulation, N.d). Appendix G shows the existing insulation materials, cellulose, cork sheets carbon factors and thermal conductivities.

Upfront carbon emissions reduction results

The in-situ concrete with 70% GGBS reduced the upfront carbon emissions for all building typologies. The average reduction in non-residential buildings is 12.4%, higher than the 8.3% for residential buildings (see Appendix H). The reason behind the highest reduction percentages in apartments, schools, and office buildings is the use of large in-situ concrete quantities. In contrast to the results of in-situ concrete substitution, the use of low-carbon steel alternatives has a slight influence on reducing the EC of the case studies. This is because steel elements are not used in semi-detached or detached houses. The average reduction in non-residential buildings is 7.3%, about four times the 1.9% for residential buildings (see Appendix I). The warehouses' EC was the most significant reduction because of the large quantities of steel in their structural frames.

Replacing the aluminium and PVC window frames with timber frames reduced the upfront carbon emissions in residential buildings more than non-residential ones. The average upfront carbon emissions reduction in residential buildings is 5.1%, higher than the 3.1% average of the non-residential buildings (see Appendix J).

Cellulose and cork insulations effectively reduced the upfront carbon emissions of residential and non-residential buildings. The average reduction in residential buildings is 13%, about six times that of non-residential buildings (2.2%) (see Appendix K). One of the key considerations in shifting from one insulation material to another is the material's thermal conductivity (k) and the design constraints. For instance, achieving the same U-value of 50 mm EPS (k = 0.035 W/m.k) would require a thicker Cork/Cellulose insulation around 60 mm with thermal conductivity of 0.040 W/m.k. Moreover, replacing a steel frame with a timber frame does not apply to this tool, as the sizes of frames would be different. Thus, the only available replacement is selecting low-carbon steel from another supplier.

Figure 7 presents the overall reductions for the case studies where the results indicate that the combination of reductions can significantly mitigate the upfront carbon emissions. The average EC reductions in the residential and non-residential buildings are 17.7% and 15%, respectively. Overall, the potential reductions in all typologies are promising.

Discussion

Substitution scenarios reduced the upfront carbon emissions for all residential and non-residential buildings. However, more material substitution scenarios will be required from the end-users to increase the opportunities for reducing the buildings' upfront carbon emissions.

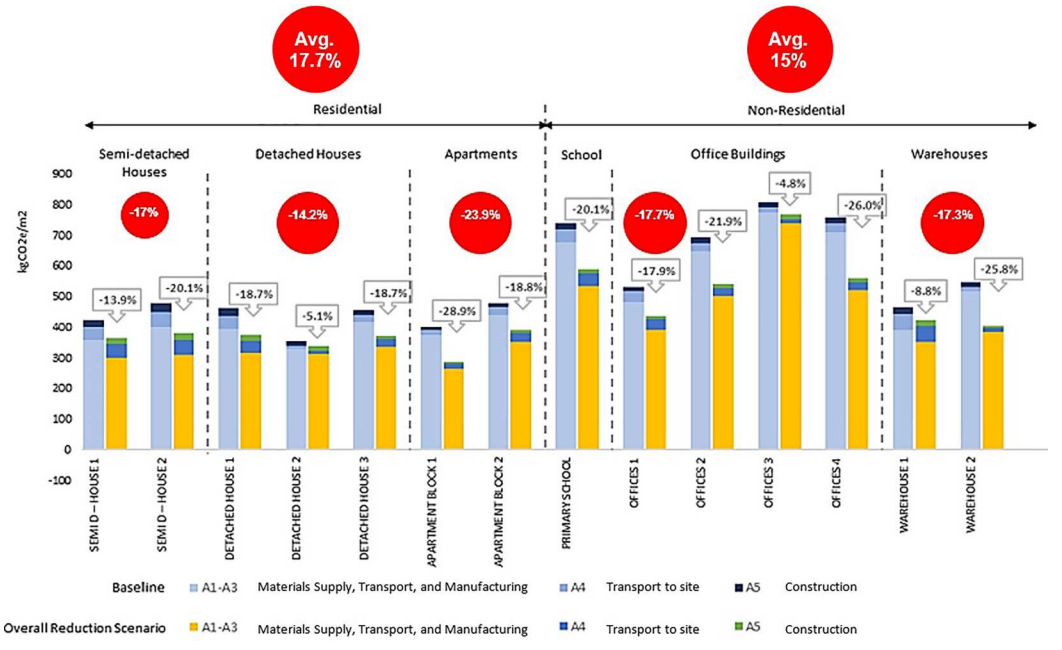

Figure 7. Baselines and their overall upfront carbon emissions reductions.

In Figure 8, natural insulations have the highest reduction average (13%) compared to in-situ concrete, with 70% GGBS (8.3%) in residential buildings. However, in non-residential buildings, in-situ concrete with 70% GGBS has the highest reduction average (12.4%), followed by steel elements with recycled scrap and EAF production (7.3%). Timber frame windows have a higher reduction average in residential buildings (5.1%) compared to 3.1% in non-residential buildings. The reduction average of sustainable steel in residential buildings is minimal (1.9%) due to this typology's low quantities of steel elements. In non-residential buildings, timber window frames and natural insulations have low upfront carbon emissions reduction averages of 3.1% and 2.2%, respectively. Table 5 demonstrates that material substitution methodology can reduce the upfront carbon emissions of residential buildings by up to 28.3% and up to 25% for non-residential buildings, using lower-EC materials widely available today. Moreover, Table 5 shows that the EC reductions in the literature

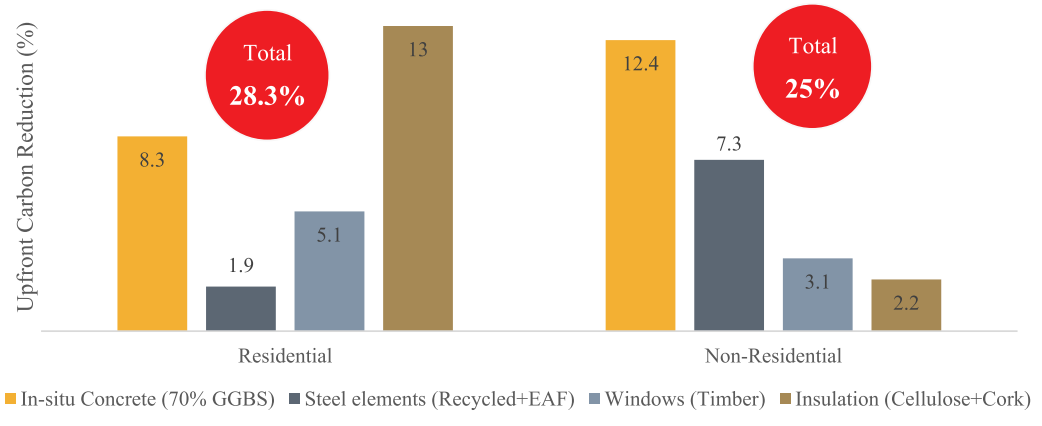

Figure 8. The average of upfront carbon reductions by substitution scenarios for residential and non-residential buildings.

Table 5. The averages of EC reductions in the current study are compared to similar averages in the literature review.

Key Materials	Material substitution				EC reduction averages in the current study		Similar EC reduction in the literature review
	Conventional		Low carbon		Residential	Non-residential	
Concrete	In-situ		In-situ with 70% GGBS		8.3%	12.4%	30% (Goggins et al., 2010; RIAI, 2023)
Steel	Cold rolled coil Galvanised steel Steel section	BOF & no scrap steel	Cold rolled coil Galvanised steel Steel section	EAF with >95% Scrap steel	1.9%	7.3%	Up to 40% (Gan et al., 2019)
Window frame	PVC Aluminium Timber-Alu	with double glass with triple glass	Timber with dou glass Timber with triple glass		5.1%	3.1%	n/a
Insulation	Polyurethane EPS PIR Polystyrene Fiberglass Mineral wool	Sheep wool Rockwool Wood fibre Paper wool Hemp fibre	Cellulose and cork		13%	2.2%	Up to 16% (Esau et al., 2023)
			Overall reductions		**Up to 28.3%**	**Up to 25%**	

review were higher for the in-situ concrete (Goggins et al., 2010; RIAI, 2023) and steel (Gan et al., 2019) substitution scenarios with vast differences. These differences refer to the Irish buildings' low quantities of concrete and steel. However, for the insulation substitution scenario, the average reduction in the current study is in the range of reductions mentioned in the literature review. The comparison between the previous and the current results shows that the material substitutions will not get us so far. Therefore, optimisation, recycling, reusing materials, and building less are recommended for significant reductions. Regarding the Irish government's CAP targets (Department of the Environment, 2023; United Nations, 2023), the developed material substitution methodology achieved and exceeded the 20% EC reduction target by 2030. Substitution scenarios can be modelled for the rest of the materials with significant contributions, such as Stone/Brick, Concrete Blocks, and Aluminium, to achieve more reductions.

Conclusions

The current study developed a standardised methodology with a tool adaptable to the national levels for calculating and reducing buildings' upfront carbon emissions. The primary objective of the present study is to cross the barriers that architecture firms face in calculating and reducing the EC of their projects due to the unreliable materials EC data, the difference between the methodologies, and the complexity of tools. The secondary objective is to enhance sustainable practices in the Irish built environment by adopting a standardised methodology to calculate and reduce the EC of buildings. Twelve architecture firms applied the developed methodology to 14 case studies in Ireland and reported their results. The findings indicate that residential and non-residential buildings' average upfront carbon emissions are 436 and 648 $kgCO_2e/m^2$, respectively. These averages validated the methodology and the calculation tool, as the results align with the EU averages.

The proposed reduction methodology substituted the top four impactful material categories (in-situ concrete, steel, insulation, and window frame). The reduction results surpassed the Irish CAP 20% EC reduction target by 2030. There were some limitations in the substitutions related to the design constraints, such as replacing a steel frame with a timber frame since the size of the timber frame would be different and require design modifications. Thus, the only available replacement was

the low-carbon steel from another supplier. Moreover, there were geographical limitations on the alternative materials that must be available in the Irish market or imported within a reasonable distance and qualified to the Irish standards. Additional reduction measures could be useful for more significant reductions, such as optimisation, recycling, reusing materials, and building less.

In the future development of the methodology, the reductions can go further by considering more key materials. The methodology can be reproduced or modified in different contexts with equal sophistication in the upfront carbon emissions inventory data. The authors would advocate implementing this methodology at scale to raise the profile of EC among building designers, encourage the demand for emissions data from manufacturers, and create transparency, driving down carbon emissions in the construction sector.

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Author contributions

Youssef Elkhayat: Data curation, Investigation, Writing – Original draft preparation, Visualisation. Paul Moran: Writing – Reviewing and Editing. Stephen Barrett: Methodology, Software, Validation. Pat Barry: Project administration. Jamie Goggins: Conceptualisation, Supervision, Funding acquisition.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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