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Promoting decarbonisation in the construction of new buildings: A strategy to calculate the Embodied Carbon Footprint

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ABSTRACT

Building construction significantly contributes to global greenhouse gas emissions, with embodied carbon playing a critical role in the environmental impact of new buildings. This research addresses the pressing need to reduce embodied carbon emissions by developing an integrated strategy to assess and compare the embodied carbon footprint of building projects. The proposed methodology, organized into three steps and grounded in Life Cycle Assessment (LCA) principles, divides buildings into four sections: structure, envelope, interior, and exterior, enabling precise identification of carbon-intensive products. Data collection is enhanced by promoting the use of Environmental Product Declarations (EPDs) for accurate material-specific carbon calculations. This strategy integrates a detailed section-level analysis with transparent reporting of embodied carbon impacts, addressing limitations in prior approaches that lack lifecycle comprehensiveness or detailed material-specific insights. The key contribution of this research lies in its practical applicability during the early phases of building design, where adjustments to reduce carbon emissions are most feasible. The novelty of the study stems from its capacity to compare entire buildings and individual sections, including promoting low-carbon innovations and benchmarking for sustainable construction practices. Besides, accounting embodied carbon footprint for the exterior section is a new contribution since the area has been underexplored, as most studies focus on the building itself rather than its surrounding environment. Thus, this research provides valuable guidance for policymakers and industry stakeholders, emphasizing the importance of early interventions and comprehensive carbon accounting in achieving decarbonization goals in the construction sector.

1. Introduction

Rising carbon levels in the atmosphere have been observed since the beginning of the Industrial Era. The globally averaged concentration of carbon dioxide (CO_2) in the atmosphere reached 418 parts per million (ppm) in 2022, being 150 % higher than 1750 levels [1]. The increasing greenhouse gas (GHG) concentrations in the atmosphere are directly linked to climate change and its catastrophic consequences [2–5]. In order to prevent such an irreversible scenario, the Paris Agreement was established under the United Nations Framework Convention on Climate Change (UNFCCC), providing a global framework to tackle climate change and

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promote international cooperation in reducing GHG emissions [6].

In this context, different regions around the globe have developed their own internal implementation plans to meet the targets set under the Paris Agreement. In Europe, the European Commission has published the European Green Deal, which sets the challenge of becoming the first carbon-neutral continent by 2050 [7]. Beyond the European Union, several other countries have declared their commitment to achieving carbon neutrality by 2050, including Canada [8], the United States of America [9], Chile Gobierno de Chile [10], South Africa [11], and Japan Kiko Network [12]. Other nations have set later targets, such as Indonesia, which aims for carbon neutrality by 2060 [13], and India, which has set its target for 2070 [14]. To accomplish this challenge, all economic sectors in different countries are directing their efforts towards GHG emissions mitigation, with the construction sector playing a particularly critical role [15–18]. This demonstrates that the construction sector is strongly affected by the carbon-neutral goals stablished for each region.

The built environment sector accounts for 37 % of the global carbon emissions [19]. From this percentage, at least 6 % are embodied emissions that come from the construction and deconstruction processes associated with building materials such as concrete, steel and aluminium [19]. The embodied carbon emissions refer to the total amount of GHG emitted during the entire life cycle of the materials and processes involved in the construction and deconstruction of the building. This includes emissions associated with the extraction of raw materials, the manufacturing of building materials, the transportation of the materials, the construction processes, the maintenance and renovations and the end-of-life disposal [20].

Thus, according to the Intergovernmental Panel on Climate Change (IPCC), the building construction sector has the potential to achieve carbon neutrality through several interventions, such as the use of low-emission construction materials, the implementation of well-designed building envelopes with integrated passive solutions, or the combination of green and grey infrastructures [21]. Furthermore, some countries have established regulations setting requirements for the safety, quality, and sustainability of construction products sold or used within their borders. For example, the Canadian Standards Association developed standards regulating construction products and materials in Canada, with a focus on safety, performance, and sustainability [22] and the Chinese National Standards also published a series of guidelines and requirements related to energy efficiency, the use of sustainable materials, the reduction of carbon emissions, and the promotion of green building [23]. In Europe, the European Construction Product Regulation (CPR) advances sustainability and transparency in the construction sector, aiming to reduce carbon emissions in the European building sector [24]. Therefore, new construction projects should adopt strategies aimed at reducing the GHG emissions to the atmosphere and increasing the GHG removals from the atmosphere [25–28].

The balance between the GHG emissions and removals in a product system calculated based on Life Cycle Assessment (LCA) methodology using the impact category of climate change is the carbon footprint (CF), expressed as CO_2 equivalents [29]. The determination of the CF when a building project is developed is paramount because it allows the effective assessment and quantification of the GHG emissions associated with the building life cycle. This essential information plays a significant role in making informed decisions regarding sustainable design, construction, and deconstruction processes, as well as in selecting sustainable construction materials. It also helps in establishing realistic targets for reducing embodied carbon emissions, which are the emissions generated during the production, transportation, construction, refurbishment, retrofitting, and deconstruction of buildings throughout their lifetime [30]. For instance, the French government has established maximum reference values for the embodied CF from construction products and equipment, as well their implementation on buildings [31]. For collective housing these values are set at 650 kg $CO_{2\ eq}/m^2$ for the period 2024–2027, 580 kg $CO_{2\ eq}/m^2$ for the period 2028–2030, and 490 kg $CO_{2\ eq}/m^2$ for 2031 and beyond. For detached or semi-detached houses, the thresholds are even lower at 530 kg $CO_{2\ eq}/m^2$ for the period 2024–2027, 475 kg $CO_{2\ eq}/m^2$ for the period 2028–2030, and 415 kg $CO_{2\ eq}/m^2$ for 2031 and beyond. The reduction of these limits is expected to lead to a significant decrease in the environmental impact of construction in France over the next years, contributing to continuous improvement in sustainability efforts.

In 2023, Denmark has also imposed limits of 12 kg $CO_{2\ eq}/m^2$/year for both operational and embodied carbon emissions for all new buildings with area above 1000 m^2. This threshold limit will be revised and its reduction to 7.5 kg $CO_{2\ eq}/m^2$/year is expected after 2029 [32]. However, in contrast to operational carbon emissions, which are associated with the ongoing maintenance and operation of buildings, embodied carbon is locked in the building upon completion of construction [33]. By measuring the embodied CF at the preliminary phase of the building project, potential sources of high emissions can be identified, enabling the implementation of effective mitigation measures to minimize environmental impacts and to fulfil national carbon regulations. This, in turn, promotes energy efficiency and facilitates the transition towards low-carbon construction practices [34,35]. Moreover, the embodied CF determination serves as a benchmark for comparing different building projects, fostering competition, and driving innovation in the construction industry towards integrating environmentally friendly practices into the entire project life cycle [36]. Overall, the quantification of the CF also provides policymakers, investors, and stakeholders with valuable information to make informed choices regarding construction materials, energy sources, transportation options, and waste management. Consequently, this contributes to the development of a more sustainable built environment in accordance with global climate change priorities [37].

The possibility of raising awareness among building stakeholders, *i.e.* building designers, engineers, architects, and planners, regarding the sustainability of buildings is vital in enhancing the environmental performance of the building construction projects. These professionals play a key role in influencing decisions that directly impact GHG emissions throughout the design, construction, operation, and demolition stages of a building. Their choices regarding low-environmental-impact building materials, design strategies in the early stages of the project, and the promotion of materials with lower GHG intensity over the building's entire life cycle are essential. Furthermore, they can contribute to sustainability through the implementation of material circularity solutions, design for deconstruction, the integration of green innovations such as nature-based solutions in the building's surroundings, as well as through advocating for incentives that promote the use of eco-friendly materials or supporting regulations that mandate carbon offsetting or carbon neutrality in new projects [38].

As the building is a complex system consisting of different construction and building materials, products, and components (hereafter referred to as “building products”), stakeholders in the construction industry must be familiar with methodologies that allow them to accurately measure the embodied CF of each element or process incorporated throughout the building’s lifespan [39,40]. Additionally, they should be able to analyse and identify alternative solutions with a lower CF Markström et al., 2018. This creates the need to reduce embodied carbon emissions in buildings, associated with construction materials, throughout the cradle-to-grave perspective of buildings - from raw material extraction to construction, maintenance, demolition and disposal. Then, the central challenge lies in reducing GHG emissions in construction and developing a transparent and effective approach to measure, compare, and mitigate these emissions.

In this context, Fang et al. [41] identified five important tasks that need to be addressed in the calculation process of the embodied CF of buildings: preparation of the building project draft, selection of the applicable methodology for calculation, data collection, results analysis, and visualisation of the results. Gan et al. [42] observed similar tasks in the established systematic approach to calculate and mitigate the embodied CF of buildings. However, they considered just one type of building construction, and the approach can only be applied to reinforced concrete buildings [42]. In contrast, Li et al. [43] developed a method to calculate the embodied carbon emissions that can be applied in different types of buildings, regardless of their material and structure. The authors explored the Work Breakdown Structure to divide the building project into construction activities in order to track the carbon emitted in the pre-occupancy stage of the construction project. This division allowed tracking the embodied carbon emissions back to the source, and thus concluding that reducing embodied carbon in construction projects has a very significant impact for designers and owners, rather than contractors, as the choice of materials and construction processes directly influence carbon emissions [43]. However, the method developed by Li et al. [43] for measuring the embodied CF only presents the results for the total building CF, which is not practical for identifying the life cycle stages with the greatest impact in terms of embodied carbon. The need of transparency in presenting the CF results was identified in the method designed by Li et al. [44]. This method combines different research methods to calculate the embodied carbon of a residential building along its lifespan. The authors divided the building into six subsystems to analyse the embodied carbon, which is an alternative division compared to the division in terms of construction activities. The subsystems consist in life cycle stages of the building: production, transportation, construction, maintenance, demolition and disposal of materials [44]. In order to calculate the embodied CF according to this method, it is crucial to understand the carbon intensity of each building product used in the construction to determine its specific impact. However, when discussing building products from different manufacturers, the accuracy of the embodied CF may vary among them. Besides that, generic data considered in the method developed by Li et al. [44] for the embodied CF of materials are not as accurate as product-specific data [45].

Considering the above limitations and the importance of making comparisons between building projects with different building products and construction processes, this paper aims to develop a strategy to support decarbonization in building projects through an embodied CF calculation strategy to quantify, analyse, and compare building embodied CF at an early stage of the construction project. This paper makes a novel contribution to the building project development as it promotes an integrated strategy to quantify the embodied CF of building projects based on LCA methodology that.

- enables the comparison between entire buildings (and building sections), following a cradle-to-grave perspective,
- identifies the building products (and building sections) that account for the largest embodied CF results, presenting the total CF and the CF of each life cycle stage,
- considers the CF of specific building products (size, model, manufacturer, production location) identified by the building stakeholders, whenever its environmental performance is available,
- promotes the use of Environmental Product Declaration (EPD).

Taking into account the importance of transparency in declaring the embodied CF of a construction project, this strategy is expected to be applied during the preliminary project phase, once the building stakeholder has defined the building design and identified the building products to be considered. However, this strategy should be executed prior to the construction phase starting on site. By implementing this strategy at this point in time, the building project can be adjusted by replacing building products with high embodied CF with low-carbon alternatives aiming to reduce the embodied CF of the constructed buildings.

2. Embodied CF calculations

The embodied CF comprises GHG emissions that may include gases such as CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (HFCs, PFCs, SF_6, NF_3) (IPCC, 2023). In the calculation of the CF, the emissions from the different GHG are expressed in a common unit relative to a reference. This means that the emissions are converted into CO_2 equivalents using the Global Warming Potential (GWP) factors for each GHG as stated in IPCC [21].

The calculation of the embodied CF of building products is based on the LCA methodology, which is normalised by ISO standards 14 040 and 14 044 [46,47]. LCA methodology starts with the goal and scope definition phase, where the objectives of the study as well as the life cycle stages considered, among other aspects, are defined. Then, the Life Cycle Inventory (LCI) phase requests the collection of the data on inputs and outputs of each process included in the system boundaries. In the next phase, the Life Cycle Impact Assessment (LCIA) phase, the embodied CF is calculated as CO_2 equivalents by multiplying the inventory results of each GHG by the respective GWP established by the IPCC. Finally, in the Interpretation phase, the life cycle results are analysed according to the defined goal (Fig. 1).

For the impact assessment method used in the LCIA phase, the European Commission recommends the use of the Product Environmental Footprint (PEF) method in assessing the impact of products [48]. This recommendation aims enhancing the measurement and communication of the environmental performance of distinct types of products in relevant European policies. By advocating for the adoption of common methods for evaluating and communicating the environmental performance of products throughout their life cycles, the PEF method has been officially endorsed in the updated version of EN 15804 standard to support the development of EPDs [49].

From the 16 environmental impacts covered by the PEF method, the climate change impact category is highlighted in this study. This impact category combines three impact subcategories within the CF [48]. The first subcategory is "climate change – fossil", which evaluates GHG emissions and removals resulting from the oxidation or reduction of fossil fuels or carbon materials through various processes such as combustion, incineration, or landfilling. The second subcategory is "climate change – biogenic", which includes either CO_2 removals by biomass (excluding native forests) and GHG emissions originating in biomass. The third subcategory is "climate change – land use and land use change (LULUC)", which considers GHG emissions and removals from changes in carbon stocks due to LULUC, including biogenic carbon resulting from deforestation. The impact category "climate change" or "climate change – total" is the sum of the three subcategories.

The embodied CF of construction materials can be found in industry, national or global databases [50,51]. Besides, EPDs are also possible sources for collecting these data. EPDs are registered by each manufacturer and account for the real environmental impact of a product, considering the energy and raw material needs used by the manufacturer at the production plants [45,52,53].

As a building is a complex system with different building products, the embodied CF of a building is calculated by summing the embodied CF of all materials, products and components integrated in the construction, taking into account the amounts of each particular building product.

3. Strategy for decarbonization in building projects

The adoption of design concepts that guide decarbonization actions in buildings, even at the initial stage of the project, encourages the use of low carbon materials and techniques. These design concepts are linked to the architectural and structural design to promote the circular value of building materials, considering the extended service lives of building materials to minimize the need for replacements throughout the building's lifespan [54]. Table 1 summarises the design concepts that should be explored when the preliminary building project is developed, namely, the design for adaptability, the design for deconstruction, the design for durability, and the design for circularity and reversible building.

To reduce the embodied CF of building projects, the aforementioned concepts have the potential to encourage the development of low carbon buildings. Nevertheless, implementing these design concepts does not necessarily guarantee a decrease in the building embodied CF [55,56]. Therefore, it is paramount to calculate the embodied CF considering a cradle-to-grave perspective of new buildings before construction begins.

The proposed strategy for quantifying the embodied CF of building projects consists of three main steps. Firstly, the scope of the building project is defined, including the project characterization, the boundary of the system, the building' lifespan, and the definition and identification of all building products considered in the project. Secondly, data collection is conducted through available data sources to gather the necessary information for calculating the embodied CF of the building. Lastly, the calculation of the embodied CF is carried out, with results being discussed and recommendations made to promote decarbonization alternatives in building construction. These steps align with established methodologies such as those outlined in EN 15978 standard [57] related to the environmental performance of buildings, ISO 14040 and 14 044 standards [46,47], PEF method [48], EN 15804 standard [49], and the Levels Methodology for determining the embodied CF for the building life stages [54].

The description of the strategy to quantify, analyse, and compare building embodied CF at an early stage of the construction project

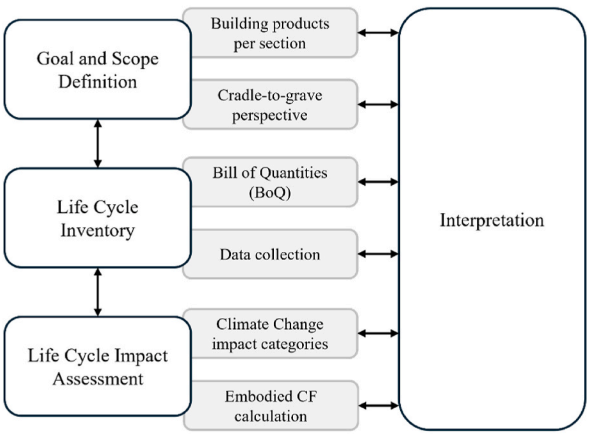

Fig. 1. Steps for calculating the Embodied Carbon Footprint (CF).

Table 1
Design concepts implemented in the strategy for decarbonization and their definition.

Design concept	Definition	References
Design for adaptability	A focus on how the design of a building could facilitate future adaptation to changing occupier needs, market conditions and environmental changes.	[55,69]
Design for deconstruction	Allows a reduction of a considerable portion of waste material flows generated from manufacturing, construction, and demolition on a site that will be directed to reuse and recycle processes.	[55,70]
Design for durability	It is anticipated that the structure will withstand various environmental factors and conditions over time, prolonging the lifespan of structures and their critical components, which are crucial points in their life cycle.	[71,72]
Design for circularity and reversible building	Buildings can easily be transformed in function and structure, promoting circular flows of resources and materials while minimizing costs for design changes. Reversible buildings and circular components not only reduce demolition wastes but also limit the need for new material inputs.	[73,74]

is presented in detail in the next sections.

3.1. Building project scope

To calculate the embodied CF of a building, the project scope should be established first. This includes defining the building products that will be integrated into the building. For this, the building is divided into four sections: building structure, building envelope, building interior, and building exterior. The building structure encompasses materials that belong to the structural framework of the building, including foundations, columns, beams, and other materials deemed part of the structure as defined by the project design. The building envelope refers to all materials that separate the interior of the building from the external environment, such as exterior walls, roofs, conventional or green façades, doors, and windows. The building interior includes all materials and products incorporated within the interior space of the building, for instance internal doors, walls, finishes, mechanical systems, electrical installations, and plumbing. Lastly, the building exterior consists of materials and products situated in the surrounding area of the building that are part of the project, including outdoor parking areas, gardens, and perimeter walls.

This four-section categorization provides a practical framework that reflects the distinct roles and performance requirements of various building components. It can be broadly adopted due to its functional clarity and alignment with design and construction processes, as every building project has at least one of the four proposed sections. As an example, if the building project includes only the structure, envelope, and interior sections, the embodied CF for the exterior section will be zero.

All the building products identified by the project are grouped according to their respective section, providing a detailed insight into the CF of each individual section of the building. To standardize the building sections, Table 2 details the four building sections and lists examples of building elements that belong to each section, along with examples of building products. While the building sections are clearly defined in this strategy, the suggested list of building elements may not be exhaustive. Additional building elements can be included as needed based on the scope of the building's embodied CF assessment. The categorization of materials in each section depends on the specific project. For example, if a building includes a photovoltaic panel on its roof, the embodied CF of that panel will

Table 2
Building sections, building elements and examples of building products.

Building section	Building elements	Examples of building products
Building structure	Foundations and piles	Concrete, timber, steel, aggregate
	Retaining walls	
	Stairs	
	Waterproofing	Membranes
	Roof structure	Concrete, timber, steel, intumescent paint, chimneys, smoke vents
	Balconies	Concrete, timber, steel, railing, glass panel
Building envelope	External walls	Concrete, timber, steel, insulation, sheathing
	Green covers	Green roofs, green façades
	Shading devices	Framing, shadings
	Windows and external doors	Framing, glazing, door, ironmongery
	Roof weatherproofing	Membrane, tiles, bitumen layer
	Renewable energy installations	Solar/photovoltaic panels
Building interior	Internal walls and ceiling finishes	Plasterboard, brick, blocks, mortar, insulation, plaster, paints, varnish
	Internal floor finishes	Membrane, screed, tiles, adhesive, grout, timber, carpet
	Internal doors	Framing, door, ironmongery
	Internal stairs	Railing, plaster, paints, varnish, timber, carpet
	Sanitary fittings	Shower trays, toilet seat, bathtub, shower equipment, taps
	Other interior building materials	Electrical installation, plumbing system, interior mechanical equipment
Building exterior	Exterior flooring	Base, asphalt, stones, pavers, mortars
	Parking	Concrete, timber, steel, aggregate
	Vegetation and gardens	Plants, soil
	Fence, railing, and walls	Timber, concrete, timber, steel, aggregate

be accounted for within the building envelope. However, if the panel is installed in a garden or yard associated with the building, it will be considered part of the building exterior.

To avoid ambiguity regarding where building materials should be categorized, careful attention must be given to the project. For instance, if ceramic tiles are used in both the building envelope and the interior, the ceramic material will be accounted for in both sections, based on the quantity required in each respective section. This means that the same building product may appear in multiple sections, depending on its quantity in each and the project specification. This approach ensures that the quantity and type of building products in each section are clearly identified.

The proposed strategy adopts a cradle-to-grave perspective and quantifies the specific proportion of the embodied CF of each life cycle stage, which is crucial to understand not only the emissions from the raw materials extraction and product manufacturing processes, but also the emissions resulting from the construction works, the replacement of building components and the disposal processes [58,59]. Therefore, for each building product, the system boundary includes all life cycle stages, *i.e.* the extraction and upstream production of raw materials, the transportation to the factory and the corresponding manufacturing processes; the distribution and installation into the building; the processes related to the use stage whenever maintenance, repair, replacement, and refurbishment works are needed, including the production and transportation of materials or products, and ancillary components for these processes; the deconstruction or dismantling and the transportation to waste processing facilities; the waste treatment for reuse, recovery or recycling; and waste disposal (Fig. 2).

The results of the building's embodied CF are presented based on 1 m^2 of building total gross floor area for the full lifespan of the building, serving as a reference for comparison between different buildings. This reference ensures the comparability of the CF results in a common unit [60].

3.2. Data collection

This step consists in the collection of all the necessary data for conducting the embodied CF calculation, in line with the scope of the building project. The quantities, in mass, of all materials and products previously identified for each building section must be registered. When the quantities are not expressed in mass units, conversion factors, such as the density of the building product, must be applied. Moreover, the identification of the Reference Service Life (RSL) for the building products is crucial since it estimates the period in which the product is in-use conditions [61]. The RSL will determine the frequency at which the building products will be replaced in the building.

In addition, the distances related to the building products transportations to the factory, to the building site and to the waste processing facilities must be provided. All these data are compiled in a detailed bill of quantities (BoQ) [43,62]. Therefore, in this strategy, the BoQ of the building project provides not only an estimated list of building products and their quantities, but also other aspects such as the RSL, the distance between sites, and their mass or density.

To calculate the embodied CF of a building, the CF of each building product integrated into the construction must be known. The use of values of CF specific for each building product is highly recommended to guarantee the veracity of the results. According to EN 15941, specific data obtained from the specific manufacturer should be the first choice when performing a LCA study for an EPD [57, 63]. Thus, EPDs are considered the most accurate sources to obtain CF data from specific manufacturers.

EPDs are verified environmental declarations conducted by manufacturers in accordance with the specifications outlined in EN

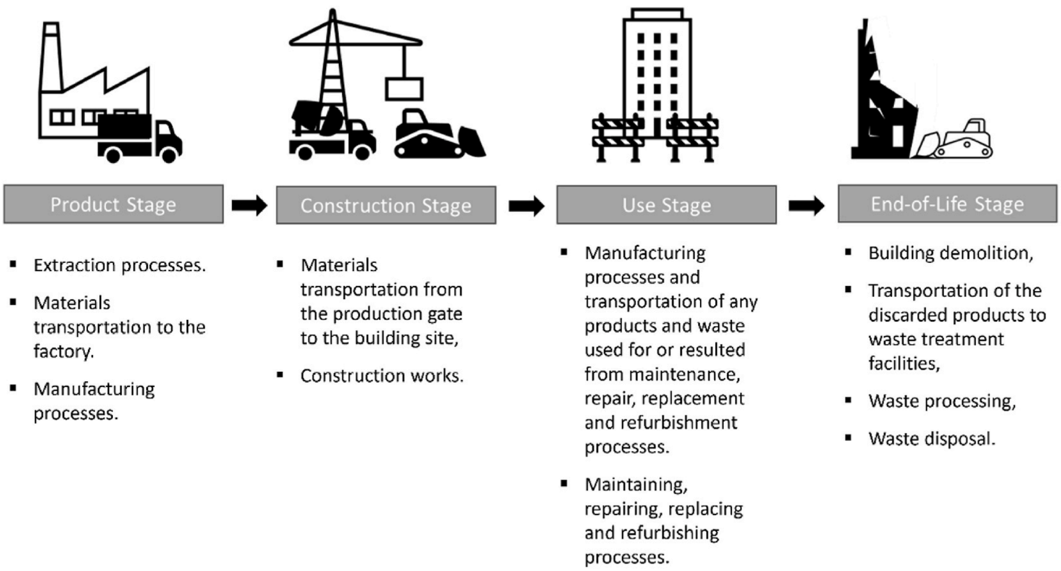

Fig. 2. Building stages and their processes included in the strategy to account for the embodied Carbon.

15804, ISO 14025, and ISO 14040–44 [46,47,49,64]. Information about the product's resource use, energy consumption, emissions, and waste generation are reported in EPDs for each life cycle stage of the product. EPDs can guide consumers to choose products that have lower environmental impacts as they provide transparent and comparable data on the environmental performance of specific products [65]. These sources of environmental data can serve as reliable tools for communicating and performing CF calculations for buildings [66].

If this information is available in an EPD, it can be used in the strategy, provided the established transportation scenario aligns with real-case conditions. Since the scenarios in EPDs may not accurately reflect actual distances, it is crucial to use real sources, such as logistics records, transportation invoices, or GPS tracking data. This ensures the accurate identification of transport modes (road, rail, air, or sea) for each building product at each stage of its life cycle. Finally, emission factors for transportation-related embodied CF should be obtained from reliable databases, such as Ecoinvent [77]. This data, together with the transport mode for each product throughout its life cycle, is essential for accurately quantifying the CF associated with transportation activities.

When collecting data from EPDs, the availability and quality of data must be observed. Key considerations should include the type of EPD (product-specific, average, or generic), the geographical relevance to the project's context, the temporal representativeness (preferably less than three years to ensure the use of current data), the life cycle system boundaries, the existence of EPD third-party verification, and the compatibility with reliable normative standards such as ISO 14025 and EN 15804.

In cases where a specific EPD is not available for a particular product, but EPDs are available for similar products from other manufacturers, it is recommended to perform sensitivity analysis. This involves testing different EPDs available for the same type of product, even if produced by different manufacturers, to understand the magnitude of variability in the results. In this analysis, worst-case and best-case scenarios can be modeled based on the minimum and maximum values reported by the EPDs. When interpreting the results, the pessimistic scenario can be presented as a prudent baseline, while the optimistic scenario can highlight potential opportunities. By employing this approach, the effects of data uncertainty and gaps can be mitigated, improving the accuracy of CF calculations and providing a more robust basis for decision-making.

EPDs that have undergone data verification procedures, such as periodic audits or third-party validations, ensure that the data used is of high quality and reflects the most current and accurate information available.

For this strategy, the calculation of the embodied CF should be based on the three subcategories "climate change – fossil", "climate change – biogenic" and "climate change – land use and land use change", for each building product used in the construction process. This requirement means that only EPDs registered according to the last version of EN 15804 are valid, as the previous version of that standard did not include the declaration of all these subcategories. Furthermore, when comparing the embodied CF of different building products based on their EPDs, the product category definition and description, *i.e.* the function, technical performance, and intended use, should be similar. The functional unit should be identical for the materials and products under comparison, which in some cases may require a conversion to the desired reference flow. The system boundaries should also be the same and the validity period of the EPDs should be equivalent for accurate product comparison [64].

Following these requirements for EPDs data collection, the CF for the product stage (modules A1-A3 in EPDs according to EN 15804) are globally valid since they are solely based on production and manufacturing processes inherent to the specific building product. However, when the EPD covers the construction stage (modules A4-A5), use stage (modules B1-B7) and end-of-life stage (modules C1-C4), it is crucial to understand and analyse the scenarios considered for the region where these stages are assumed to take place. For instance, the end-of-life alternatives (e.g. recycling, landfilling, incineration) may vary depending on the country. This analysis is imperative as it enables the understanding of whether the aspects considered in an EPD for construction works, product use, transportation options, waste processing and disposal align with the aspects considered for the building project under study.

Table 3
European Programme Operators for Environmental Product Declarations registration [67].

Country	Programme operator	Available EPDs on July 1st' 2024	Reference
Sweden	The International EPD® System	4410	www.environdec.com
France	Programme INIES	3502	www.hqegbc.org
France	PEP ecopassport®	2472	www.pep-ecopassport.org
Germany	IBU – Institut Bauen und Umwelt	1894	ibu-epd.com
Norway	The Norwegian EPD Foundation	1792	www.epd-norge.no
Denmark	EPD Danmark	361	www.epddanmark.dk
Netherlands	Stichting MRPI®	284	www.mrpi.nl
United Kingdom	BRE Global	271	www.bregroup.com
Germany	Kiwa-Ecobility Experts	242	www.kiwa.com
Italy	EPD Italy	217	www.epditaly.it
Poland	ITB EPD Program	196	www.itb.pl
Finland	RTS EPD	159	https://cer.rts.fi/en/rts-epd/
Spain	Global EPD	154	www.aenor.com
Germany	ift Rosenheim	144	www.ift-rosenheim.de
Spain	DAPconstrucción®	110	www.cateb.cat/dapcons
Ireland	EPD Ireland	89	www.igbc.ie
Portugal	DAPHabitat	33	daphabitat.pt
Austria	Bau EPD	26	www.bau-epd.at
Slovenia	ZAG EPD	24	www.zag.si
Switzerland	Programm für Umweltproduktedeklarationen des SÜGB	22	www.sugb.ch

The existence of a common European database for EPDs of construction and building products – ECO Platform – which centralises the EPDs of hundreds of European construction products in one place [67], makes easier the collection of data. Besides that, different Programme Operators from Europe have their own EPD databases (Table 3).

Despite the increasing amount of European EPDs published at the ECO Platform (16 402 in the last ECO Platform updated [67]), EPDs are not mandatory documents, which leads to a restricted availability of these documents related to some specific materials and products previously integrated in the building project. When the CF of a particular building product is not available through EPDs, other sources can be used to collect CF data, such as industry data, databases or literature. However, the updating of the European CPR addresses environmental aspects that ensures efficient operation of the single market and the free movement of construction products in the European Union (EU), including the promotion of low-carbon and carbon-storing construction products [24]. Under the updated CPR, manufacturers will have the obligation to declare the climate change impact category of their construction products [24]. This means that according to the European CPR, in the near future there will be more reliable and available data information relating to the CF of each specific building product in the European market. All this data will be crucial to accurately calculate building embodied CF.

However, given the European specificity of the CPR, in regions where EPDs are not widely used, and where their quality does not follow standards regulated by legislation or other normative frameworks that consider the specific conditions of the region, or even where they are not required, the alternative is to use data from databases, LCA studies, or other available information in the literature.

3.3. Calculation of building embodied CF

The calculation of the building embodied CF is the final step of this strategy. Since this strategy divides the building into four sections, to calculate the embodied CF of the building, it is necessary to determine the embodied CF of each section and consequently the embodied CF of each building product considered in the project.

Thus, considering a cradle-to-grave perspective, the embodied CF of each building product is determined by multiplying the respective specific embodied CF along the building's lifespan, *i.e.* considering all the stages presented in Fig. 1, by the mass of the building product indicated in the BoQ. Equation (1) elucidates this operation.

$$\mathrm{CF_p} = \sum_{s=1}^{4} \textit{Specific embodied } CF_{sp} \times Q_p \qquad \text{Equation 1}$$

Where:

$\mathrm{CF_p}$ refers to the embodied CF of the specific building product *p,* in kg $CO_{2\ eq}$;

Specific embodied $\mathrm{CF_{sp}}$ refers to the embodied CF of each life cycle stage *s* of the specific building product *p,* in kg $CO_{2\ eq}$/kg building product. The index *s* refers to the life cycle stages represented in Fig. 1, as $s = 1$ for product stage, $s = 2$ for construction stage, $s = 3$ use stage and $s = 4$ end-of-life stage.

$\mathrm{Q_p}$ refers to the mass of the building product *p,* in kg.

According to the division of building products in their respective building section, the embodied CF of each building section is determined through Equation (2).

$$\mathrm{CF_{bs\ i}} = \sum \mathrm{CF_p} \qquad \text{Equation 2}$$

Where:

$\mathrm{CF_{bs\ i}}$ refers to the embodied CF of a building section *bs i,* in kg $CO_{2\ eq}$.

$\mathrm{CF_p}$ refers to the embodied CF of each building product *p* that belongs to the building section *i,* in kg $CO_{2\ eq}$;

The index *i* represents each building section, as $i = 1$ is for building structure, $i = 2$ is for building envelope, $i = 3$ is for building interior, and $i = 4$ is for building exterior. As the building is divided into these four sections, the embodied CF of a building is the sum of the embodied CF determined in each building section (Equation (3)).

$$CF_b = \sum_{i=1}^{4} \mathrm{CF_{bs\ i}} \times (1 / A_b) \qquad \text{Equation 3}$$

Where:

$\mathrm{CF_b}$ refers to the total embodied CF of the entire building along its lifetime, in kg $CO_{2\ eq}/m^2$;

$\mathrm{CF_{bs\ i}}$ refers to the embodied CF of the building section *bs i,* in kg $CO_{2\ eq}$;

$\mathrm{A_b}$ refers to the building total gross floor area, in m^2.

By dividing the environmental impact of a building by its total area, it is possible to compare the embodied CF in a more effective way, as this provides a more accurate representation of the CF associated to the entire structure, no matter the differences in building designs, sizes, and layout. Moreover, dividing the embodied CF by the building total area in alternative to the building useful area offers a more comprehensive understanding of the overall embodied CF of the total building, including areas that are not accessible to building users.

The results obtained for the embodied CF in buildings and in each of their four sections can be compared between them. When analysing building sections or building projects, the use of visual and graphical elements that allow for immediate comparison is relevant, as the immediate interpretation of the results is an asset for building stakeholders to understand in a relatively simple way which building project has a better environmental impact in terms of embodied CF, what are the sections with better performance, and consequently which materials or products are significantly contributing to the CF obtained. These elements facilitate the interpretation of results and support decision-making towards sustainable construction design.

When interpretating the obtained results for the building embodied CF, the identification of critical sections in buildings will guide building stakeholders in prioritizing actions towards sustainable construction design through the selection of alternative building products to convert buildings into more eco-friendly infrastructures [68]. If the expected decarbonization goals for the building project is not observed due to the high contribution of building products to the calculated embodied CF, building stakeholders are free to reanalyse the building project, considering different solutions at the beginning of the building project scope. At that time, the processes, materials, components, and products integrated into the building construction are reconsidered to take better low carbon options.

4. Discussion

Compared to existing strategies for calculating embodied CF in buildings, the proposed approach stands out for its ability to combine detail, flexibility, and practical applicability across diverse contexts. Many sectoral strategies focus on calculations based on broad material categories or consider only limited life cycle stages, such as product manufacturing or on-site installation [42–44,76]. For instance, Xie et al. [78] developed a novel regulatory model for estimating carbon emissions using readily available data from multiple accounting stages, such as construction drawing budgets and contract pricing. However, due to the extensive data processing required, the model is limited to multi-story buildings and specific life cycle stages (A1-A3 and A5). In contrast, the proposed strategy encompasses the building's entire life cycle, including also transportation, maintenance, and disposal stages. This allows for the identification of mitigation opportunities throughout the project's phases, adopting a cradle-to-grave perspective and making it applicable to any building type.

Incorporating verified EPDs for each material or product significantly enhances the accuracy of CF calculations. Unlike approaches that rely solely on generic data [42,44,76], this methodology ensures that results reflect the specific characteristics of the products used in each project. The importance of EPDs as transparent sources of environmental performance data is emphasized by Soust-Verdaguer et al. [53]. Although generic databases are often employed during initial design phases, more detailed data, such as EPDs, are essential for precise life cycle inventory analyses in later stages of the project design. Nonetheless, significant challenges persist, including the limited availability of EPDs for certain products and variability in regional CF calculation methodologies.

The division of the building into four distinct sections facilitates precise tracking of the impacts associated with each section, offering a practical approach to segmental CF analysis. This level of granularity is uncommon in traditional methodologies, which often treat the building as an indivisible unit [43,78,79]. This methodology is particularly useful for designers and decision-makers seeking to prioritize interventions based on the identified impact [54,80]. Additionally, approximately 80 % of the costs and carbon emissions can be identified during the design phase, as identified by [81]. Thus, by emphasizing the significance of comprehensive embodied CF calculations, the suggested strategy not only identifies critical building sections but also encourages the substitution of high-impact materials with low-carbon alternatives.

Moreover, accounting for the building's surroundings, here characterized as the "building exterior section", is an area that has been underexplored, as most studies focus on the building itself rather than its surrounding environment, as demonstrated by Butters et al. [79]. Nikologianni et al. [82] also highlighted that the calculation of embodied carbon for infrastructures and landscaping, which yield carbon-intensive results, is vital for sustainable design and urban planning. Holistic approaches that integrate large-scale landscape CF calculations are urgently needed. However, the limited availability of carbon calculation tools specifically developed for landscape projects poses a challenge for sustainable architectural practices, resulting in fragmented policies that neglect open and green spaces [82]. Although embodied CF is typically calculated for buildings or materials, this remains a relatively novel area concerning landscapes and open spaces. In accordance with the aforementioned study, this study reinforces the importance of integrating the building's exterior into the proposed strategy.

While the proposed strategy does not aim to calculate the embodied CF in a standardized manner that requires no environmental or civil engineering expertise as some authors suggest [83], its implementation during early design phases, coupled with the ability to reevaluate and replace high-impact materials, offers an iterative and adaptive approach [84]. These advancements render the proposed methodology not only innovative but also a practical and theoretical contribution to the field of sustainable construction. By enabling detailed comparisons between buildings, this approach fosters the adoption of low-carbon practices and technologies while establishing benchmarks and stricter regulations in the sector [85,86].

From a public policy perspective, the findings underscore the need for regulations mandating embodied CF quantification methodologies in construction projects. The 2024 revision of the Energy Performance of Buildings Directive (EPBD) sets Zero-Emission Building (ZEB) as a goal for all new buildings starting in 2030 [27]. This may necessitate significant efforts to the building sector, as the 2024 recast EPBD mandates the calculation and disclosure of life cycle carbon equivalent GHG emissions. These calculations, based on GWP and the emissions of individual GHG, will start in 2030 for all new buildings, as part of a broader initiative toward achieving zero life cycle GHG emissions in the building sector [27]. To this, using locally available, low-carbon materials to reduce emissions associated with materials and transportation has been widely suggested as a strategy to intensify embodied CF reduction [27,87,88]. Examples include forest-based materials, recycled components, or locally sourced alternatives, which can emerge as solutions for lowering the building's CF. Moreover, policies encouraging carbon limits based on local conditions should be expanded to promote circular design strategies, such as reusing building components [89–91]. The emphasis lies on the importance of addressing all these issues during the design phase, as adjustments can still be made to the project at this stage, considering the selected materials, as highlighted by the proposed strategy.

Despite the demonstrated benefits, the strategy presents limitations that warrant future research. The reliance on specific EPDs restricts the analysis's scope to regions or products where these declarations are readily available [92]. Additionally, variability in the quality of data across different EPDs may introduce uncertainties, as observed by Durão et al. [94] and Sambataro et al. [93]. Future studies should explore harmonizing regional and international databases to bridge information gaps.

Another limitation involves modelling the impact of transportation and final material disposal. This is a limitation because modelling the impacts of transportation and final material disposal introduces significant variability and uncertainty into the analysis. Transportation emissions depend on factors such as distance, mode of transport, and load efficiency, all of which can vary widely. Similarly, the final disposal of materials is influenced by regional waste management practices, recycling rates, and disposal methods, which are often not standardized or consistently reported. These complexities can make it challenging to achieve precise and reliable estimates, potentially affecting the robustness and comparability of the results.

The current limited availability of EPDs for all specific construction and building materials, components, and products, which can impact the accuracy of the embodied CF calculations. Ensuring that the data collected from EPDs is of high quality and reliability may also require additional effort. Besides the CF collected from EPDs regarding the product stage, it is important to also consider other stages, such as transportation of construction materials and waste disposal in the end of the product life cycle. Assessing and quantifying these impacts can be a challenge for building stakeholders if the expected scenarios are not considered in the EPDs.

These stages can significantly influence projects in remote areas or those with underdeveloped transportation infrastructure. Customized scenarios for transportation and disposal should be further developed to improve result accuracy.

5. Conclusions

The findings of this study highlight the critical importance of quantifying the embodied CF as a key tool for driving decarbonization in the construction sector. The proposed methodology leverages established LCA practices, incorporates precise data from EPDs, and systematically divides buildings into four sections that enables a detailed analysis of the specific contributions of each building component to the total embodied CF, fostering targeted strategies for GHG mitigation.

Thus, the strategy to support decarbonization outlined in this paper is crucial for promoting sustainability and reducing GHG emissions in the construction sector. Unlike previous methodologies, this approach allows for direct comparisons between building sections and entire projects, offering stakeholders actionable insights to replace high-impact materials with low-carbon alternatives during early design phases. Furthermore, this study contributes to filling gaps in LCA by integrating comprehensive data from EPDs, ensuring accurate and transparent CF calculations.

However, there are challenges to consider when implementing this strategy, as the limited availability of EPDs or quantify impacts on transportation of construction materials and waste treatment due to different scenarios rather than the ones considered in the EPDs. The strategy has strengths such as early intervention in the project design phase, precision in embodied CF calculation by considering the CF of specific building products, the possibility to identify building sections and building products that account for the largest embodied CF results of the total building embodied CF, and also the ability to compare different building projects. By identifying critical building sections and products, this strategy provides guidance for prioritizing decarbonization actions and enables stakeholders to target interventions effectively. Additionally, the strategy integrates established frameworks and guidelines for calculating the building CF, ensuring consistency and reliability for meaningful comparisons.

From a policy perspective, the implementation of embodied CF reduction strategies offers significant opportunities to shape regulatory frameworks and industry standards. Policymakers play a central role in incentivizing the adoption of low-carbon materials and technologies through tools such as carbon pricing, mandatory reporting of embodied CF, and embodied carbon limits in building codes. Regulatory measures can also drive innovation by encouraging the development of advanced materials and construction processes that minimize embodied emissions. Furthermore, embedding CF considerations into public procurement policies and large-scale infrastructure projects would set a strong precedent for the private sector, accelerating the transition toward a low carbon built environment. By aligning regulatory efforts with the strategic goals outlined in this paper, policymakers and regulators can provide the necessary support to ensure the strategy's success and long-term impact.

To further strengthen the practical applicability of this strategy, policymakers could incentivize the production of comprehensive EPDs and standardize its usage in construction projects to improve data availability. Simultaneously, practitioners are advised to adopt tools and templates that facilitate the efficient collection and analysis of EPD data, incorporating aspects such as transportation and end-of-life impacts. Additionally, establishing guidelines for integrating CF considerations into early project phases and providing funding for research on advanced, low-carbon building materials could accelerate the adoption of decarbonization practices across the industry. These measures would not only drive innovation but also accelerate the transition towards a sustainable built environment aligned with global climate goals. Therefore, the strategy proposed in this paper is not just theoretical but also practical and actionable. By providing a clear methodology and step-by-step process for calculating embodied CF, building stakeholders can easily implement this strategy, aiming the decarbonization of their building projects.

Future research will explore the application of this methodology across different building types and geographical contexts, analysing how building materials and products influence embodied CF results. Additionally, adopting the methodology to include emerging construction technologies, such as prefabricated or modular construction, could uncover new opportunities for carbon reduction. Moreover, accounting for the carbon sequestration effects of vegetation in green roofs, façades and gardens, using this methodology, would also be a valuable addition, with the potential to quantify how much vegetation can reduce a building's CF. These future efforts would refine the strategy, ensuring its adaptability, and further highlight its relevance, broadening its impact in advancing decarbonization across the construction industry.

CRediT authorship contribution statement

Ana Karolina Santos: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Victor M. Ferreira:** Writing – review & editing, Supervision, Conceptualization. **Ana Cláudia Dias:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors 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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Data availability

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

References

[1] W.M.O. Wmo, *State Of the Global Climate 2023* (Issue WMO-No. 1347), Chair, Publications Board, 2024. https://library.wmo.int/idurl/4/68585.

[2] Y. Costa, I. Martins, G.C. de Carvalho, F. Barros, Trends of sea-level rise effects on estuaries and estimates of future saline intrusion, in: Ocean and Coastal Management, vol. 236, Elsevier Ltd, 2023, https://doi.org/10.1016/j.ocecoaman.2023.106490.

[3] J. Qiu, Z. Shen, H. Xie, Drought impacts on hydrology and water quality under climate change, Sci. Total Environ. 858 (2023), https://doi.org/10.1016/j.scitotenv.2022.159854.

[4] D.R. Rounce, R. Hock, F. Maussion, R. Hugonnet, W. Kochtitzky, M. Huss, E. Berthier, D. Brinkerhoff, L. Compagno, L. Copland, D. Farinotti, B. Menounos, R. W. McNabb, Global glacier change in the 21st century: every increase in temperature matters, Science 379 (6627) (2023) 78–83, https://doi.org/10.1126/science.abo1324.

[5] L.J.Z. Weeda, C.J.A. Bradshaw, M.A. Judge, C.M. Saraswati, P.N. Le Souëf, How climate change degrades child health: a systematic review and meta-analysis, Sci. Total Environ. 920 (2024) 170944, https://doi.org/10.1016/J.SCITOTENV.2024.170944.

[6] UNFCCC, U. N. F. C. on C. C., Paris agreement. https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf, 2016.

[7] European Commission, The European green deal. https://doi.org/10.4324/9781003246985-3, 2019.

[8] Government of Canada, Strategic assessment of climate change - revised. https://www.canada.ca/en/services/environment/conservation/assessments/strategic-assessments/climate-change.html, 2020.

[9] The White House, Building a clean energy economy: a guidebook to the Inflation Reduction Act's investments in clean energy and climate action, The White House 1 (2023) 1–150. https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf.

[10] Gobierno de Chile, Green growth opportunities for the decarbonization goal for Chile. https://documents1.worldbank.org/curated/en/968161596832092399/pdf/Green-Growth-Opportunities-for-the-Decarbonization-Goal-for-Chile-Report-on-the-Macroeconomic-Effects-of-Implementing-Climate-Change-Mitigation-Policies-in-Chile-2020.pdf, 2020.

[11] Government of South Africa, South Africa's low emission development strategy 2050. https://www.dffe.gov.za/sites/default/files/docs/2020lowemission_developmentstrategy.pdf, 2020.

[12] Kiko Network, Japan's path to net zero by 2050. https://www.kikonet.org/wp/wp-content/uploads/2021/05/NetZero-Report-2050_EN.pdf, 2021.

[13] D.A. Halimatussadiah, P.D. Jahen Fachrul Rezki, P.D. Kiki Verico, F.A. Maizar, B.A. Sisungkunon, M. Adriansyah, G. Sutiyono, J. Giwangkara, Z. Hakim, D. Suyoto, P.J. Supriatna, A. Asmoro, P.D. Teguh Yudo Wicaksono, Accelerating Indonesia's climate agenda to achieve sustainable development. https://files.unsdsn.org/IndonesiaReport-Phase1-web.pdf, 2021.

[14] Government of India, Ministry of external affairs - annual report. https://www.mea.gov.in/Uploads/PublicationDocs/34894_MEA_Annual_Report_English.pdf, 2021.

[15] F.D. Agbajor, M.C. Mewomo, Green building research in South Africa: a scoping review and future roadmaps, Energy Built Environ. 5 (2) (2024) 316–335, https://doi.org/10.1016/J.ENBENV.2022.11.001.

[16] Y. Bai, N. Yamashita, J. Guo, S. Nagata, H. Shirakawa, H. Tanikawa, Dynamic analysis of carbon emissions from construction and demolition activities in Japan: revealed by high-resolution 4D-GIS modeling, J. Environ. Manag. 360 (2024) 121099, https://doi.org/10.1016/J.JENVMAN.2024.121099.

[17] J.F.T. de Souza, S.A. Pacca, A low carbon future for Brazilian steel and cement: a joint assessment under the circular economy perspective, Res. Conservat. Recycling Adv. 17 (2023) 200141, https://doi.org/10.1016/J.RCRADV.2023.200141.

[18] F. Grossi, H. Ge, R. Zmeureanu, F. Baba, Assessing the effectiveness of building retrofits in reducing GHG emissions: a Canadian school case study, J. Build. Eng. 91 (2024) 109622, https://doi.org/10.1016/J.JOBE.2024.109622.

[19] United Nations Environment Programme, Building materials and the climate: constructing a new future. https://wedocs.unep.org/handle/20.500.11822/43293, 2023.

[20] H.-Y. Chang, S.-N. Ma, Y.-C. Chiang, C.-M. Lai, The effects of structural design alternatives on the embodied carbon emissions of steel buildings, J. Build. Eng. (2024) 111603, https://doi.org/10.1016/J.JOBE.2024.111603.

[21] IPCC, Climate change 2023 synthesis report, in: H. Lee, J. Romero (Eds.), Contribution of Working Groups I; II and III to the Sixth Assessment Report of the I, 2023, pp. 35–115, https://doi.org/10.59327/IPCC/AR6-9789291691647.

[22] Canadian Standard Association Products, Canadian standard association products. https://www.scribd.com/document/662463288/Canadian-Standard-Association-Products, 2022.

[23] China National Standards, China national standards. https://www.gbstandards.org/index/Standards_Search.asp?word=Construction, 2024.

[24] European Commission, Regulation (EU) 2024/3110 of the European parliament and of the council - construction producta and repealing regulation No 305/2011, 3110(3), 1–106, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202403110, 2024.

[25] W. Craft, P. Oldfield, G. Reinmuth, D. Hadley, S. Balmforth, A. Nguyen, Towards net-zero embodied carbon: investigating the potential for ambitious embodied carbon reductions in Australian office buildings, Sustain. Cities Soc. 113 (2024) 105702, https://doi.org/10.1016/J.SCS.2024.105702.

[26] 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 (2024) 107005, https://doi.org/10.1016/J.ISTRUC.2024.107005.

[27] C. Maduta, D. D'Agostino, S. Tsemekidi-Tzeiranaki, L. Castellazzi, From nearly zero-energy buildings (NZEBs) to zero-emission buildings (ZEBs): current status and future perspectives, Energy Build. 328 (2025) 115133, https://doi.org/10.1016/J.ENBUILD.2024.115133.

[28] M.R. Seyedabadi, U. Eicker, S. Karimi, Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint, Environmental Challenges 4 (2021) 100119, https://doi.org/10.1016/J.ENVC.2021.100119.

[29] ISO, ISO 14067 - Greenhouse Gases: Carbon Footprint of Products Requirements and Guidelines for Quantification, International Organization for Standardization, 2018. https://www.iso.org/standard/71206.html.

[30] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs. embodied emissions in buildings - a review of current trends, Energy Build. 66 (2013) 232–245, https://doi.org/10.1016/j.enbuild.2013.07.026.

[31] MTE, & CEREMA, Réglementation ENVIRONNEMENTALE des bâtiments neufs (RE2020), Ministère de la Transition écologique (MTE), Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Cerema). https://rt-re-batiment.developpement-durable.gouv.fr/IMG/pdf/guide_re2020_dhup-cerema.pdf, 2020. Volume 1. pp. 1-100.

[32] Ministry of Interior and Housing, National strategy for sustainable construction (Denmark), https://im.dk/Media/637602217765946554/National_Strategy_for_Sustainable_Construktion.pdf, 2021.

[33] C. Chen, Z. Zhao, J. Xiao, R. Tiong, A conceptual framework for estimating building embodied carbon based on digital twin technology and life cycle assessment, Sustainability 13 (24) (2021), https://doi.org/10.3390/su132413875.

[34] N. Ni, M. Shafique, Case Studies in Construction Materials Embodied carbon emissions of buildings : taking a step towards net zero buildings, Case Stud. Constr. Mater. 20 (March) (2024) e03024, https://doi.org/10.1016/j.cscm.2024.e03024.

[35] Y.S. Tsay, Y.C. Yeh, H.Y. Jheng, Study of the tools used for early-stage carbon footprint in building design, E-Prime - Advances in Electrical Engineering, Electronics and Energy 4 (January) (2023) 100128, https://doi.org/10.1016/j.prime.2023.100128.

[36] E. Giama, A.M. Papadopoulos, Benchmarking carbon footprint and circularity in production processes: the case of stonewool and extruded polysterene, J. Clean. Prod. 257 (2020) 120559, https://doi.org/10.1016/J.JCLEPRO.2020.120559.

[37] F. Pacheco-Torgal, Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020, Constr. Build. Mater. 51 (2014) 151–162, https://doi.org/10.1016/j.conbuildmat.2013.10.058.

[38] J. Falana, R. Osei-Kyei, V.W. Tam, Towards achieving a net zero carbon building: a review of key stakeholders and their roles in net zero carbon building whole life cycle, J. Build. Eng. 82 (2024) 108223, https://doi.org/10.1016/J.JOBE.2023.108223.

[39] E. Markström, M.K. Kuzman, A. Bystedt, D. Sandberg, M. Fredriksson, Swedish architects view of engineered wood products in buildings, J. Clean. Prod. 181 (2018) 33–41, https://doi.org/10.1016/J.JCLEPRO.2018.01.216.

[40] S. Moosavi, A. Hurlimann, J. Nielsen, J. Bush, G. Warren Myers, A. March, Transforming the agency and influence of landscape architects in climate change actions: an empirical analysis of barriers and facilitators, Landsc. Urban Plann. 234 (2023) 104735, https://doi.org/10.1016/J.LANDURBPLAN.2023.104735.

[41] Z. Fang, J. Yan, Q. Lu, L. Chen, P. Yang, J. Tang, F. Jiang, T. Broyd, J. Hong, A systematic literature review of carbon footprint decision-making approaches for infrastructure and building projects, Appl. Energy 335 (January) (2023) 120768, https://doi.org/10.1016/j.apenergy.2023.120768.

[42] V.J.L. Gan, J.C.P. Cheng, I.M.C. Lo, A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings, J. Clean. Prod. 229 (2019) 582–597, https://doi.org/10.1016/J.JCLEPRO.2019.05.035.

[43] X. Li, F. Yang, Y. Zhu, Y. Gao, An assessment framework for analyzing the embodied carbon impacts of residential buildings in China, Energy Build. 85 (2014) 400–409, https://doi.org/10.1016/J.ENBUILD.2014.09.051.

[44] S. Li, H. Yan, J. Chen, L. Shen, A life cycle analysis approach for embodied carbon for a residential building. Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate, 2017, https://doi.org/10.1007/978-981-10-0855-9.

[45] A. Loli, C. Skaar, H. Bergsdal, M. Reenaas, Comparing embodied GHG emissions between environmental product declaration and generic data models: case of the ZEB laboratory in Trondheim, Norway, Build. Environ. 242 (2023) 110583, https://doi.org/10.1016/J.BUILDENV.2023.110583.

[46] ISO, ISO 14040 - Environmental Management — Life Cycle Assessment — Principles and Framework, International Organization for Standardization, 2006. https://www.iso.org/standard/37456.html.

[47] ISO, ISO 14044 - environmental management — life cycle assessment — requirements and guidelines. https://www.iso.org/standard/38498.html, 2006.

[48] European Commission, *Annex I. Product environmental footprint method.* 1–198. https://environment.ec.europa.eu/system/files/2021-12/Annexes1to2.pdf, 2021.

[49] CEN/TC 350, Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products (EN 15804:2012+A2:2019), 2019.

[50] BRE Group, The IMPACT database. https://bregroup.com/products/impact/the-impact-database/, 2018.

[51] G.H.C. Jones, Embodied carbon—the ICE database. https://circularecology.com/embodied-carbon-footprint-database.html, 2019.

[52] I. Bourgeois, A. Queirós, J. Oliveira, H. Rodrigues, R. Vicente, V.M. Ferreira, Development of an eco-design tool for a circular approach to building renovation projects, Sustainability 14 (14) (2022) 1–14, https://doi.org/10.3390/su14148969.

[53] B. Soust-Verdaguer, E. Palumbo, C. Llatas, Á. Velasco Acevedo, M.D. Fernández Galvéz, E. Hoxha, A. Passer, The use of environmental product declarations of construction products as a data source to conduct a building life-cycle assessment in Spain, Sustainability 15 (2) (2023) 1284, https://doi.org/10.3390/su15021284.

[54] N. Dodd, M. Cordella, M. Traverso, S. Donatello, Level(s) – A Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings: Parts 1 and 2: Introduction to Level(s) and How it Works (Beta v1.0), Publications Office of the European Union, 2017, 10.2760/827838.

[55] N. Dodd, S. Donatello, M. Cordella, Level(s) indicator 1.2: life cycle global warming potential (GWP), in: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2021-01/UM3_Indicator_1.2_v1.1_37pp.pdf, 2021.

[56] L. Jankovic, P. Bharadwaj, S. Carta, How can UK housing projects be brought in line with net-zero carbon emission targets? Frontiers in Built Environment 7 (2021) https://doi.org/10.3389/fbuil.2021.754733.

[57] CEN/TC 350, Sustainability of construction works - assessment of environmental performance of buildings - calculation method (EN 15978:2024). https://standards.iteh.ai/catalog/standards/sist/2e9fa5c3-d06a-4b1c-b5e6-76352826324c/osist-pren-15978-2024?srsltid=AfmBOop4ep8VpV1sr_bxDx3VlPpXBDTQRo1534vdGJHg9YC4O_dXLhvJ, 2024.

[58] L. Felicioni, J. Gaspari, J. Veselka, Z. Malík, A comparative cradle-to-grave life cycle approach for addressing construction design choices: an applicative case study for a residential tower in Aalborg, Denmark, Energy Build. 298 (2023) 113557, https://doi.org/10.1016/J.ENBUILD.2023.113557.

[59] D. Pan, X. Yu, Y. Zhou, Cradle-to-grave lifecycle carbon footprint analysis and frontier decarbonization pathways of district buildings in subtropical Guangzhou, China, J. Clean. Prod. 416 (June) (2023) 137921, https://doi.org/10.1016/j.jclepro.2023.137921.

[60] M.A. Curran, Life Cycle Assessment Handbook - A Guide for Environmentally Sustainable Products, first ed., Wiley-Scrivener, 2012 https://doi.org/10.1002/9781118528372.

[61] T. Potrč Obrecht, R. Kunič, S. Jordan, A. Legat, Roles of the reference service life (RSL) of buildings and the RSL of building components in the environmental impacts of buildings, IOP Conf. Ser. Earth Environ. Sci. 323 (1) (2019), https://doi.org/10.1088/1755-1315/323/1/012146.

[62] S. Donatello, N. Dodd, M. Cordella, Level (s) indicator 2.1: bill of Quantities, materials and lifespans, Publication Version: The European Commission 1 (January) (2021) 1–34.

[63] CEN/TC 350, Sustainability of construction works - data quality for environmental assessment of products and construction work - selection and use of data (FPREN 15941). https://standards.iteh.ai/catalog/standards/cen/95f4bf84-5e4b-4136-b6f9-6fc4ca959886/pren-15941, 2024.

[64] ISO, ISO 14025 - environmental labels and declarations - type III environmental declarations - principles and procedures. http://www.cscses.com/uploads/2016328/20160328110527052705.pdf, 2006.

[65] D.A. Arellano-Vazquez, L. Moreschi, A. Del Borghi, M. Gallo, G.I. Valverde, M.M. Rojas, L. Romero-Salazar, J.C. Arteaga-Arcos, Use of EPD system for designing new building materials: the case study of a bio-based thermal insulation panel from the pineapple industry by-product, Sustainability 12 (17) (2020), https://doi.org/10.3390/SU12176864.

[66] B.M. Galindro, S. Welling, N. Bey, S.I. Olsen, S.R. Soares, S.-O. Ryding, Making use of life cycle assessment and environmental product declarations: a survey with practitioners, J. Ind. Ecol. 24 (Issue 5) (2020) 965–975, https://doi.org/10.1111/jiec.13007.

[67] ECO Platform, ECO Platform organisation. https://www.eco-platform.org/home.html, 2024.

[68] R. Sinha, M. Lennartsson, B. Frostell, Environmental footprint assessment of building structures: a comparative study, Build. Environ. 104 (2016) 162–171, https://doi.org/10.1016/j.buildenv.2016.05.012.

[69] H. Watt, B. Davison, P. Hodgson, C. Kitching, D.T. Danielle's, What should an adaptable building look like? Res. Conservat. Recycling Adv. 18 (2023) 200158 https://doi.org/10.1016/J.RCRADV.2023.200158.

[70] G. Bertino, J. Kisser, J. Zeilinger, G. Langergraber, T. Fischer, D. Österreicher, Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials, Appl. Sci. 11 (3) (2021) 1–31, https://doi.org/10.3390/app11030939.

[71] R. Kim, S. Tae, S. Roh, Development of low carbon durability design for green apartment buildings in South Korea, Renew. Sustain. Energy Rev. 77 (2017) 263–272, https://doi.org/10.1016/J.RSER.2017.03.120.

[72] D.S. Macozoma, Understanding the concept of flexibility in design for deconstruction, in: Proceedings of the CIB Task Group 39 – Deconstruction Meeting, 9 April, 2002. www.cce.ufl.edu/affiliations/cib.

[73] M. van der Zwaag, T. Wang, H. Bakker, S. van Nederveen, A.C.B. Schuurman, D. Bosma, Evaluating building circularity in the early design phase, Autom. ConStruct. 152 (November 2022) (2023) 104941, https://doi.org/10.1016/j.autcon.2023.104941.

[74] K. Wang, S. De Regel, W. Debacker, J. Michiels, J. Vanderheyden, Why invest in a reversible building design? IOP Conf. Ser. Earth Environ. Sci. 225 (1) (2019) https://doi.org/10.1088/1755-1315/225/1/012005.

[76]] R. Giordano, F. Gallina, B. Quaglio, Analysis and assessment of the building life cycle. Indicators and tools for the early design stage, Sustainability 13 (11) (2021) 6467, https://doi.org/10.3390/su13116467.

[77] Gregor Wernet, Christian Bauer, Bernhard Steubing, Juergen Reinhard, Ruiz Emilia Moreno, Bo Weidema, The ecoinvent database version 3 (Part I): Overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1–13, https://doi.org/10.1007/s11367-016-1087-8.

[78] Q. Xie, Q. Jiang, J. Kurnitski, J. Yang, Z. Lin, S. Ye, Quantitative carbon emission prediction model to limit embodied carbon from major building materials in multi-story buildings, Sustainability 16 (13) (2024) 5575, https://doi.org/10.3390/su16135575.

[79] C. Butters, A. Cheshmehzangi, R. Bakhshoodeh, Sustainable construction: the embodied carbon impact of infrastructures and landscaping, Urban Sci 8 (3) (2024) 76, https://doi.org/10.3390/urbansci8030076.

[80] S. Su, Z. Zang, J. Yuan, X. Pan, M. Shan, Considering critical building materials for embodied carbon emissions in buildings: a machine learning-based prediction model and tool, Case Stud, Constr. Mater. 20 (2024), https://doi.org/10.1016/j.cscm.2024.e02887. ISSN 2214-5095 e02887.

[81] M. Robati, P. Oldfield, A.A. Nezhad, D.G. Carmichael, A. Kuru, Carbon value engineering: a framework for integrating embodied carbon and cost reduction strategies in building design, Build. Environ. 192 (2021), https://doi.org/10.1016/j.buildenv.2021.107620, 107620 ISSN 0360-1323.

[82] A. Nikologianni, T. Plowman, B. Brown, A review of embodied carbon in landscape architecture, Practice and policy, C 8 (2) (2022) 22, https://doi.org/10.3390/c8020022.

[83] C. Szigeti, Z. Major, D.R. Szabó, Á. Szennay, The ecological footprint of construction materials—a standardized approach from Hungary, Resources 12 (1) (2023) 15, https://doi.org/10.3390/resources12010015.

[84] A. Al-Najjar, T. Malmqvist, Embodied carbon saving of reusing concrete elements in new buildings: a Swedish pilot study, Resour. Conserv. Recycl. 212 (2025) 107930, https://doi.org/10.1016/j.resconrec.2024.107930. ISSN 0921-3449.

[85] Y. Liu, J. Zhang, J. Xu, Y. Wang, B. Li, S. Zhang, Carbon emission-based life cycle assessment of rural residential buildings constructed with engineering bamboo: a case study in China, J. Build. Eng. 76 (2023) 107182, https://doi.org/10.1016/j.jobe.2023.107182. ISSN 2352-7102.

[86] S. Zhang, K. Wang, W. Xu, U. Iyer-Raniga, A. Athienitis, H. ua Ge, D. Cho, W. Feng, M. Okumiya, G. Yoon, E. Mazria, Y. Lyu, Policy recommendations for the zero energy building promotion towards carbon neutral in Asia-Pacific Region, Energy Policy 159 (2021), https://doi.org/10.1016/j.enpol.2021.112661. ISSN 0301-4215 112661.

[87] N.N. Myint, M. Shafique, Embodied carbon emissions of buildings: taking a step towards net zero buildings, Case Stud. Constr. Mater. 20 (2024), https://doi.org/10.1016/j.cscm.2024.e03024e03024. ISSN 2214-5095.

[88] M. Ibrahim, F. Harkouss, P. Biwole, F. Fardoun, S. Ouldboukhitine, Building retrofitting towards net zero energy: a review, Energy Build. 322 (2024), https://doi.org/10.1016/j.enbuild.2024.114707, 114707 ISSN 0378-7788.

[89] A. Meijer, M. Arora, L. Cheah, Material stock-service and circularity prospects of buildings in Singapore, Resour. Conserv. Recycl. 208 (2024), https://doi.org/10.1016/j.resconrec.2024.107697, 107697 ISSN 0921-3449.

[90] A. Laveglia, D.V. Madrid, N. Ukrainczyk, V. Cnudde, N.D. Belie, E. Koenders, Circular design, material properties, service life and cradle-to-cradle carbon footprint of lime-based building materials, Sci. Total Environ. 948 (2024) 174875, https://doi.org/10.1016/j.scitotenv.2024.174875. ISSN 0048-9697.

[91] J. Nußholz, S. Çetin, L. Eberhardt, C.D. Wolf, N. Bocken, From circular strategies to actions: 65 European circular building cases and their decarbonisation potential, Resour. Conserv. Recycl. Adv. 17 (2023) 200130, https://doi.org/10.1016/j.rcradv.2023.200130. ISSN 2667-3789.

[92] M. Rangelov, H. Dylla, A. Mukherjee, N. Sivaneswaran, Use of environmental product declarations (EPDs) of pavement materials in the United States of America (U.S.A.) to ensure environmental impact reductions, J. Clean. Prod. 283 (2021) 124619, https://doi.org/10.1016/j.jclepro.2020.124619. ISSN 0959-6526.

[93] L. Sambataro, F. Bre, N. Ukrainczyk, E.A.B. Koenders, Environmental benchmarks for the European cement industry, Sustain. Prod. Consumpt. 45 (2024) 429–449, https://doi.org/10.1016/j.spc.2024.01.020. ISSN 2352-5509.

[94] V. Durão, J.D. Silvestre, R. Mateus, J. de Brito, Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes, Resour. Conserv. Recycl. 156 (2020) 104703, https://doi.org/10.1016/j.resconrec.2020.104703. ISSN 0921-3449.