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A BIM-based tool for embodied carbon assessment using a Construction Classification System

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ABSTRACT

Life Cycle Assessment (LCA) is widely accepted for evaluating a building's environmental footprint. Building Information Modelling (BIM) has become the go-to strategy for LCA during design. Still, despite BIM-LCA automating detailed quantity extraction, challenges persist, such as a lack of standardised geometry modelling and information management, as well as a common language between LCA and BIM data.

This study proposes a method to assess embodied carbon from BIM models classified using a construction classification system that provides a data structure, maps BIM objects and environmental impacts in LCA databases, and matches different levels of development (LoD) in BIM models. The method was tested on real-world models, resulting in 375 $kgCO_2e/m^2$ for the single residential and 426 $kgCO_2e/m^2$ for the multi-residential building. These findings revealed its ability to adapt to different LoD and modelling techniques, expedite assessing different design options, and potentially save up to 20 hours of work remodelling.

1. Introduction

The built environment accounts for approximately 40% of European greenhouse gas (GHG) emissions and 30% of worldwide energy consumption. These emissions will double by 2050 if no action is taken (Raturi, 2019). In response, the Architecture, Engineering, Construction, and Operation (AECO) industry has embraced regulatory frameworks and building codes, such as the Energy Performance of Building Directive (Directive 2010/31/EU), alongside awareness campaigns and economic incentives (Economidou et al., 2020). These measures aim to address the ongoing energy crisis and mitigate GHG emissions by optimising heating and cooling systems, building envelope, lighting, and appliances. However, energy-efficient measures may inadvertently raise the absolute and relative importance of embodied emissions, as noted by Röck et al. (2022), Lützkendorf et al. (2015) and Maierhofer et al. (2022). Röck et al. (2020) research revealed that near-zero-energy buildings (NZEB) (i.e., buildings with almost zero energy needs that are covered by renewable sources) could come at the cost of a 25% increase in GHG emissions from materials production, transportation, maintenance, and end-of-life treatment compared to buildings conforming to legacy European energy standards. This upsurge emphasises the importance of trade-offs between embodied and operational impacts.

Life cycle assessment (LCA) is an established methodology to quantify the environmental impact of products throughout their entire life cycle, including the production, construction, use, and end-of-life stages, encompassing all emissions (ISO 14040: 2006). Building-LCA becomes increasingly frequent as a mandatory post-design evaluation method for the European framework Level(s) and sustainability building certification schemes such as BREEAM and LEED. *Building LCA* involves multiplying the bill of quantities (BoQ) and energy operational consumption estimations with environmental impact values extracted from Environmental Product Declarations (EPD) and/or generic data about building materials, products, or processes (Cavalliere et al., 2019). However, establishing the BoQ and finding the correct data sets can be challenging and time-consuming due to the extensive information requirements, resulting in high costs for sustainability certification (Hollberg et al., 2020); as a result, LCA is often performed when all definitive data is available towards the conclusion of the design process, limiting its potential to influence high-impact decisions (Hollberg and Ruth, 2016).

Digital transformation, as highlighted in the "Europe's digital decade" communication (European Commission, 2023), is a driver for a resilient and climate-neutral economy. The 2020 EU Circular Economy Action Plan (European Commission, 2024) and Level(s) framework recognise the role of digital technologies, including Building Information Modelling (BIM), Internet of Things, and Geographical Information

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Systems, for assessing, tracking, tracing, and mapping resources and environmental impacts in the built environment (Çetin et al., 2021).

Emerging BIM tools and technologies have gradually changed how stakeholders create, store, and exchange information. In this context, BIM-based tools reduce the additional effort required for LCA and accelerate the process (Santos et al., 2019, Morsi et al., 2022, Hollberg et al., 2018). Examples of BIM-LCA integration yield quick and reliable results when certain conditions are met (Obrecht et al., 2020). One is the Tally Autodesk Revit® add-on, developed by KT Innovations and Autodesk, which allows LCA analyses in the BIM environment and facilitates continuous monitoring during design by establishing a dynamic link between BIM objects and LCA data (Tally®). The other is the *One-Click LCA* web application developed by Bionova Ltd. in Helsinki, which allows extraction of the Bill of Materials (BoM) from Autodesk Revit or its Common Data Environment Autodesk Construction Cloud, from Industry foundation classes (IFC) models or Excel sheets (OneClick LCA ®).

Several limitations hinder the widespread use and potential benefits of BIM-based LCA. LCA software often demands a high level of development (LoD). Models may not be sufficiently rich to conduct LCA owing to conflicts with other BIM uses, modelling economy and efficiency, or during early design when there are many uncertainties. Although ISO 19650: 2018 states that modelling and information requirements must be defined according to each project's BIM uses and established in the Building Execution Plan (BEP), LCA analysis is seldom considered in these early stages. Moreover, while good modelling and information management practices are essential, fulfilling the information requirements for LCA can be extremely demanding and, as such, is rarely accommodated.

The lack of standardised environmental data and a common language, i.e., data structure and naming conventions, further complicates the mapping process between building elements and their corresponding environmental impacts on LCA databases, which must be done manually.

Finally, given these requirements, integrating the LCA process into BIM workflows in design offices is advantageous. BIM uses such as construction specification and cost estimation rely on construction classification systems (CSS), such as Uniclass and Omniclass.

This research addresses these constraints to LCA analysis during design by developing a BIM-based methodology to estimate the global warming potential (GWP), tackling the challenges associated with data exchange and manual editing in a flexible way, meaning it can be applied from concept to detailed design and considers different LoD, heterogeneously developed models and BIM object modelling techniques. The SECCLasS - Sustainability enhanced construction classification system - derived from Uniclass (Mendez et al., 2022, SECClasS, 2021) frequently employed in construction specification, is used to establish a link between the BIM model and an external database (Obrecht et al., 2020) and thus provide a consistent data structure for mapping building elements to the corresponding environmental impacts in LCA databases, reducing the need for manual intervention.

We test the developed method with architectural and structural models of two residential buildings designed by engineering and architecture offices as part of their current processes. We discuss the method's potential to overcome the limitations identified in this introduction, highlighting the obstacles and solutions created during the experimental process.

The paper's first and current section introduces the problem and briefly describes the proposed methodology. The section 2 reviews the current practices of BIM-based LCA. It highlights the implementation challenges and barriers, examines the existing BIM-LCA methods according to the design stages they apply, and the importance of CCS for quantity takeoff (QTO) and construction specifications. The section 3 describes the development of the proposed BIM-LCA method using a classification structure. Then, the methodology is tested in two real cases, as described in Section 4. Section 5 discusses the findings and highlights how the classification-based method overcomes existing barriers and facilitates the adoption of LCA in building design. Section 6 closes the paper with final remarks and future development paths.

2. State-of-the-art

2.1. Current practices and methods of BIM-based LCA

The integration of LCA into the BIM methodology is an emerging topic in both academia and industry. Numerous publications have explored different approaches that use BIM for sustainable building design (Budig et al., 2021; Bouhmoud et al., 2022; Zheng et al., 2023). However, these approaches still have methodological limitations, such as the lack of interoperability resulting in inefficient data input into LCA tools, inaccuracy of the BoQ automatically generated from BIM, and LCA database inflexibility. Further work is necessary before BIM and LCA can be integrated effortlessly across the project life cycle, as highlighted in (Cavalliere et al., 2019). Furthermore, automated LCA is crucial for leveraging big data and artificial intelligence, enabling the identification of analysis flaws, GHG emissions, and optimal strategies for minimising environmental impact.

Soust-Verdaguer et al. (2017) and Wastiels and Decuypere, (2019) proposed a comprehensive categorisation of LCA-BIM integration, identifying five distinct types: a) export the BoQ from the BIM tool to LCA tools (as followed by, *OneClick LCA*, *Athena Impact Estimator*); b) export BIM models in IFC format and then load them into the LCA tool, where the BoQ is aligned with LCA data; c) using a BIM viewer to handle data and then transfer it to LCA software; d) employ add-ons that enable LCA analysis within the BIM application, such as the Tally add-on; e) embed LCA information directly into the BIM objects, as suggested by Santos et al. (2019).

The most used approach is a) exporting the BoQ from a BIM model and sending it to LCA software, where the BoQ and LCA values are combined and multiplied (Soust-Verdaguer et al., 2017). However, during QTO, the BoQ is often transferred to a spreadsheet and manually edited due to the incompleteness of the model; for example, elements such as the metal profiles of partition walls are rarely represented explicitly (Peng, 2016). For example, Ajayi et al. (2015) used Microsoft Excel to manually aggregate the material information for each building component. However, because manual processes are involved, it is time-consuming and prone to human error, and as soon as the BoQ is edited, the LCA results are no longer integrated with the BIM model, complicating the iterative analysis as the model is updated.

The second method, b), involves exchanging data via IFC, a non-proprietary BIM file format. This method has the benefit of using the Information delivery specifications (IDS) of objects for data sharing. This application simplifies model updates because geometric and environmental data need not be combined again (Guignone et al., 2023).

The third method, c), uses an intermediary "viewer" in a 3D environment, where information from the BIM and environmental data are combined. The use of IDS offers the same benefit as the previous approach. In the fourth strategy, d), the "LCA add-on" provides an iterative process design in the BIM environment where the results are dynamically combined and visualised (Guignone et al., 2023).

The last strategy, e), proposed by Santos et al. (2019), is not commonly employed due to several factors. Modifying the BIM objects within the model, for example, due to a trade-off in selecting different materials, is less effective than using specialised LCA software. Additionally, BIM objects with LCA data are scarce, editing object parameters is inefficient in current modelling software, and there is no consensus on how to structure the data in objects.

The precision of BoQ is critical for LCA, often hindered by insufficient or low-quality data due to poor model management and undefined information requirements. Moreover, uncoordinated federated models, a lack of quality assurance model checks and "creative" modelling techniques that employ unexpected categories (e.g., railings for skirting boards or floors for furniture) contribute to undetected quantity errors.

Bueno et al. (2018) found other limitations of LCA software, such as the unavailability of environmental data and the underlying assumptions of each tool, which are not transparent to the user. Comparing results from different software tools is challenging because of variations in their simplifications and databases, resulting in outcome variations whose origins are difficult to understand (Dalla Mora et al., 2020). Dalla Mora et al. (2018) compared Autodesk Tally, and One Click LCA, which rely on different building material databases, structure organisation, and calculations. Autodesk Tally provides flexibility by assigning an environmental profile to a BIM element or treating it as a sum of layers of different materials. On the other hand, One Click LCA takes a different approach by extracting each material separately, which disconnects materials from their BIM objects. As a result, assigning LCA data and identifying the most significant contributors to the GWP is challenging. Moreover, the workflow is one-way from the model, as the process must restart each time the BIM model is edited. The same difficulty in comparing methods and results was found between the Athena Impact Estimator and GaBi with Autodesk Tally (Schultz et al., 2016) (Bueno et al., 2018). The inflexibility of LCA databases, i.e., the impossibility of including and editing environmental information, is also a constraint on the cited tools.

2.2. BIM-based LCA and design stages

Tools for LCA-BIM integration can be developed for specific design phases. Some methods focus on the early conceptual stages (Budig et al., 2021; Najjar et al., 2022; Röck et al., 2018), while others target highly refined design stages (Yang et al., 2018; Abanda et al., 2017; Marzouk et al., 2017), where comprehensive material data is available.

The ILCD Handbook defines three distinct levels of comprehensive building LCA: screening LCA, simplified LCA, and complete LCA (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Additionally, the Enslic project (Malmqvist et al., 2011) categorises the different levels of conducting LCA as follows: basic calculation, performed using Excel and involving simple input and output data considering a few environmental impact indicators; medium calculation, entails using specialised software tools such as Ecosoft, Equer, and Athena Impact Estimator; advanced analysis involves using advanced LCA software such as SimaPro, requiring a high level of experience and detailed information about the project (Soust-Verdaguer et al., 2017).

A BIM model contains geometrical and non-geometrical information about the materials and components of a building, which vary in their level of development, or LoD, which is defined by the American Institute of Architecture as describing *"the minimum dimensional, spatial, quantitative, qualitative, and other data included in a Model Element"* and recognises five levels, from 100 to 500 (American Institute of Architects, 2013).

Performing a building LCA analysis in the early design stages poses challenges owing to inherent uncertainty. The inefficiency of developing models with a high LoD prompts designers to opt for geometric and information simplifications or adaptations, which impact the accuracy of QTO and LCA results, potentially leading to wrong decisions. Nevertheless, the early design phases present a crucial window for influencing the design with minimal cost for alterations; therefore, developing strategies for reliable comparisons among solutions without requiring extensive and detailed models is essential.

Moreover, it is crucial to consider the heterogeneity of model development; models are not developed in all dimensions simultaneously. The LoD of the elements evolves from low to high according to the needs of each design phase. Structural elements, for example, are typically quite detailed in the early stages, whereas cladding materials are only defined during the execution phase (Cavalliere et al., 2019).

To overcome these limitations, Jalaei and Jrade (2014) used simplified families and types and save information about quantities and environmental impacts in an external database. Houlihan Wiberg et al. (2014) simplified the representation of wall components in the BIM model and calculated load-bearing wood stud members independently of the BIM software. Basbagill et al. (2013) developed formulas based on the BIM model to determine the minimum and maximum quantities of each building component material. Other studies, such as those by Georges et al. (2015) and Ajayi et al. (2015) exported length, area, and volume from Revit to Excel and manually edit building elements. Iddon and Firth (2013) created an Excel spreadsheet that can be used with a BIM database to generate operational and embodied carbon emissions. Bueno et al. (2018) developed a procedure for the BIM-LCA integration by combining visual programming to obtain a BoQ and a spreadsheet that automatically generates environmental profiles for early design phases.

At LoD 300, the most relevant materials and components are defined, including the wall thickness and structural elements in their actual sizes, shapes, and locations. It has been suggested that LoD 300–350 is the reference point for accurate LCA calculations (Santos et al., 2019).

Schlueter argues that achieving the highest possible LoD is not crucial for decision-making during early design. Instead, the focus should be on evaluating the decision-making patterns and interdependence of these decisions (Schlueter and Thesseling, 2009). Cavalliere et al. (2019) suggested that having specific tools for each design phase obstructs a continuous and accurate LCA and developed a method using LCA databases ranging from generic data to EPDs, matching the LoD and design stage. This approach allows for continuously examining embodied impacts with the most representative information concerning the current design phase. Santos et al. support this perspective, stating that a LoD below 300 may only include generic LCA data. At the same time, a LoD of 300 or higher allows the use of EPDs, which recognise specific materials and product manufacturers. By contrast, Hollberg et al. (2020) tracked design decisions continuously and concluded that embodied GWP is highly overestimated in early design, which could be misleading. This discrepancy arises from fluctuations in material quantities; highly detailed BIM elements tend to have less material, or an element is reassigned to different materials compared to earlier design phases.

2.3. Quantity takeoff (QTO) and construction classification systems

QTO is crucial for construction projects and LCA. It encompasses measurements derived from building schematics or on-site, depending on the design stage. These measurements are consolidated into a BoQ, which details the quantities of various materials, labour, and other resources needed for the project (Alshabab et al., 2017).

Although BIM significantly enhanced the QTO efficiency, manual or semi-automatic intervention is still required to refine the extracted quantities. This involves integrating data from external databases containing specifications and unit cost information and addressing elements or activities not directly modelled but necessary for project documentation (Vieira et al., 2022).

Establishing a predefined structure for information is essential to overcome these challenges and automate QTO. This organisational framework is known as a work breakdown structure (WBS): adopting a universally accepted WBS helps prevent stakeholder conflicts, errors, and omissions throughout the project. The WBS is usually built on increasingly detailed levels and different domains. Each element of the WBS is identifiable by a specific code, which is supposed to connect specification information directly to the BIM object, reducing rework and revisions (Monteiro and Poças Martins, 2013). Various WBS options are available and categorised under CCS, such as MasterFormat, OmniClass and Uniformat, tailored for North America, UniClass for the United Kingdom, or SECClasSS for Portugal (Monteiro and Poças Martins, 2013).

An example of using CCS for BIM-based construction specifications is NBS Chorus®, developed by NBS (NBS, 2024). This cloud-based solution integrates a specification database structured according to Uniclass 2015 with the BIM model. Similarly, BSD SpecLink connects the BIM model to a specification database utilising the MasterFormat CSS (RIB North America, 2024). Vieira et al. (2022) developed a BIM-based framework for automatised coordinated construction specifications using Uniclass 2015.

The proposed method uses the CCS to link BIM objects to external specifications and the LCA database. Naneva et al. (2020) implemented a similar approach; they performed an LCA analysis and a cost estimation using the Swiss cost planning framework (eBKP-H). The objective of employing CCS in this context is to address several limitations inherent in current LCA practices: first, the repetitive manual combination of environmental and geometric data throughout the decision-making process and the absence of standardised naming conventions that further complicate the selection of appropriate datasets; second, the time-consuming nature of modelling different construction solutions in early design and the need for diverse LCA tools for each design phase.

3. Proposed methodology

This study develops a BIM method for calculating the GWP of a building project, considering the A1-A3 and B4 building lifecycle stages, as defined in EN 15978.

The methodology aims to overcome the abovementioned limitations using the CSS, which is enhanced for this purpose. The SECCLasS classification system was chosen because it aligns with the regional context, is tailored to Portuguese nomenclature and construction practices and is compatible with Uniclass, a widely employed CSS in BIM object libraries.

SECCLasS systematically categorises objects in a construction described in a BIM model with a unique code. This code can correspond to a building type (e.g., commercial, residential), a function of a part of the building (e.g., envelope, partitions), a system (e.g., composite wall, indirect foundations, water supply), a product (e.g., ceramic brick, reinforcement bar), or a material (e.g., concrete or bitumen).

The SECClasS code dynamically links specifications and environmental information in an external database with a particular system, product, or material in the BIM model, eliminating the need to recombine LCA data and BIM during design changes (Fig. 1).

For early design, when information about products and materials is unavailable, we propose creating a pre-established building assemblies catalogue containing information on the relative quantities of materials or the total GWP value for BIM objects in an external database. For a brick partition wall system, we might have 10% mortar, 10% render, and 80% clay bricks by mass or 16 kg/m^2 of gypsum boards, 1.2 kg /m^2 of mineral wool and 149 kg/m^2 of clay bricks. We can, therefore, obtain the absolute quantities of materials in BIM objects based on the relative quantities and BIM model quantities (i.e., m, m^2, unit) using the SECCLasS code.

This approach shares similarities with building performance simulations using thermal models, often called *"shoe-box"* models, composed of 2D surfaces. The material variants are stored externally from the model. As such, the constructive solution can be easily assessed without altering the model, avoiding remodelling construction scenarios in the early design stages to determine the performance of the building. Because most spatial and structural decisions are made early in a project, most model changes that impact embodied carbon are related to material evolution. When a new system, product, or material is changed, it is only necessary to adapt the catalogue. This preserves the flexibility of designers during early design changes, allowing for efficient evaluation of different material options.

As the project progresses and the LoD advances, more specific classifications and LCA data are assigned to products and materials. Various modelling techniques are also considered to ensure the adaptability of this method, facilitating continuous monitoring of the building's embodied carbon throughout the project.

The proposed methodology for BIM-based LCA was developed in five steps (Fig. 2). The first step identifies the calculation method for the GWP calculation (A1-A3 and B4), the data available from the BIM models, the data introduced by the LCA practitioner, and data harvested from the LCA databases. The second step establishes a "common language" between the building information, environmental data, and calculation engine through a CSS enriched for environmental analysis - SECClasS. This step also defines how to classify the BIM objects and materials. The third step defines methods for QTO, considering the design stages, LoDs, information granularity, and BIM modelling

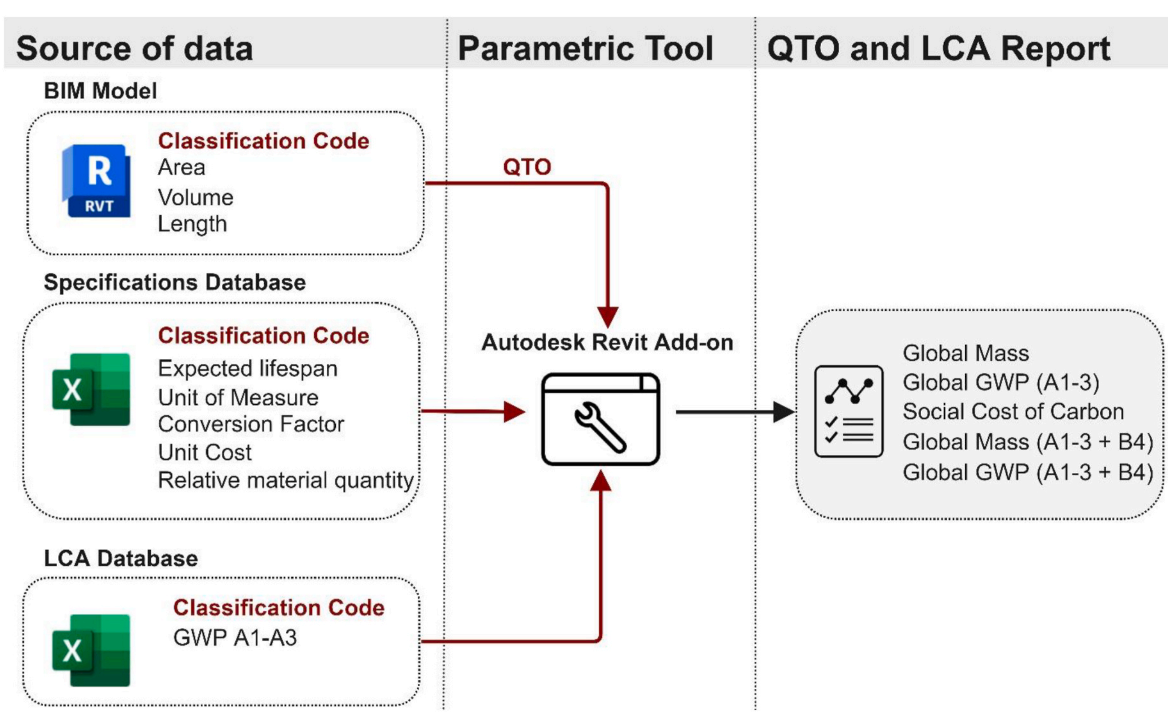

Fig. 1. Conceptual diagram of the proposed framework.

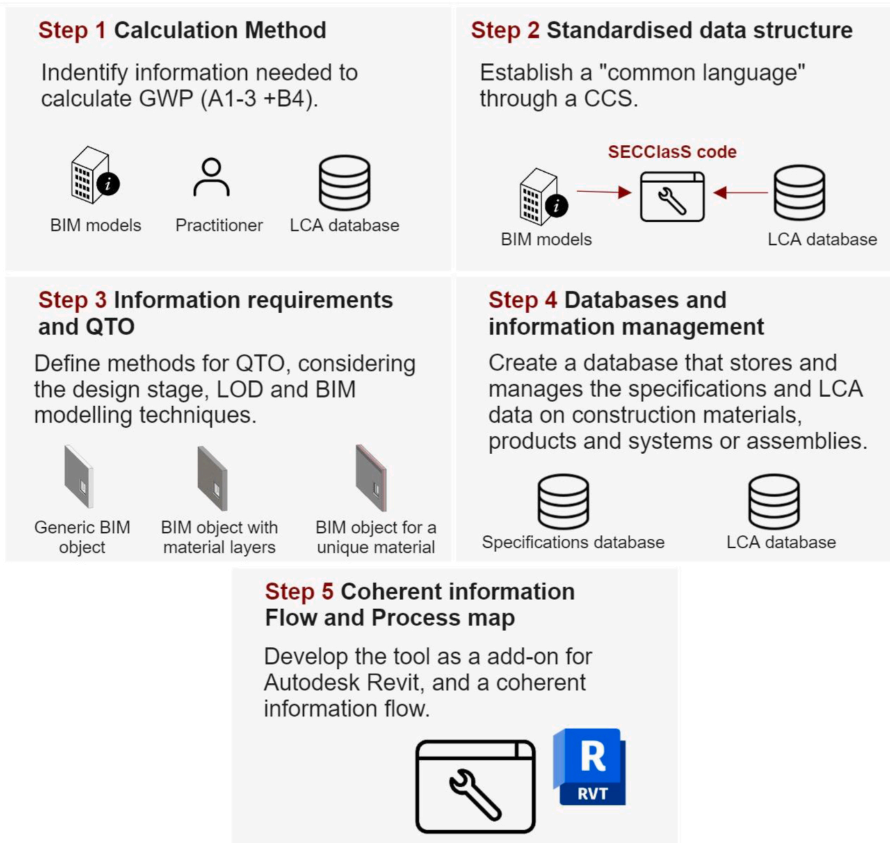

Fig. 2. Schematic illustrating the five stages of the proposed methodology.

techniques. The fourth step creates an editable relational database that stores and manages the environmental and LCA data on construction materials, products, systems, and assemblies. The fifth step develops a coherent information flow.

The following section describes the steps established for developing the proposed BIM-Based Tool.

3.1. Calculation method

The A1-3 modules for the 'Product stage' of building design, *i.e.*, the GWP due to material extraction, processing, and manufacturing of building products, as defined in EN 15978. This encompasses cradle-to-gate processes for construction materials and services.

A1-3 GWP is determined by multiplying the quantity of each product or material in a project by its environmental impact, as formulated in Equation (1).

$$EI_X^{MC} = \sum_{a=1}^{i} \left(Q_a^M \times EI_a^M \right) \tag{1}$$

where:

EI_X^{MC} environmental impact of category X resulting from manufacturing (A1-3);

Q_a^M quantity of material *a;* (can be automatically provided by BIM models);

EI_a^M environmental impact (of category X) of material a; (provided by LCA database);

i number of existing materials i.

B4 'Use Stage: Replacements' phase concerns replacing components that become damaged and cannot be repaired or that reach the end-of-life specified by manufacturers during the LCA Study period—reference study period (RSP) (Donatello et al., 2021). The B4 module is calculated by assessing the number of replacements (Nr) during operation and rounded to the next integer.

$$EI_X^{MC} = \sum_{a=1}^{l} \left(Q_a^M \times N_R \times EI_a^M \right) \tag{2}$$

$$N_R = \left(\frac{RSP}{RSLp} - 1 \right) \tag{3}$$

where:

EI_X^{MC} environmental impact of category X resulting from manufacturing (B modules);

Q_a^M quantity of material *a;* (can be automatically provided by BIM models);

EI_a^M environmental impact (of category *x*) of material *a;* (provided by LCA database);

N_R number of replacements during the use phase (i.e. operation phase) based on material durability (not considering repairs) and rounded up to the upper integer;

l number of existing materials to be replaced;

RSP Study period of the LCA, for example, 60 years (default value in this methodology);

RSLp estimated /reference service life of the component (can be provided by LCA database).

A BoQ can be extracted from BIM models and environmental impact information from LCA databases. EPDs provide the estimated service life of the components. When this information is unavailable, typical service lives *can be used* (Donatello et al., 2021).

Social cost refers to buildings' negative externality, encapsulating the adverse impact of building carbon emissions on humans, ecosystems, and society (Lu and Deng, 2023). It is calculated based on the unit CO_2 emissions per square meter per year at the average annual price of 1 ton.

CO_2e is applicable in the EU. The cost was assumed to be 50€, as defined in the Level(s) methodology (Tol, 2011, Kania et al., 2021).

3.2. "Common language" through the classification system

Establishing a "common language" enables automatic data exchange between LCA and BIM databases. A classification code is assigned to all BIM objects in the LCA analysis.

The *SECClasS* classification system provides a standardised data structure and unique codes and terminology for materials, products, and assemblies, thus enabling information coordination. Four SECClasS tables describe building elements and materials with an evolving degree of detail. In the early stages, models are classified primarily with Elements and Functions (EF) and/or Systems (Ss) tables. Products (Pr) and Materials (Ma) tables are generally assigned to BIM objects during the project execution phase. Many BIM object families already include Uniformat or Uniclass codes. These classification parameters are applied as a Family & Type parameter rather than an instance parameter.

BIM authoring tools typically include native attributes for this information, *i.e.*, *"Assembly Codes"* or "*Keynote*" parameters in Autodesk Revit®, which are designed for tagging objects but can also be used with other classification tables expressed in a hierarchical tree in an ASCII file, as proposed by Vieira et al. (2022). ArchiCAD also has built-in classification parameters, and the software manufacturer provides several classification systems, including SECClasS, on its website (Graphisoft, 2024).

Add-ons and automation strategies can enhance the procedure for adding element classification codes. With the Standardised Data Tool for Revit, it is possible to map BIM object categories and codes to slightly automate the classification.

In this method, BIM objects are classified through shared parameters (Fig. 3 a), and materials are classified in the *"Keynote"* parameter (Fig. 3 b). The classification tables in Excel format are available on the SECClasS project website (SECClasS, 2021). Six shared parameters, *described in* Fig. 3 and Table 1, are created by the classification addon or manually by the user *to* store codes and descriptions of objects. These parameters have an English correspondence in Uniclass, for example, "ClassificationSecclassEFNumero" and "UniclassClassificationEFCode". BIM objects are classified based on their LoD and BIM modelling techniques, as depicted in Table 1. Objects with low LoD are categorised within Family & Type Parameters, employing codes from the EF and Ss tables. Multiple material layer objects are classified, like the previous, but added Keynote Material Parameters codes from the Pr and Mr tables. Objects representing a single product or material are classified within Family & Type Parameters, using codes from EF and Ss, as well as the Pr and Ma tables.

Table 1
Classification of a masonry wall with the SECClasS classification system according to different LoD and BIM modelling techniques.

BIM object description	Family & Type Parameter	Keynote Material Parameter
Objects with low LoD and no information about materials, i. e. the various layers/materials, are represented as a single generic material.	ClassificacaoSecclassEFNumero: **EF_25_10_25** ClassificacaoSecclassEFDescricao: **External walls** ClassificacaoSecclassSsNumero: **Ss_25_13_50** ClassificacaoSecclasssDescricao: **Masonry wall systems**	None
BIM objects representing a single construction element, with different layers/materials from an internal BIM material library.		Keynote (for each layer): **Pr_35_31_64 - Plaster and render** **Ma_40_85_53 - Mineral Rock Wool** **Pr_20_93_52_15 - Clay Bricks** **Pr_25_71_35 - Gypsum boards and Sheets**
Objects with high LoD, which represent only one material/layer of a	ClassificacaoSecclassEFNumero: **EF_25_10_25** ClassificacaoSecclassEFDescricao: **External walls** ClassificacaoSecclassSsNumero: **Ss_25_13_50** ClassificacaoSecclasssSsDescricao: **Masonry wall systems** ClassificacaoSecclassPrNumero: **Pr_25_57_06_53** ClassificacaoSecclasssPrDescricao: **Mineral wool insulation**	None

The SECClasS system, despite its comprehensive nature, particularly in the Products table, is not sufficiently precise to differentiate among all construction materials or manufacturers. Consequently, we adopted the approach used by Vieira et al. (2022), which involved appending

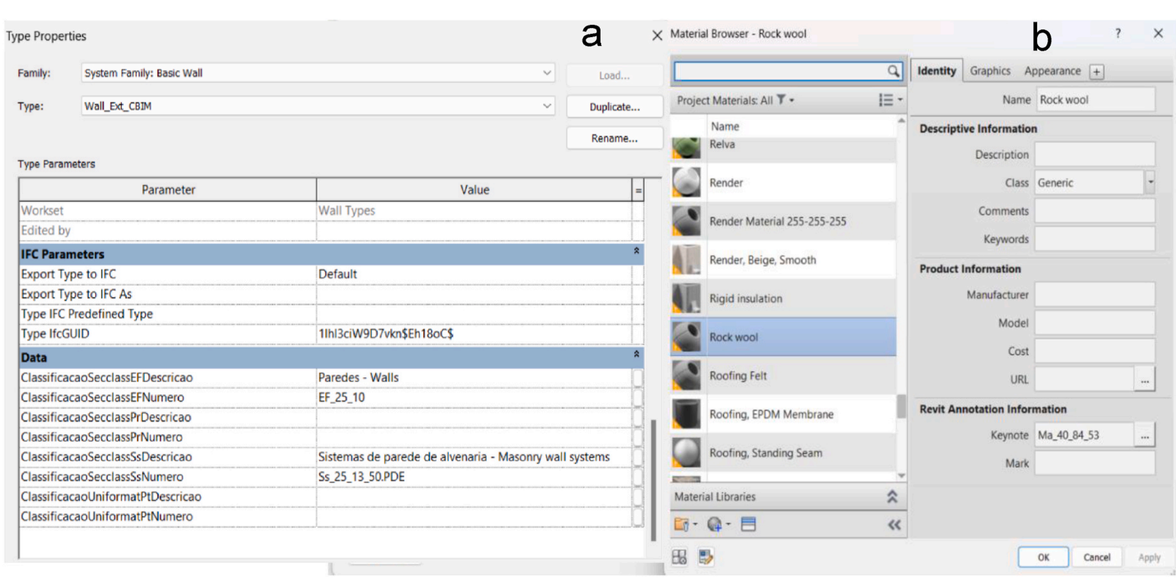

Fig. 3. a) Example of a wall type with the SECClasS classification assigned (EF and Ss tables) through the Standardised Data Tool. b) Example of a Revit material with the SECClasS classification assigned (Ma tables) with an ASCII file.

suffixes that convey additional information. These suffixes may comprise a code denoting the manufacturer for the Product table (Pr) and a code specifying the particular wall or roof assembly designed for a specific function (whether it serves an exterior or interior purpose), as illustrated in Fig. 4.

3.3. Information requirements and QTO

Undertaking a Building LCA requires the extraction of a BoQ from the BIM model, identifying the type of construction element and the products and materials that comprise it. The accuracy of an LCA analysis is contingent upon the precision of the BoQ. Although it is accepted that the model simplifies reality, it must not contain gross errors, as an inaccurate BoQ will yield similarly inaccurate results in the LCA. Modelling techniques intended to produce 3D renders or schematic drawings may introduce errors such as the duplication or overlapping of objects within the same model or across different specialities, i.e., a slab modelled in architecture and structure models, walls extending into the slabs or objects that are left in the margins of the model, a practice inherited from CAD modelling. No analysis technique can overcome improper materials and product quantities; thus, adherence to standardised methods and clash detection is recommended.

This methodology establishes three QTO methods, considering the project phases, the LoD, the information granularity and the BIM modelling techniques.

The first is suitable for objects with a low LoD without information on materials (Fig. 5 a). Walls, floors, and roofs are modelled using a generic modelling technique as several materials are represented as a single object and one generic material. These objects are classified using codes from the Elements and Functions (EF) and/or Systems (Ss) tables. The proposed solution consists of pre-calculating the relative quantities of materials or the total GWP per unit for each construction solution and creating a catalogue of construction assemblies stored in an external database that can be adapted. The quantities of classified BIM objects are extracted from the model, i.e. volume, area, linear meter or unit, and the code establishes a link with the relative quantities in the database. By changing the code of the BIM object, the assembly and its products change.

The second method is adapted for BIM objects representing a building element with different material layers from an internal BIM material library (Fig. 5 b). This modelling technique is the most common, striking the best balance between modelling economy and complete material representation. However, avoiding modelling errors, such as overlapping structural elements, walls, and floors, is more difficult. The proposed solution involves extracting the quantities of materials from each BIM layer and maintaining the link with the Element Type classified with a Systems code. In contrast, One Click LCA extracts the BoM from the model, disconnecting materials from their Element Type. This disconnect complicates the comparison of results and the identification of significant contributors to embodied carbon.

The third method works with BIM objects representing a single material or product, e.g., in elements such as floors, walls and roofs, each layer is modelled separately as a BIM object (Fig. 5 c). The separate technique is highly detailed; however, modelling is more time-consuming and complicates modifying building elements since the layers must be edited separately. The solution involves extracting the quantities of all classified objects. For products that are not usually modelled, such as rebar and paints, it is necessary to introduce pre-established parameters such as the reinforcement percentage or the coating type. This proposed approach offers greater flexibility than the Autodesk Tally. Although Tally also allows objects to be treated as either a set of materials or a single object, it does not consider elements that are not modelled, such as paints and reinforcements.

3.4. Databases and information management

Our approach stores most information in external databases rather than within the BIM model. This eliminates the need to edit the model to update the specifications or carbon footprint and allows for more efficient and effective data management. Fig. 6 shows the type of LCA data used depending on the LOD project phase and modelling technique; a similar approach has already been suggested by Cavalliere et al. (2019) and Meex et al. (2018). In the early stages of the project, when the brands and types of products and materials were not yet defined, generic or average data was used. As the project progressed and specific information became available, specific data from EPDs was used.

We developed an editable relational database for storing and managing data related to the LCA of construction materials, products, and systems or assemblies. Relational databases offer a robust framework for managing information connecting entities across tables. Additionally, the inherent design of the database allows new tables and connections to support new features such as cost estimation or construction planning. CSV (comma-separated values) format was selected for storing the data since users can easily edit and update information using Microsoft Excel without third-party software installation.

Fig. 7 presents the organisational structure of the database. The Specifications table includes details such as the unit of measurement (Area A, Volume V, Linear Metre L, and Unit U), the conversion factor (Kg/m^3, Kg/m^2, kg/m, kg/u), the Unit cost (€/m3, €/m2, €/m, €/u), and the A1-A3 GWP (kg $CO_{2}e$/m^3, kg CO_{2e}/m^2, kg CO_2/m, kg CO_2/unity). The Relative Material table is utilised when calculating the total GWP based on relative quantities. The WBS Level(s) table comprises the WBS proposed in the Levels(s) methodology, as well as the typical service lives of building parts and elements. Lastly, the LCA tables contain the GWP values of materials and products.

The selection of the LCA data is crucial and should reflect the local market, construction and material production. However, EPD repositories are limited to most regions. The main EPD repository in Portugal is DAPHabitat (DAPHabitat, 2023), which contains 42 entries from December 2023.

The international databases available include Ecoinvent, Gabi, and Athena. Ecoinvent is frequently utilised because of its availability in numerous platforms and tools, such as SimaPro, OneClick LCA, and Open LCA. Athena and GABI have a comprehensive database of the North American building sector (Mora et al., 2020). The Inventory of Carbon & Energy (ICE), an open-source database developed by the University of Bath, is also commonly utilised in practice. We rely on this resource as a primary source of information in conjunction with EPDs when available. The ICE dataset provides comprehensive data on total CO_2e emissions and embodied energy.

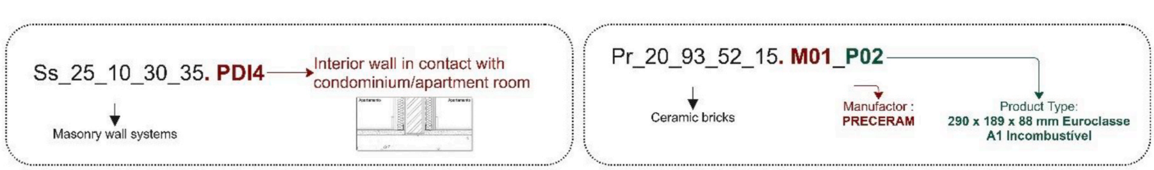

Fig. 4. Example of restructured classification code by adding suffixes to the original SECCLasS code.

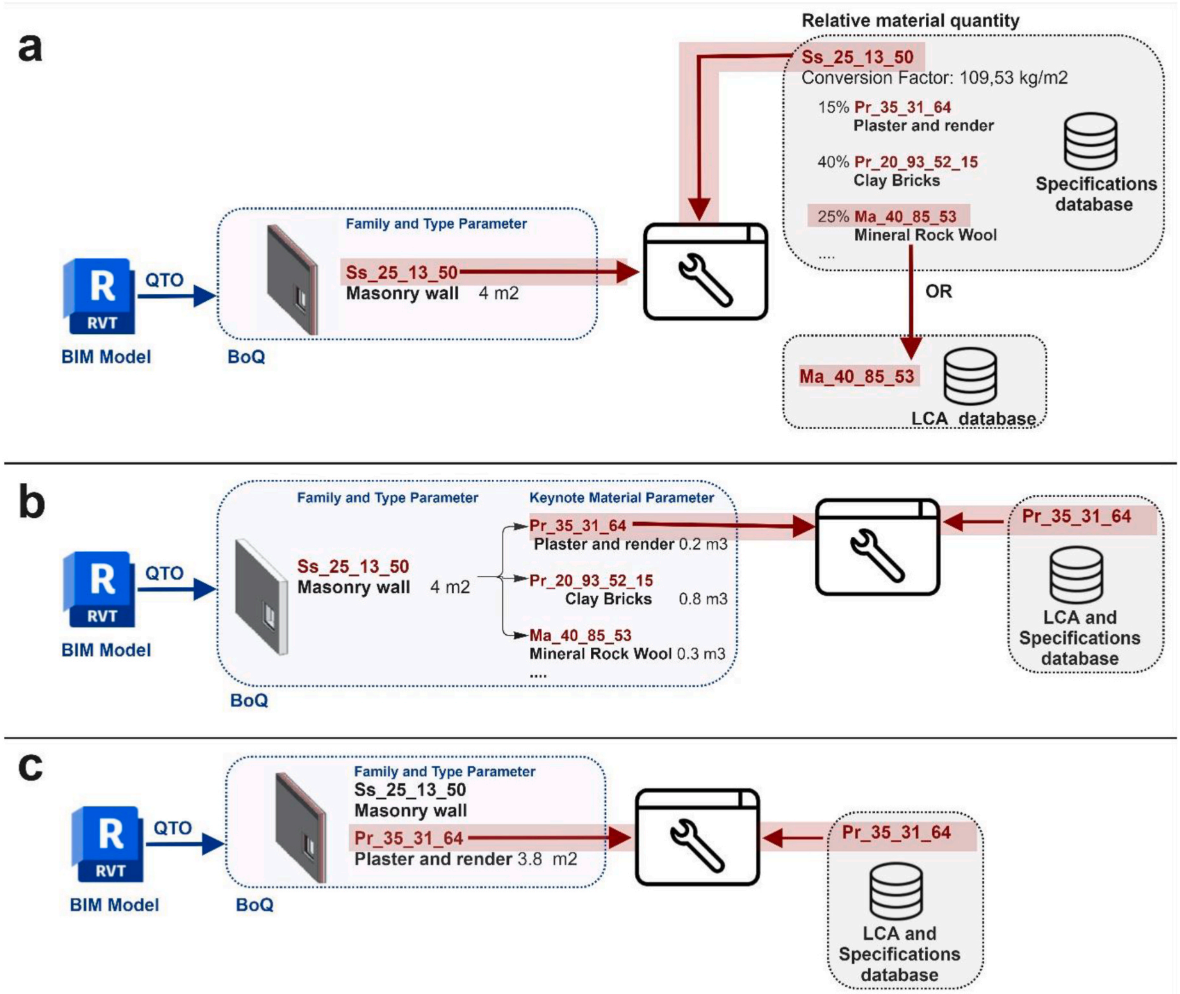

Fig. 5. Conceptual diagram of the information flow for BIM objects representing products and materials.

Design Phases	Schematic-Developed Design	Detailed Design	As built
LoD	100 - 200	300 +	500
Modelling Technique	Generic BIM objects, and no material information	BIM objects with material layer, or representing each product or material	BIM objects representing each product or material
SECClasS Classification	Elements and Fuctions (EF) Systems (Ss)	Systems (Ss), Products (Pr), Materials (Ma)	Systems (Ss), Products (Pr), Materials (Ma)
Recomended LCA data	Generic data or Average data	Specific data (EPDs), if unavailable Generic or Average data	Specific data (EPDs) and Measured data
Complemetary Data about Materials	Relative material quantaties	______	______

Fig. 6. SECClasS classification and LCA data used depending on the LOD project phase and modelling technique.

3.5. Coherent information flow and process map

The tool is a Python add-on for Autodesk Revit®, functioning as an "LCA add-on" in line with the categorisation by Soust-Verdaguer et al. (2017) and Wastiels and Decuypere (2019). It provides an iterative process design within the BIM environment, where results are

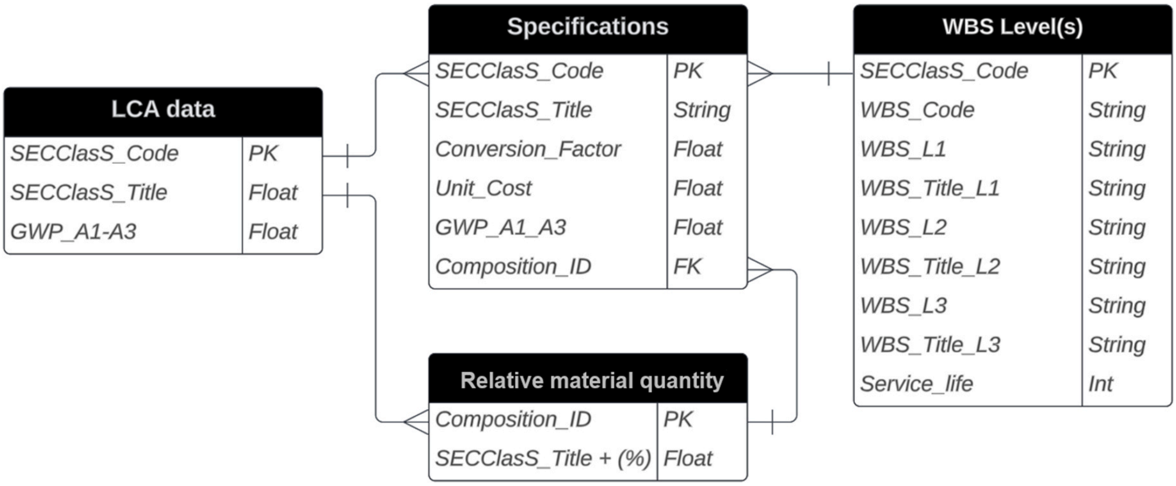

Fig. 7. Entity-Relationship diagram for the proposed specification database.

dynamically combined and visualised. It was developed using the PyRevit open-source scripting library which enables the execution of scripts in CPython and grants access to Revit's application programming interface (API).

The tool consists of two modules (Fig. 8). The first generates two files, Building_Information.csv and Building_Element_Information.csv. First, the user enters information about the building: project code and name, gross area, and reference period of the LCA study, e.g. 60 years. The second is a list of the model's unique codes, which serves to verify and validate the model and the information in the database and makes it possible to identify objects that did not assign a classification code or without a corresponding record in the database or essential attributes not specified in the database.

The second module extracts the quantities of classified elements, products, and materials from the model and links them to the data in the database needed to calculate the LCA. Finally, a new shared instance parameter, "*GlobalWarmingPotential (A1-3)*", is added to each object in the model. Finally, a CSV and JSON document containing detailed environmental and technical information for each BIM object is generated. The CSV file with the results can be added to a preformatted Excel file to produce a graphical report. The proposed tool (Fig. 9) is available for download (GitHub, 2024).

4. Case study application and results

Two buildings constructed with reinforced concrete and brick masonry walls are selected, one being a single-family dwelling and the other a multi-family residence developed by different design companies in Autodesk Revit.

Reinforced concrete is a widely used building material and a major contributor to GWP (Belizario-Silva et al., 2021). Reinforced concrete structures in Europe exhibit a notable disparity in GWP per square meter compared to other structures (Röck et al., 2022). This suggests that concrete is often overused, providing an opportunity to optimise its usage in buildings during design with circular economy strategies.

Both case studies (CS) were in the licensing phase when they were evaluated. However, the models presented different BIM modelling techniques and LoD, allowing us to test the methodology's flexibility and the proposed QTO methods. The BIM models of single-family dwellings have LoD 300 and material characterisation for all BIM objects. The BIM models of multi-residential buildings have LoD 200 and BIM objects without material information; therefore, it was necessary to establish a catalogue of the construction solutions used with relative material quantities.

The environmental data utilised in the LCA studies is sourced from the ICE of the University of Bath, with some exceptions: data from EPD were employed for windows and doors. LCA studies consider an RSP of 60 years.

4.1. Case study 1

The first CS is a detached, single-family residential building in northern Portugal with a gross floor area (GFA) of 350 m^2 in two stories, one of which is semi-buried. The building construction is typical in northern Portugal, with a reinforced concrete frame structure and brick masonry walls.

The architecture and structure BIM models have LoD 300 created for the licencing phase of the project. The architecture model includes exterior and interior walls, roofing, cladding, finishes, and openings. The structure model includes slabs, beams, columns, and foundations (Fig. 10). Clash detention was conducted between both models to ensure no collisions and overlaps.

As illustrated in Fig. 11, all BIM objects have been assigned the correct Revit materials from an internal material library. The BIM objects were classified using the SECClasS system's Elements and Functions (EF) and Systems (Ss) tables. Revit materials were classified using the Keynote parameter's Products (Pr) and Materials (Ma) tables.

The developed tool extracted the material quantities from each BIM object and calculated the GWP from the LCA values in the database. The reinforcement bars on the concrete elements—foundations, columns, slabs, and beams—were not modelled. Due to the extensive effort required, these elements are typically only modelled for specialised purposes, such as structural analysis. Therefore, the rebar and GWP from reinforced concrete elements were pre-calculated and added to the database, as shown in Table 2.

The architecture has a normalised GWP estimated at 119 $kgCO_2e/m^2$. The structure has a normalised GWP of 256 $kgCO_2e/m^2$. This yields a total carbon emission of 375.5 $kGgCO_2e/m^2$ (Table 3). Together, these models result in a total carbon emission of 375.5 $kgCO_2e/m^2$ and 32 $kgCO_2e$/cap, based on the number of beds (4 users).

The information presented in Tables 4 and 5, and Fig. 12 illustrates the building elements that have the most significant impact on Mass and GWP in the architecture and structure model of CS 1. The reinforced concrete floor or roof deck systems - Ss_30_12_85_18 significantly contribute to embodied carbon, accounting for approximately 171.4 $kgCO_2e/m^2$ or 46% of the total. The exterior masonry wall systems - Ss_25_13_50, composed of bricks, mortar, plasters and EPS, follow closely behind, accounting for 13% of the total embodied carbon, or 49 $kgCo_2e/m^2$. Lastly, the reinforced concrete wall structure systems - Ss_20_30_16_70 contribute 40.5 $kgCo_2e/m^2$ (11%). Elements such as

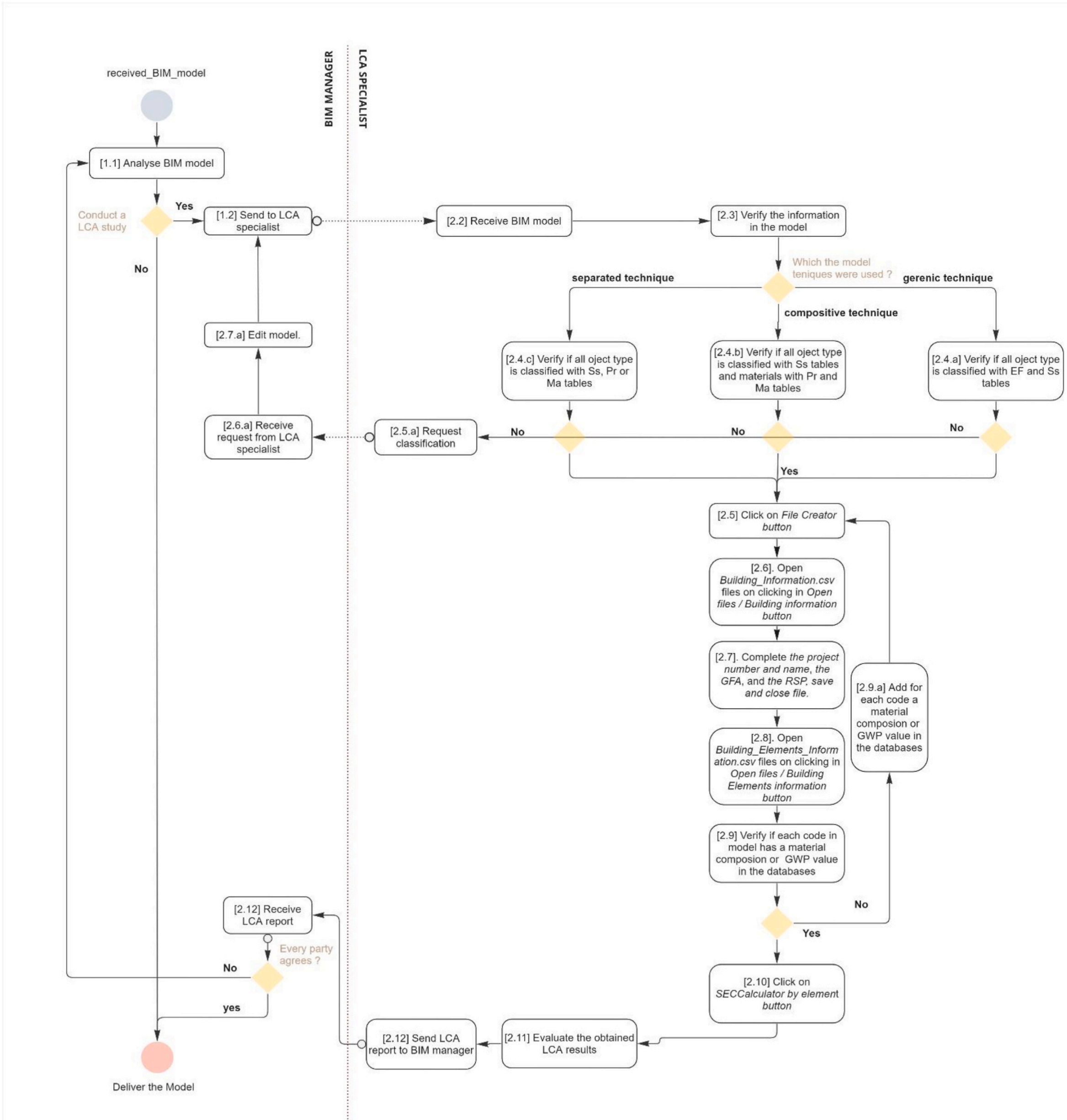

Fig. 8. Process map to perform the LCA with the proposed tool.

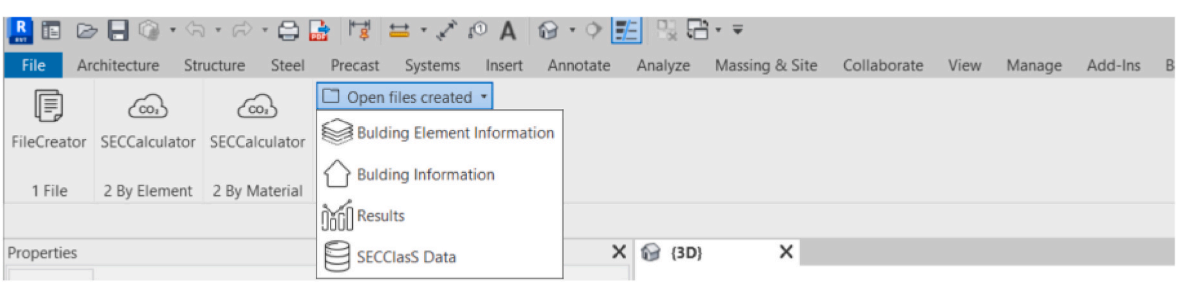

Fig. 9. Proposed Autodesk Revit add-on.

external walls and structural elements have an estimated useful life of 60 years. This study only considered an RSP of 60 years, so replacing these materials is not considered during building operation (phase B4).

4.2. Case study 2

The second CS is a multi-residential building in Portugal with a GFA of 19,680 m2 and 14 stories, three underground, and a single brick masonry facade supported by a reinforced concrete structure. Quadrante

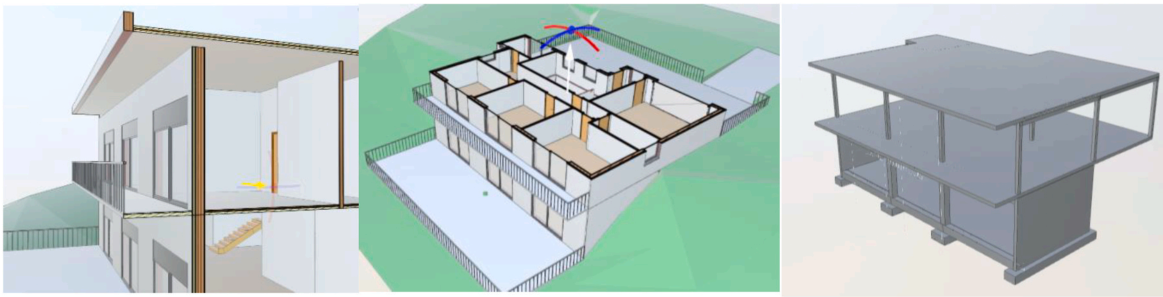

Fig. 10. CS 1-Architecture (left and centre) and structure (right) Autodesk Revit models.

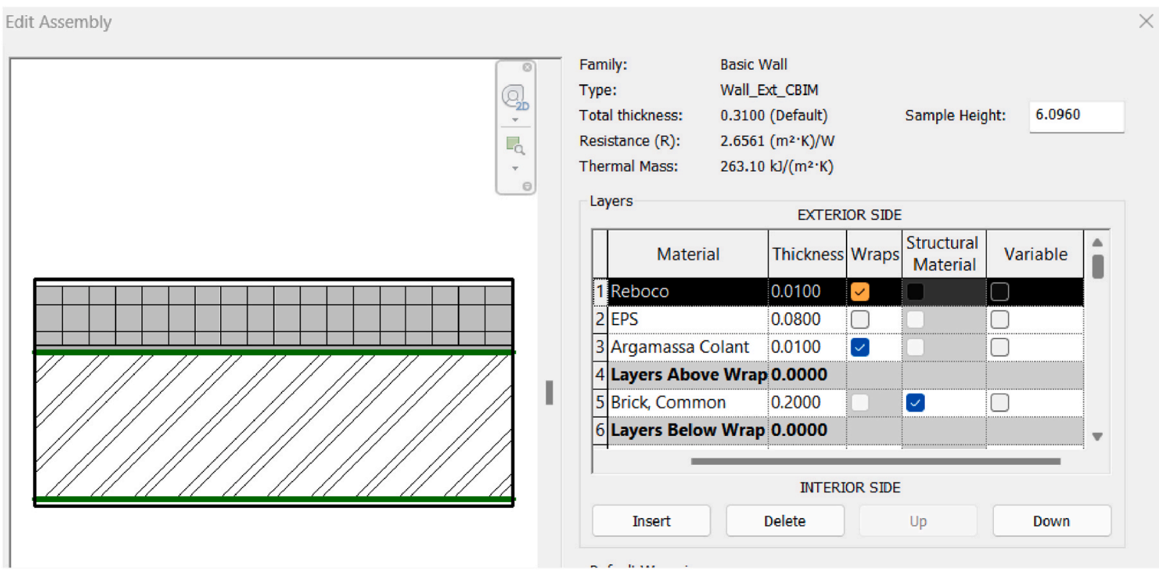

Fig. 11. Example of an exterior wall from CS 1 with different layers of material classified using the SECClasS system.

Table 2
GWP values considered in structural elements depending on the rebar percentage. GWP values from the ICE.

Keynote classification	SECClasS_Title	Description and width (cm)	Rebar (S400) (kg/m^3 of concrete)	Concrete density (C25/30) (kg/m^3)	Rebar (%) (GWP = 1,99 kgCO$_2$e/kg)	Concrete (%) (GWP = 0.149 kgCO$_2$e/kg)	Density Reinforced concrete (kg/m3)	Reinforced concrete (kgCO2e/kg)
Ma_40_19_71.Co	Reinforced concrete	Column (20x20)	140	2400	4,9	95.1	2540	0.237
Ma_40_19_71.Be		Beam (20x30)	150	2400	5,9	94.1	2550	0.2576
Ma_40_19_71.Sl		Slab (20 cm)	105	2400	4,2	95.8	2505	0.2263
Ma_40_19_71.Fo		Footing	50	2400	2	98	2450	0.1842
Ma_40_19_71.RW		Retaining wall (20)	50	2400	2	98	2450	0.1842

Table 3
Results from CS 1.

Indicator	Architecture	Structure
Mass A1-3 (t)	197	411
GWP A1-3 (tCo$_2$e)	41	89
Mass A1-3 (kg/m2)	562	1176
Normalised GWP A1-3 (kgCo$_2$e/m^2)	119.1	256.3
Social Cost of Carbon A1-3 (euro)	2050	4445
Mass A1-3 + B4 (t)	324	411
GWP A1-3 + B4 (t Co$_2$e)	66	89

Engenharia, a large Portuguese design company, coordinated the project and other specialities.

BIM models were only developed to produce 2D drawings and, as a result, did not fulfil the QTO requirements. Several adjustments were necessary before calculation, including reclassifying inconsistently used Families and Types and several overlapping and colliding objects. The wall and floor slab thickness did not follow the project documentation, and elements were duplicated in both BIM models.

The architecture model includes exterior and interior walls, roofing, cladding, chimneys, finishes, and openings, while the structure model includes slabs, beams, columns, and foundations (Fig. 13).

The architecture and structure models had a LoD 200 with generic BIM objects without information on the materials. As shown in Fig. 14,

Table 4
Results from CS 1 architectural model by classification code.

Element type			Revit material (Keynote Parameter)		Results					
SECClasS_Code	SECClasS_Title	Suffix Description	SECClasS_Code	Description and width (cm)	Mass A1-3 (kg)	Mass A1-3 + B4 (kg)	GWP A1-3 ($kgCO_2e$)	GWP A1-3 + B4 ($kgCO_2e$)	GWP A1-3 (%)	GWP A1-3 ($kgCO_2e/m^2$)
Ss_25_13_50.PDE	Masonry wall systems	External Wall	Pr_35_31_64_32 Ma_60_65_85_27 Pr_20_31_53_08 Pr_20_93_52_15 Pr_35_31_64_32	Finish plasters (1) EPS (8) Brick slip adhesive mortars (1) Clay Brick (20) Finish plasters (1)	71181	71181	17146	17146	13%	49
Ss_25_13_50.PDI		Internal Wall	Pr_35_31_64_32 Pr_20_93_52_15 Pr_35_31_64_32	Finish plasters (1) Clay Brick (11 Finish plasters (1)	24634	49269	5358	10717	4%	13.3
Ss_25_13_50.PEI1		Interior parapet	Pr_35_31_64_32 Pr_20_93_52_15 Pr_35_31_64_32	Finish plasters (1) Clay Brick (9) Finish plasters (1)	284	569	62	124	0.1%	0.2
Ss_25_30_20_25	Doorset systems	Wooden door with wood frame	–		490	980	850	1700	0.6%	2.4
Ss_25_30_95.AX	Window systems	Aluminium window, double glass	–		1552	3104	4624	9250	3.5%	13.2
Ss_25_30_95.AW		Sliding aluminium window, double glass	–		352	705	1077	2155	0.8%	3.1
Ss_30_42_32.PE	Floor tiling systems	Exterior Floor -Ground floor - without slab	Pr_35_93_96_19 Pr_20_31_53 Ma_40_19 Ma_60_65_85_27 Pr_25_57_08_08	Ceramic tiles (2) Adhesive mortar (1) Concrete regularisation screed (6) EPS (8) Bitumen sheet (0.43)	24905	49810	5067	10133	4%	14.5
Ss_30_42_32.PI		Interior Floor -Ground floor - without slab	Pr_35_93_96_19 Pr_20_31_53 Ma_40_19 Pr_25_57_08_08	Ceramic tiles (2) Adhesive mortar (1) Concrete regularisation screed (6) Bitumen sheet (0.43)	5000	10001	878	1755	0,7%	2.5
Ss_30_40_30.NA	Flat roof covering systems	Not accessible	Ma_40_84_41_34 Ma_60_65_67 Ma_60_65_85_27 Pr_25_57_08_08 Ma_40_19	Gravel (20) Geotextile (0,4) EPS (0.08) Bitumen sheet (0.43) Concrete regularisation screed (6)	32673	65345	4812	9624	4%	13.7
Ss_30_40_30.PB		Platibanda	Pr_35_31_64_32 Pr_25_57_08_08 Ma_40_19_71 Pr_35_31_64_32	Finish plasters (1) Bitumen sheet (1) Reinforced Concrete (20) Finish plasters (1)	13460	26921	1526	3052	1%	4.4
Ss_30_20_90_95	Wood block flooring systems	First floor - without a slab	Ma_60_97 Ma_60_64_18 Ma_40_19	Wood (2) Cork (3) Concrete regularisation screed (6)	23298	46596	302	605	0,2 %	0.9
Total					197830	324480	41703	66260	32 %	119.1

Table 5
Results from CS 1 structural model by classification code.

Family and Type		Revit material	Results					
SECClasS_Code	SECClasS_Title	Keynote classification	Mass A1-A3 (kg)	Mass A1-A3 + B4 (Kg)	GWP A1-A3 ($kgCO_2e$)	GWP A1-A3 + B4 ($kgCO_2e$)	GWP A1-A3 (%)	GWP A1-3 ($kgCO_2e/m^2$)
Ss_20_05_15	Concrete Foundation Systems	Ma_40_19_71.Fo	40450	40450	7478	7479	6%	21.4
Ss_20_20_75_70	Reinforced concrete beam systems	Ma_40_19_71.Be	23567	23567	5950	5949	5%	17.0
Ss_20_30_75_70	Reinforced concrete column systems	Ma_40_19_71.Co	8804	8804	2096	2096	2%	6.0
Ss_20_30_16_70	Reinforced concrete Wall structure systems systems	Ma_40_19_71.RW	76759	76759	14191	14191	11%	40.5
Ss_30_12_85_18	Concrete floor or roof deck systems	Ma_40_19_71.Sl	262086	262086	60000	60000	46%	171.4
Total			411665	411665	89716	89716	68%	256.3

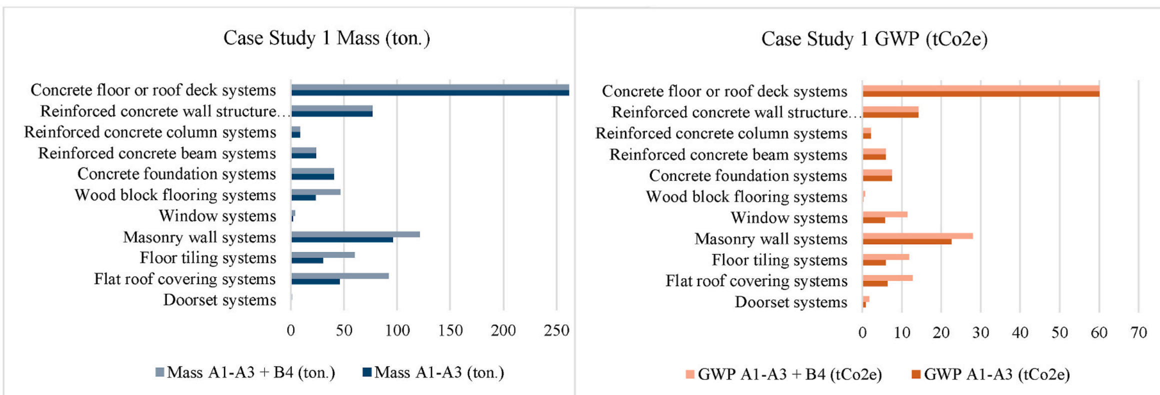

Fig. 12. Charts displaying CS 1 - structural model results, detailing the breakdown by SECClass title.

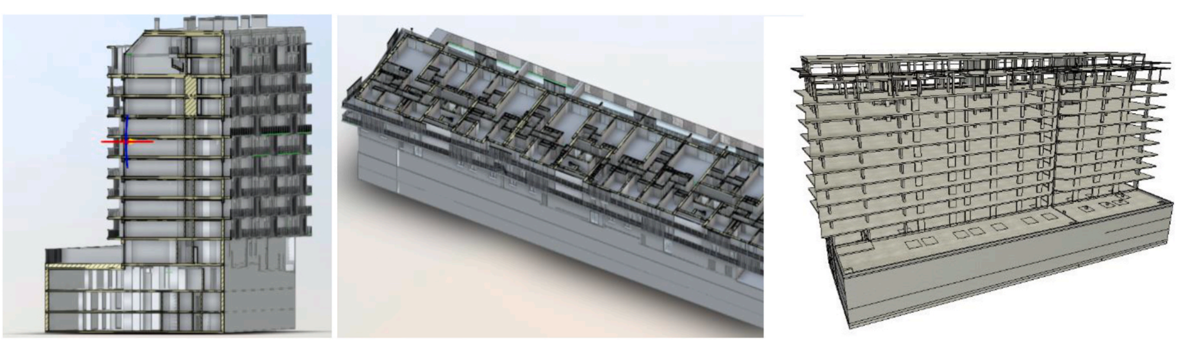

Fig. 13. CS 2 architecture and structure BIM models.

all materials in the model are identified as generic materials. Therefore, the LCA study was conducted using relative material quantities stored in the database. Table 6 illustrates the calculation of the relative material quantities for a masonry wall system of exterior wall Type 1; the same method was applied to roofs and floors.

Correcting the wall, roof, and floor thicknesses and the duplicate BIM objects in both models was impractical, as these tasks would be time-consuming for day-to-day architecture practice.

The proposed methodology allows for the redefinition of thickness and material composition without remodelling, as this information is external to the model. This distinguishes the current method from other tools, such as OneClick LCA, which does not offer this capability. The thicknesses and relative quantities of the materials were adjusted according to the project documentation and stored in a database.

Duplicate objects were not classified and thus were not considered in the analysis.

The architecture model has a normalised GWP of 200 $kgCO_2e/m^{2,}$ and the Structure model 225 $kgCO_2e/m^2$, as shown in Table 7. Globally, the building emits 426 $kgCO_2e/m^2$ and 20 tCO_2e/cap, based on the number of beds (401 users). The building contains nine one-bedroom apartments, 35 two-bedroom apartments, 39 three-bedroom apartments and eight four-bedroom apartments.

The most substantial contributors to GWP are reinforced concrete floor systems or slabs - Ss_30_12_85_18 that contribute roughly 150 $kgCo_2e/m^2$, accounting for approximately 35% of the total emissions. Coming in second are Roof, floor and paving systems - Ss_30, which include, for example, concrete, XPS, geotextile, bitumen sheet, mineral wool, steel profiles, Gypsum boards and sheets, but not including reinforced concrete slabs. These systems contribute to 65 kg $CO2e/m^2$, representing around 14% of the total emissions. Gypsum board partition walls - Ss_25_10_30_35, on the other hand, contribute 37 $kgCo_2e/m^2$, representing 9% of the total carbon emissions. Masonry wall systems - Ss_25_13_50 account for 32 $kgCo_2e$/m2, corresponding to approximately 7% of the total emissions.

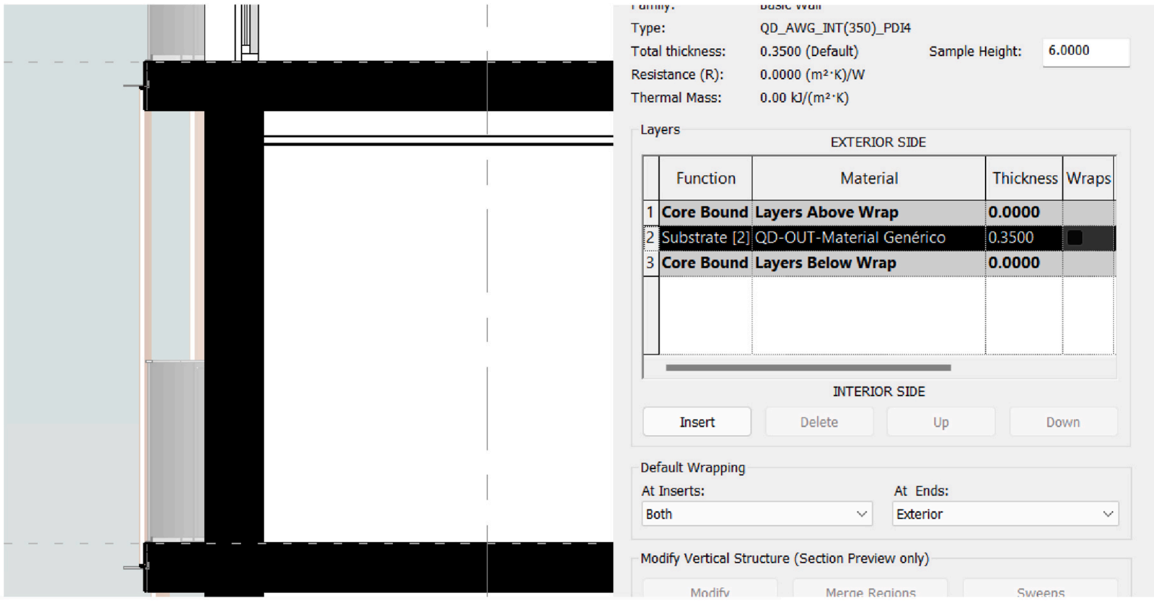

Fig. 14. The identification of wall materials in the Revit models of CS 2.

Table 6
Example of wall calculation: masonry wall system, exterior wall type 1 (Ss_25_13_50. PDI1).

SECClasS_Code	SECClasS_Title	Thickness (m)	Density (kg/m^3)	ConversionFactor (kg/m^2)	Percentage of material (%)
Pr_25_71_35	Gypsum boards and sheets	2x 0.0125	675	16.175	9.2%
Ma_40_84_53	Mineral wool	0.04	30	1.2	0.7%
AIR	AIR	0.085	0	0	0%
Pr_20_93_52_15	Clay bricks	0.2	746	149.2	84.9%
Ma_60_65_85_27	Expanded polystyrene (EPS)	0.1	16	1.6	0.9%
Pr_35_31_64	Plasters and renders	0.005	1500	7.5	4.3%
Ss_25_13_50.PDE1	Masonry wall systems	0.46	–	175.67	100%

Table 7
Results from CS 2 architecture and structure BIM models.

Indicator	Architecture	Structure
Mass A1-3 (t)	8000	21517
GWP A1-3 (t Co_2e)	3951	4441
Mass A1-3 (kg/m^2)	406	1093
Normalised GWP A1-3 ($kgCo_2e/m^2$)	200.8	225.7
Social Cost of Carbon A1-3 (euro)	197550	222050
Mass A1-3 + B4 (t)	12113	21517
GWP A1-3+ B4 (t Co_2e)	6545	4441

Table 8 and Table 9 present a comprehensive categorisation of the architecture and structure Model, while Fig. 15 illustrates the results breakdown by SECCLasS Title from CS 2.

5. Discussion

5.1. Results

According to the "Towards EU embodied carbon benchmarks for buildings in Europe" report (Röck et al., 2022), the embodied carbon throughout the entire life cycle of European residential buildings fluctuates between 400 and 800 $kgCO_2e/m^2$. Specifically, the production phase (A1-3) emissions average 300 $kgCO_2e/m^2$. These calculations encompass various building elements, such as ground and load-bearing structure (e.g., structural frame, walls, and floors), envelope (e.g., external insulation and windows), internal elements (e.g., partition walls, floor and wall finishes), as well as services and appliances. When focusing solely on the elements considered in our study, namely the ground, load-bearing structure, envelope, and internal elements, the emissions averaged 430 $kgCO_2e/m^2$.

The RIBA Climate Challenge sets current embodied carbon benchmarks and 2030 targets for medium-scale residential buildings, with an average value of 275 $kgCO_2e/m^2$ for phases A1-3 and 118 $kgCO_2e/m^2$ for B1-5 (LETI, 2024; Alwan and Jones, 2022). Table 10 outlines the breakdown by building life cycle modules and compares the results of the case studies with the results available in the literature (Röck et al., 2022; LETI, 2024).

Our findings align with this established benchmark. CS 1, a single-family residential building, produces 375 $kgCO_2e/m^2$ and 32 tCO_2e/cap, and CS 2, a multi-residential building, generates 426 $kgCO_2e/m^2$ and 20 tCO_2e/cap (A1-3).

Röck et al. (2022) assert that multi-family buildings exhibit a higher embodied carbon per square meter, and single-family buildings have a more significant impact per capita. Multi-family buildings generally feature smaller individual living areas, shared common spaces, and amenities. When assessing the total area available for each resident, CS 1 offers 84 m^2/cap, and CS 2 provides 49 m^2/cap.

Evangelista et al. (2018) concluded the opposite: single-family dwellings tend to have higher impact figures after analysing different typologies of residential buildings because highly impacting elements such as the building roof and envelope have a higher share in single-family. According to Hoxha et al. (2017), the average GWP value considering the entire life cycle and all building elements, including external works, is 1035 $kgCO_2e/m^2$ for multi-family buildings and 615 $kgCO_2e/m^2$ for single-family houses. Moreover, Alwan and Jones (2022) and Evangelista et al. (2018) confirm that this is largely due to design and construction characteristics (module A).

Analysing the results of our study, we identified that the contribution

Table 8
Results from CS 2 architecture BIM model including slabs by Classification Code.

SECClasS_Code	SECClasS_Title	Suffix	Material Composition	Mass A1-3 (ton.)	Mass A1-3 + B4 (ton.)	GWP A1-3 (ton. CO_2e)	GWP A1-3+B4 (tonCO_2e)	GWP A1-3 (%)	GWP A1-3 (kgCO_2e /m^2)
Ss_25_10_20	Curtain walling systems	–	–	7.9	7.9	28.6	28.6	0.34%	1.45
Ss_25_10_30_35. PDI0	Gypsum board partition systems	Interior wall	Steel, Mineral Wool, Gypsum boards and sheets	572.3	1144.7	662.1	1324.3	7.83%	33.65
Ss_25_10_30_35. PDI3		Interior wall in contact with couretes	Steel, Mineral Wool, Gypsum boards and sheets	64.5	129.0	74.6	149.2	0.88%	3.79
Ss_25_10_30_35. PDI4		Interior wall with contact with condominium room	Steel, Mineral Wool, Gypsum boards and sheets	2.8	5.5	3.2	6.4	0.04%	0.16
Ss_25_11_16. PDI2	Concrete wall systems	Interior Wall with contact with stairs	Concrete, Steel	1709.2	3418.5	254.4	508.7	3.01%	12.92
Ss_25_13_50.AQ	Masonry wall systems	Exterior Wall	Clay Bricks, Plasters and Mortars	3.1	3.1	0.6	0.7	0.01%	0.03
Ss_25_13_50.BE		Exterior Wall with contact with bays	Clay Bricks, Plasters and Mortars	2.5	2.5	0.5	0.5	0.01%	0.03
Ss_25_13_50.JD		Wall Expansion joint	Clay Bricks, Plasters and Mortars	120.7	120.7	25.2	25.2	0.30%	1.28
Ss_25_13_50.MP		Boundary Wall	Clay Bricks, Plasters and Mortars	24.7	24.7	5.2	5.2	0.06%	0.26
Ss_25_13_50.PB		Exterior Wall PlatBand	Clay Bricks, Plasters and Mortars	20.6	20.6	4.3	4.3	0.05%	0.22
Ss_25_13_50. PDE1		Exterior Wall ETICs	Clay Bricks, Plasters and Mortars, Motars, EPS, Mineral wool, Gypsum boards and sheets	552.5	552.5	133.5	133.5	1.58%	6.78
Ss_25_13_50. PDE2		Exterior Wall ETICs with Lioz stone	Clay Bricks, Plasters and Mortars, Motars, EPS, Mineral wool, Gypsum boards and sheets, Stone	197.6	197.6	33.9	33.9	0.40%	1.72
Ss_25_13_50. PDEC		Parking Floor Walls	Clay Bricks, Plasters and Mortars	260.3	260.3	54.5	54.5	0.64%	2.77
Ss_25_13_50. PDEP		Parking Floor Walls	Clay Bricks, Plasters and Mortars	8.1	8.1	1.7	1.7	0.02%	0.09
Ss_25_13_50. PDI0		Interior wall	Clay Bricks, Plasters and Mortars, Motars, EPS, Mineral wool, Gypsum boards and sheets	260.2	520.4	215.8	431.6	2.55%	10.96
Ss_25_13_50. PDI1		Interior wall in contact with the common circulation		70.6	141.1	62.2	124.4	0.74%	3.16
Ss_25_13_50. PDI4		Interior wall with contact with condominium room		115.1	230.2	84.0	168.0	0.99%	4.27
Ss_25_13_50. PDI7		Interior wall with laundry contact		1.2	2.4	1.0	2.0	0.01%	0.05
Ss_25_30_95	Window systems	All model window types	–	102.6	205.1	292.3	584.6	3.5%	14.85
Ss_25_30_20_25	Doorset systems	All model door types	–	97.3	194.6	168.8	337.6	2%	8.58
Ss_25_50_35	Grille systems	–	Steel	197.4	394.9	596.2	1192.5	7%	30.30
Ss_30.AH	Roof, floor and paving systems	Interior floor-Parking	Concrete, Steel	66.1	132.2	12.0	24.0	0.14%	0.61
Ss_30.CBC		Interior floor-Parking 1	Bitumen sheet, Concrete, Steel, XPS, Gypsum boards and sheets	72.3	72.3	5.3	5.3	0.06%	0.27
Ss_30.CBE1		Roof of the upper floor	Gravel, XPS, Geotextil, Bitumen sheet, Concrete, Mineral Wool, Gypsum; Gravel, XPS, Geotextil, Bitumen sheet, Concrete, Steel, Mineral Wool, Gypsum	652.0	652.0	23.1	23.1	0.27%	1.17
Ss_30.CBE2		Terrace/balcony roof	Concrete, XPS, Geotextil, Bitumen sheet, Mineral Wool, Steel, Gypsum boards and sheets	37.5	37.5	22.9	22.9	0.27%	1.16
Ss_30.PVC		Interior floor-Parking 2	Bitumen sheet, Concrete, XPS, Steel, Gypsum boards and sheets	680.7	1361.4	123.6	247.3	1.46%	6.28

(*continued on next page*)

Table 8 (*continued*)

SECClasS_Code	SECClasS_Title	Suffix	Material Composition	Mass A1-3 (ton.)	Mass A1-3 + B4 (ton.)	GWP A1-3 (ton. CO_2e)	GWP A1-3+B4 (tonCO_2e)	GWP A1-3 (%)	GWP A1-3 (kgCO_2e /m^2)
Ss_30.PVE		Interior floor-Apartments	Ceramic, Concrete, Tiles, XPS, Aluminium, Steel, Gypsum boards and sheets	52.0	51.2	26.1	25.7	0.31%	1.33
Ss_30.PVI3		Interior flooring with high air gap ceilings	Wood, Cork, Concrete, Mineral Wool, Aluminium, Steel, Gypsum boards and sheets	1656.8	1656.8	880.2	880.2	10.40%	44.73
Ss_30.PVI4		Interior flooring over houses	Wood, Cork, Concrete, Mineral Wool, Aluminium, Steel, Gypsum boards and sheets	206.7	206.7	109.1	109.1	1.29%	5.54
Ss_30_30_72	Rooflight and roof window systems	–	–	0.8	1.6	2.6	5.2	0,03%	0.13
Ss_35_10_85_15	Concrete stair or ramp systems	–	Concrete, Steel	7.4	14.7	5.0	10.1	0,06%	0.26
Ss_37_17_13_50	Masonry chimney stack systems	–	Clay Bricks, Plasters and Mortar	177.2	343.0	38.9	75.4	0,46%	1.98
Total				8000.6	12113.6	3951.5	6545.4	47 %	200.7

Table 9
Results from CS 2 structure model including slabs by classification.

SECClasS_Code	SECClasS_Title	Mass A1-3 (ton.)	Mass A1-3 + B4 (ton.)	GWP A1-3 (ton. CO2e)	GWP A1-3 + B4 (ton.CO_2e)	GWP A1-3 + B4 (%)	GWP A1-3 + B4 (kgCO_2e/m^2)
Ss_20_05_15_70	Reinforced concrete pad and strip foundation systems	2867.1	2867.1	454.2	454.2	5.41%	23.1
Ss_20_20_75_15	Concrete beam systems	467.8	467.8	127.4	127.4	1.52%	6.5
Ss_20_20_75_80	Steel beam systems	1.0	1.0	3.0	3.0	0.04%	0.2
Ss_20_30_75_15	Concrete column systems	1259.0	1259.0	306.0	306.0	3.65%	15.6
Ss_20_30_75_80	Steel column systems	4.7	4.7	14.2	14.2	0.17%	0.7
Ss_20_60_35_70	Reinforced concrete retaining wall systems	1274.9	1274.9	201.9	201.9	2.41%	10.3
Ss_25_11_16_70	Reinforced concrete wall structure systems	2304.1	2304.1	365.0	365.0	4.35%	18.5
Ss_30_12_85_18	Reinforced concrete floor systems	13338.9	13338.9	2969.8	2969.8	35.38%	150.9
Total		21517.4	21517.4	4441.4	4441.4	53%	225.7

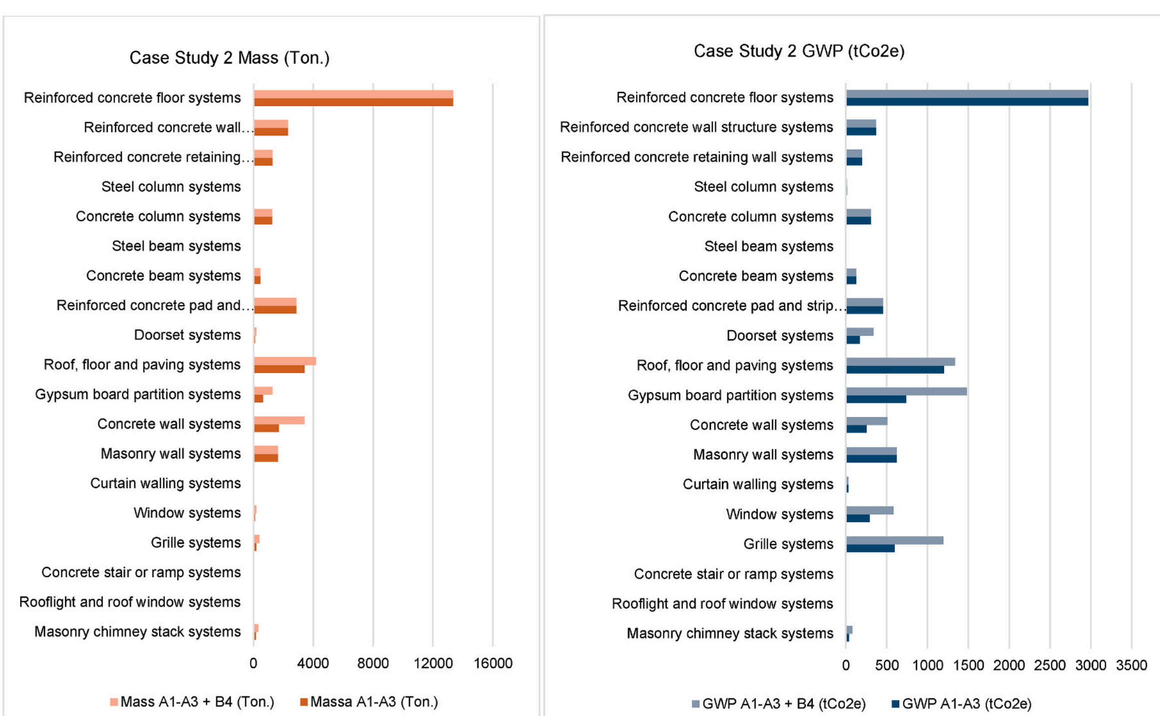

Fig. 15. Charts displaying results for CS 2 detailing the breakdown by SECClass Title.

Table 10
The breakdown by modules of the building's life cycle, comparing the results available in the literature and the CS1 and CS2 results.

Stage	Embodied carbon benchmarks (Röck et al., 2022)			RIBA 2030 benchmarks (LETI, 2024)						Case Study results	
				Current Benchmark			2030 Target			CS1	CS2
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max		
Products/materials [A1-3]	70	300	520	210	275	368	42	110	179	375	426
Maintenance and replacements [B1-5]	0	120	350	90	118	157	18	47	76	71	131

of the interior walls in CS1 is 49 $kgCO_2e/m^2$, while in CS2 it is 10 $kgCO_2e/m^2$. When examining the use of reinforced concrete per square meter, CS1 uses 1117 kg/m^2, contributing 256.3 $kgCO_2e/m^2$, while CS2 uses 1093 kg/m^2, contributing 225.7 $kgCO_2e/m$, consistent with single-family homes being more carbon-intensive. However, embodied carbon emissions are higher per square meter in the multi-residential building because CS2 has more interior walls than CS1, with 155 kg/m^2 and 70 kg/m^2, respectively.

In addition, the plasterboard ceilings and plasterboard partition walls in CS2 are 80 per cent more carbon-intensive than the masonry partition walls used in CS1, resulting in a difference of 57 $kgCO_2e/m^2$ for the partition walls and 30 $kgCO_2e/m^2$ for the ceilings. To illustrate, we simulated CS2 and replaced the plasterboard partition walls, totalling 77.6 $kgCO2e/m^2$ of the wall, with masonry walls totalling 24.5 $kgCO_2e/m^2$. This replacement led to a 13 per cent reduction in the building's carbon footprint (Table 10), from 426 $kgCO2e/m^2$ to 400 $kgCO2e/m^2$. Additionally, removing the plasterboard ceilings from CS2 results in a 32.5 $kgCO_2e/m^2$ reduction, bringing the total to 368 $kgCO_2e/m^2$ (Table 11).

Table 12 presents the distribution of embodied carbon by construction element, comparing literature results with the findings from case studies CS1 and CS2. Both sources and case studies indicate that the load-bearing structure is the largest contributor to embodied carbon. According to Röck et al. (2022) these elements contribute an average of 24% of the total carbon, while LETI (2024) indicates a higher contribution of 46%. In the case studies, CS1 reports 235 $kgCO_2e/m^2$ (53%) and CS2 reports 202 $kgCO_2e/m^2$ (36%) for the load-bearing structure.

The second largest contributor is the interior walls and finishes. Röck et al. (2022) state that these elements contribute an average of 21% of total GWP, while (LETI, 2024) indicates a contribution of 16%. For CS1, the contribution is 108 $kgCO2e/m^2$ (24%), and for CS2, it is 221 $kgCO2e/m^2$ (40%).

Moreover, findings from CS 1 parallel the conclusions of a study evaluating a single-family house with similar construction specifications (Kylili et al., 2017). Reinforced concrete floors and foundations (combined) are singled out as primary contributors, accounting for 63% of the building's carbon footprint, while in CS 1, they represent 52% of the carbon footprint. Interior and exterior walls collectively contribute 17% in CS 1, compared to 9% in the referenced study (Kylili et al., 2017).

According to Minunno et al. (2021), using less carbon-intensive materials is one of the most widely employed strategies for minimising buildings' environmental impact. Replacing concrete and steel with cross-laminated timber (CLT) can result in a 68% reduction in a building's carbon footprint, and replacing reinforced concrete with steel structures can contribute to a 15% reduction in embodied carbon if considering recycling and reuse of resources in the analysis (Minunno et al., 2021). Hart et al. (2021) report that the median lifetime embodied carbon per GFA is 119 $kgCO_2e/m^2$ for timber structural systems, 185 $kgCO_2e/m^2$ for reinforced concrete, and 228 $kgCO_2e/m^2$ for steel. De Wolf et al. (2016) found that wooden structures have the lowest median value at approximately 200 $kgCO_2e/m^2$, compared to steel and concrete systems, which range between 350 and 380 $kgCO_2e/m^2$. Skullestad et al. (2016) state that the embodied carbon for mid-rise reinforced concrete structures is between 111 and 121 $kgCO_2e/m^2$, while for wooden structures, it is significantly lower, ranging from 26 to 40 $kgCO_2e/m^2$. Spear et al., 2019 found that using CLT in the structures of apartment buildings resulted in embodied carbon savings of 220–260 $kgCO_2e/m^2$ of internal area compared to using concrete.

Table 12
The breakdown by building elements, comparing the results ($kgCO_2e/m^2$) available in the literature and the CS1 and CS2 results. *Only MEP.

Description	Embodied carbon benchmarks (Röck et al., 2022)	RIBA 2030 Climate Challenge Target benchmark (LETI, 2024)	CS1	CS2
Foundation	50 (7%)	168 (21%)	21 (5%)	23
Loadbearing structure	170 (24%)	368 (46%)	235 (53%)	202 (36%)
Envelope	110 (15%)	104 (13%)	82 (18%)	111 (20%)
Interior wall and finishes	150 (21%)	128 (16%)	108 (24%)	221 (40%)
Services	190 (27%)	32 (4%) *	–	–
Appliances	40 (6%)	–	–	–
Total	710 (100%)	800 (100%)	446 (100%)	557 (100%)

In CS 2, we conducted a simulation where reinforced concrete floor systems were replaced with CLT floor systems, resulting in a 69% reduction in the building's total carbon footprint (Table 13). Another strategy involves using recycled and reused materials and the reduction

Table 11
Results from CS 2 simulations, where Masonry wall systems replaced Gypsum board partition systems.

Current option			Alternative option				
SECClasS_Code	SECClasS_Title	GWP per m^2 of wall ($KgCo_2e/m^2$)	SECClasS_Code	SECClasS_Title	GWP per m2 of wall ($KgCo_2e/m^2$)	Reduction ($KgCo_2e/m^2$)	Reduction (%)
Ss_25_10_30_35.PDI0 Ss_25_10_30_35.PDI3	Gypsum board partition systems	77.6	Ss_25_13_50.PDI0 Ss_25_13_50.PDI3	Masonry wall systems	24.5	−26.7	13
Ss_30_12_85_18.PVC Ss_30_12_85_18.PVE Ss_30_12_85_18.PVI3	Concrete floor or roof deck systems	124.8	Ss_30_12_85_18.PVC Ss_30_12_85_18.PVE Ss_30_12_85_18.PVI3	Concrete floor or roof deck systems without plasterboard ceilings	38.4	−32.9	16

Table 13
Results from CS 2 simulations, where CLT floor systems replaced Reinforced concrete floor systems.

Current option			Alternative option				
SECClasS_Code	SECClasS_Title	GWP A1-3 ($KgCo_2e/m^2$)	SECClasS_Code	SECClasS_Title	GWP A1-3 ($KgCo_2e/m^2$)	Reduction ($KgCo_2e/m^2$)	Reduction (%)
Ss_30_12_85_18. CBE1	Reinforced concrete floor systems	349.0	Ss_30_12_33_90. CBE1	CLT floor systems	−110	−293	69%
Ss_30_12_85_18. CBE2		100.8	Ss_30_12_33_90. CBE2		−92.9		
Ss_30_12_85_18. PVI3		124.8	Ss_30_12_33_90. PVI3		−124.9		
Ss_30_12_85_18. PVI4		123.1	Ss_30_12_33_90. PVI4		−124.9		
Ss_30_12_85_18. PVE		119.4	Ss_30_12_33_90. PVE		−98.7		
Ss_30_12_85_18. PVC		92.5	Ss_30_12_33_90. PVC		−98.7		
Ss_30_12_85_18.AH		92.5	Ss_30_12_33_90.AH		−98.7		
Ss_30_12_85_18. CBC		116.9	Ss_30_12_33_90. CBC		−98.7		

of clinker and cement in concrete, coupled with using alternative and less intensive aggregates.Parece et al. (2022) proposes alternative and low-impact materials that can be applied in buildings.

5.2. Critique of the developed methodology

The BIM models of the two CS showcased distinct BIM and LoD modelling techniques, which enabled us to examine the adaptability and effectiveness of the proposed QTO methods. In CS 2, BIM models had no material information, and the thicknesses of the roofs, walls, and floors did not align with the project documentation. We opted not to adjust the BIM object thicknesses as the proposed method uses relative quantities of material and thickness from the database and only absolute quantities (i.e., m, m^2) from the BIM model. By implementing this strategy, we estimate saving 20 hours of work remodelling. Additionally, this approach enables the simulation of various project options by merely reclassifying the objects in the BIM model, as assigning a new code to a BIM object allows for setting a new assembly with different materials, for example, replacing concrete with cross-laminated timber slabs as we proposed in CS 2. This strategy facilitated ongoing automated assessments of varying material options without requiring remodelling.

We found a significant lack of construction product and material databases in Portugal and Europe. Moreover, available LCI databanks, such as Ecoinvent, are subscription-based, and many EPDs are not provided in a machine-readable format. Therefore, during the development of our database, we manually mapped 32 SECCLasS codes with ICE data from the University of Bath and existing EPDs. Suppose existing databases adopted a standardised code structure related to the various CCS commonly utilised in practice, such as the SECClasS and Uniclass classification. In that case, we may expediently access this data and more easily identify the environmental impacts of products. This endeavour must also consider the different levels of representativeness of the data in the context of the building design phases. Our work demonstrates how the structure and hierarchy of the SECClasS and UniClass classification systems can accommodate a step-by-step refinement of the LCA data. During early stages, generic or average LCA values can be assigned to the Systems codes. As the design progresses, additional classification of individual products and materials is assigned in object types to set EPD values to Product and Material codes.

On the other hand, the absence of catalogues featuring potential construction solutions for various construction buildings (e.g., facades and structures) for new buildings or renovation projects, along with their environmental and technical characterisation, is evident. The availability of databases containing pre-defined solutions representing regional contexts and presented in machine-readable formats will be game-changing, as it will allow for rapid simulations for different solutions within the BIM model, as we proposed for CS 2. This could be accomplished using tools like the one proposed in this research or Dynamo routines.

Moreover, facilitating direct Application Programming Interface access to these databases is paramount. This step would propel the development of increasingly sophisticated and automated Building LCA tools, opening avenues for the application of data science and machine learning algorithms to optimise decision-making and predict the environmental impacts of buildings.

There are both limitations and prospects for future developments. Presently, the proposed tool is exclusively accessible for Revit models or a BoQ structured in a particular Excel format. An essential next step is to develop the tool to accept the IFC open format. This enhancement will enable the BIM model to be initially generated in a preferred BIM software tool and exported as an IFC file. Additionally, it will be imperative to incorporate other life cycle stages to facilitate a comprehensive life cycle analysis. Furthermore, the inclusion of additional LCA indicators such as acidification potential, ozone depletion potential, and others warrants exploration in future research endeavours.

6. Conclusions

LCA is frequently difficult to apply throughout the building design. It is often hindered by its time-consuming nature and the limited availability of crucial data until the later design stages. A BIM-based methodology is presented that calculates GWP in phases A1-3 and B4 of the building's life cycle and facilitates continuous LCA throughout the project phases, i.e. from the licensing phase to the execution project and in heterogeneously developed models.

The SECCLasS CCS dynamically links the technical and environmental information in an external database to geometrical data in BIM models. This strategy can eliminate manual mapping when assigning LCA data to BIM objects and streamline the process when certain conditions are met, namely, a classified, well-structured library of BIM families, objects, and materials.

This methodology proposes three methods for QTO, considering design phases, LoD, information granularity, and BIM modelling techniques. It also develops a database that matches the LoD of the elements and accommodates a step-by-step refinement of the LCA data.

Two CS using different modelling techniques and LoD were evaluated. The results show that the proposed methodology can provide reliable information for decision-making during the design process, even when information on materials is limited.

CS 2 had inaccuracies in the thicknesses of the BIM objects and lacked information on the materials; the BoQ was calculated using the relative quantities of the materials from an external database, saving 20 hours of work on remodelling and correcting the model. This approach allows for LCA studies during the design phases without requiring highly detailed models and the quick simulation of different material options since it is only necessary to reclassify the objects to assign a new assembly.

The proposed tool offers several advantages, including complete data control, continuous LCA study throughout the design process, integration with finish maps and quantities, and free use (available at GitHub, 2024). However, some limitations exist, such as the user's responsibility for updating LCA databases, the absence of a user-friendly interface, and the inability to import IFC files. Future research should explore all building life cycle stages, operational impact, and additional case studies in different national contexts. Additionally, incorporating Life Cycle Costing and circular economy indicators like adaptability and disassembly, sensitivity analyses, and multi-objective optimisation can further enhance decision-making processes.

Ethics approval and consent to participate

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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CRediT authorship contribution statement

Sara Parece: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ricardo Resende:** Writing – review & editing, Supervision, Resources, Conceptualization. **Vasco Rato:** Supervision.

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.

Data availability

Data will be made available on request.

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