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RESEARCH ARTICLE

Balancing Carbon Emissions in Façade of Residential Buildings Through BIM-LCA: A Comparative Analysis of Insulation Materials

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ABSTRACT

Thermal insulation materials play a significant role in balancing buildings' total carbon emissions. Balancing involves applying the optimized amount of insulation materials to avoid excessive emissions in either the operational or embodied phases. Due to the wide range of insulation materials and variations of their specifications, it is vital to analyse them individually.

The focus of this study is to optimize the amount of insulation materials in the facades of Residential Buildings (RB) to balance the amount of Operational Carbon Emissions (OCE) and Embodied Carbon Emissions (ECE) by applying the Building Information Modelling-Life Cycle Assessment (BIM-LCA) integration method. The Life Cycle Assessment (LCA) stages, from extraction of raw materials, manufacturing, construction, usage, and end-of-life, as well as the impact assessment categories, are based on European standards. 49 building materials are utilized during this research activity, which includes the three insulation materials as alternatives, such as Glass wool, polyurethane (PUR), and Natural Cork from mineral, synthetic, and natural categories, and lightweight concrete blocks made from pumice, and clay brick blocks as other alternatives for the main core of the Facades. The RB under study is a prototype sample located in Milan. After performing the methodology and analyses, the results demonstrate that thermal conductivity and density play an important role. For instance, Natural Cork in higher thickness values performs better, while PUR in lower ones.

Keywords: Sustainable design, Building information modelling (BIM), Life cycle assessment (LCA), Global warming potential (GWP), Embodied carbon emissions (ECE), Operational carbon emissions (OCE)

1. Introduction

Global warming is like a cancer, gradually destroying the earth. Despite countless protocols, conferences, and agreements, no significant changes have been achieved so far. The building sector is by far the largest energy consumer and emitter in the world. In 2021, the operational carbon from buildings reached a record of 10 gigatons of carbon dioxide, 5% more than when the Paris Agreement was signed in 2015 [1]. In Italy, the construction sector is responsible for 45% of energy consumption, which causes 17.5% of Carbon Dioxide (CO₂) emissions [2]. Due to prospective energy demand, Residential Buildings (RBs) are

seen as far from building carbon neutrality. They account for approximately half of building-related carbon emissions and consume over 60% of the energy used in the building sector [3]. Furthermore, compared to non-residential structures, RBs provide more potential and cost-effectiveness for increasing energy efficiency and mitigating carbon emissions [4]. Insulation materials have an undeniable role in managing the operational energy consumption in buildings. On the other hand, applying excessive building materials would contribute to embodied emissions. At this stage, finding a balance between Embodied Carbon Emissions (ECE) and Operational Carbon Emissions (OCE) leads to an optimized design.

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During this study, the focus is on the environmental performances of buildings like the reviewed articles [5–7]. However, performing other assessments would be beneficial to reach more precise results. Some research studies combine Life Cycle Assessment (LCA) with life cycle cost (LCC) [8, 9]. The 3D modelling of the building structure and elements is performed in a Building Information Modelling (BIM) environment, and then the data is transferred to an LCA software tool for analysis. The process is done by a new methodology that is called BIM-LCA integration. The carbon footprint of materials from the extraction of raw materials to the end of life, besides the operational emissions, is evaluated and compared together. The challenge is to find the optimized thickness of insulation materials for the façades of RBs that cause the least carbon emissions, both embodied and operational. This will lead to a balance in ECE and OCE of RBs during their whole service life.

1.1. LCA in buildings

LCA attempts to evaluate the potential environmental impact of the structures during their whole life cycle, from the production of materials to their end-of-life and waste disposal management. Initially, LCA were designed to analyse simple products, meaning those with limited lifespans and distinct functions. Applying it to buildings, which typically have many purposes and a long span, is therefore a complex problem. The LCA model has two purposes, to evaluate a building's life cycle early in the design process, and to benchmark a building's life cycle performance [10]. Generally, LCA is not performed during the design phase to have a comparative analysis of different building materials; therefore, it does not have a considerable effect on the design phases [11]. According to [12–14], LCA is time-consuming and needs a huge amount of information. Therefore, the LCA is performed after the design process is completed [14, 15]. Choosing the right materials and structural systems to use in the design process is within the power of structural engineers. Thus, giving structural engineers the opportunity to take environmental factors into account when making decisions about building designs will encourage resource efficiency and, as a result, make it possible to lessen the environmental effects of construction projects. From this angle, structural engineers are at the forefront of the effort to create a built environment that is sustainable [16].

1.2. Total building emissions

Building emissions are categorized according to life cycle stages, which include embodied, operational,

disposal, and recycling following end-of-life usage [17, 18]. The term “ECE” refers to two categories of emissions: initial and recurring. The emissions incurred during a building's original construction are its initial emissions [19, 20]. This is the amount of energy used for obtaining raw materials, processing them, producing them, transporting them to the construction site, and construction. Direct emissions and indirect emissions make up the initial ECE. In the process of construction, a wide range of materials is employed. Some of these materials may wear out sooner than the structure. They are therefore changed to restore the building. Furthermore, structures need to have some yearly maintenance done regularly. Over a building's whole life, the emissions associated with these repairs and replacements must be taken into consideration, and they are recurring ECE [20]. The energy needed to run a building's appliances, lighting, heating, and cooling systems is known as operational energy. On the other hand, a building's embodied energy is the total energy used in all the processes involved in its construction and production [20, 21]. The energy needed to destroy a structure and move its waste materials to recycling facilities or landfills as a building's useful life comes to an end is known as demolition energy. Thus, a building's total lifecycle emissions are the result of adding together all its ECE, operating emissions, maintenance and replacement material, and component emissions, and emissions related to recycling building materials after destruction [20].

1.3. Building envelope role in ECE and OCE

The building industry has made major expenditures in research and regulation focused on energy efficiency and decreased OCE, and the ECE has drawn less attention [22]. A large portion of the ECE in most buildings is caused by the envelope [23]. The designer should consider a balance between ECE and OCE during the life span of the building. The amount and selection of materials, as well as their carbon intensity, influence the envelope's ECE, while the local climate and the carbon intensity of the local energy system influence the operational emissions. Although it is desirable for materials to originate from nearby suppliers to save transportation expenses and emissions, material supply chains are sometimes quite intricate [24]. Insulation materials greatly impact thermal comfort, energy efficiency, and carbon emissions. Since the focus of this study is environmental impacts, the important point is to select materials with the least emissions. Gathering data is time-consuming and expensive; therefore, the most efficient way is using EPDs, which provide a wide

range of data for each material. The application of insulation material depends on many factors, such as weather conditions, availability, and economic aspects. Another important factor is the energy source in each area; for instance, in some countries, where most of the energy is supplied from green sources, utilizing excess insulation materials is not reasonable, and, on the contrary, in areas that are not using green energies, more insulation materials work better.

1.4. BIM-LCA integration

BIM is a comprehensive approach to creating and managing information for constructed assets. Underpinned by an intelligent model and facilitated by a cloud-based interface, BIM brings together structured, multi-disciplinary information to provide a digital representation of an asset throughout its whole life cycle, encompassing phases from planning and design through construction to operational maintenance [25]. There are two options provided by the BIM software for users: information modelling and information management. Through the BIM software, various design options are presented to analyse their effect on the environment [26, 27]. By adopting BIM, construction projects can achieve better coordination among architects, engineers, contractors, and owners. The two perspectives that are introduced by BIM to evaluate sustainability are design optimization and integrated project delivery. Besides this, they have found that high-performance design solutions can be produced when BIM and sustainable practices are merged [28]. The integration of BIM-LCA is a new idea in sustainable construction. The purpose of this interface is to coordinate the design offered by the BIM with the environmental impact analyses to achieve optimized design solutions. The integration has great potential to optimize the designs towards sustainability. It is hard and time-consuming to manage and sort the huge amount of data needed for the whole LCA of a building. Therefore, BIM needs to be utilized to simplify and speed up the process and to make the designs more precise. BIM-LCA integration has the potential to provide sufficient information on building geometry and function for building sustainability analysis [29]. The integration of BIM-LCA is also utilized to execute sustainable construction, green building certification, and the circular economy [30–33]. Various tools, plug-in functions, and software have been developed for facilitating BIM-based LCA through the integration of the quantity take-off and common material libraries of a BIM authoring tool with a local LCA database for determining the environmental impact at different project life cycle stages [34, 35].

Several studies have applied the BIM-LCA methodology to perform environmental analysis [36–42]. However, these studies reveal critical research gaps that limit their practical applicability and scalability. The existing works often lack broader material coverage, global applicability, operational impact assessment, and dynamic data integration, which reduces the comprehensiveness of the results [37]. In addition, sustainability data extraction from BIM models still relies heavily on manual processes [38], and a comprehensive framework that fully integrates BIM and LCA for automated, real-time environmental evaluation is still missing [40, 41]. Moreover, most previous studies have focused primarily on structural components, overlooking façade systems and the combined influence of ECE and OCE [42]. To address these limitations, this research proposes an innovative automated BIM-LCA workflow connecting Revit and One Click LCA to evaluate the environmental performance of different façade insulation materials. The study extends the analysis to both ECE and OCE, providing a comprehensive framework for low-carbon façade design in RBs.

1.5. Research objectives and questions

The primary aim of this study is to develop and demonstrate an integrated BIM–LCA workflow that supports comparative, early-stage decision-making for façade insulation design in RBs. The research evaluates how different insulation materials and façade configurations influence the balance between ECE and OCE across the building life cycle. Specifically, the study implements a Revit–One Click LCA workflow to compare alternative insulation materials and façade core systems under three structured scenarios, equal thermal resistance, equal insulation mass, and variable insulation thickness, and to identify material-specific insulation thickness ranges that minimize total life-cycle CO₂ emissions while remaining compatible with practical design constraints. Accordingly, the study investigates how BIM–LCA integration enhances the efficiency and reproducibility of façade-level LCA, how material properties such as thermal conductivity and density affect environmental performance, and which insulation thickness ranges yield the most sustainable façade solutions.

Scope of the research: This study exclusively concentrates on residential buildings and analyses alternative designs for façade insulation strategies in the early design stage. The study utilizes specific LCA stages (A1–A3, A4, A5, B4–B6, C2–C4) supported by EPDs, as these data sets must be accurate. Certain life cycle phases, such as C1 demolition and B2 maintenance, as well as B7 water use, have been

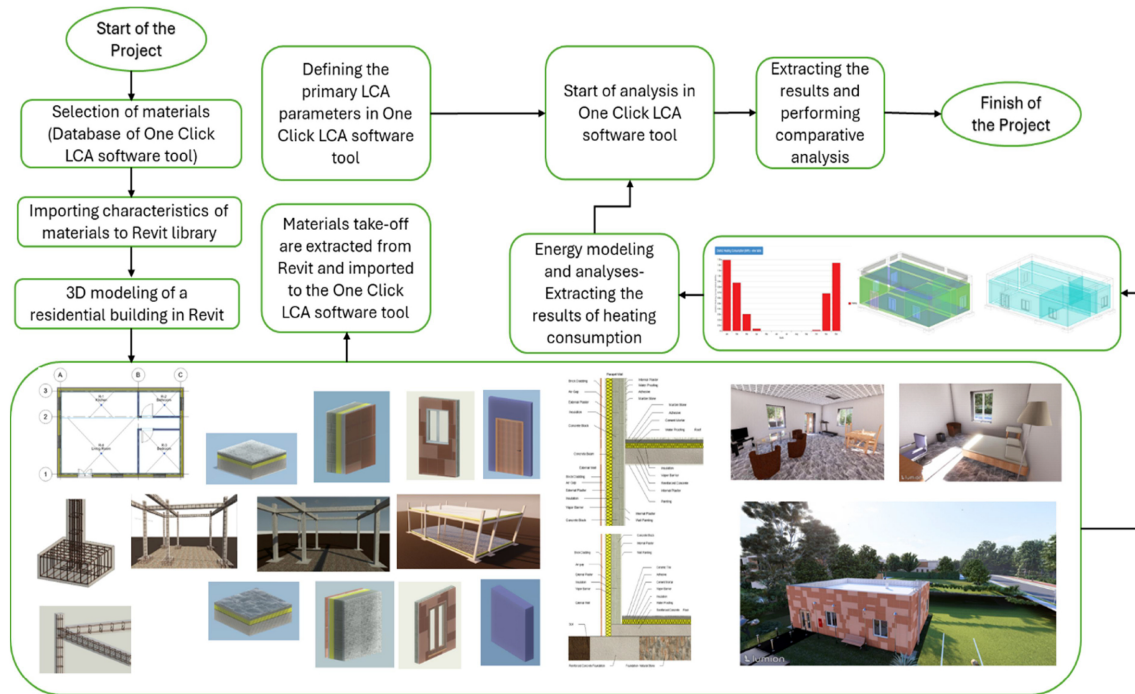


Fig. 1. The whole steps and workflow of the study.

excluded due to data limitations. The three scenarios are designed for relative comparative assessment of insulation materials and thicknesses rather than absolute impact quantification.

2. Methodology

One of the main ideas of this research is to perform an LCA by integrating a BIM environment (Revit software) with an LCA tool (One Click LCA). As it is mentioned in ISO 14040 and 14044 [43, 44], performing LCA studies should follow 4 phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation, which are the basis of any LCA research. The LCA stages and impact assessment categories are based on the EN15804 + A2 and EN15978 [45, 46]. This study covers the LCA stages A1-A3 manufacturing, A4 transportation, A5 construction, B4-B5 replacement, B6 operational energy, C2 waste transport, C3 waste processing, and C4 waste disposal. The assessment and reporting tool used for this research is “Level(s) life-cycle assessment (EN 15804 + A2),” which follows the 6 macro-objectives of LEVEL(s) [47] and the standard EN 15804 + A2, which is based on the criteria of the PEF method [48]. In this study, the results of 12 impact assessment categories are going to be assessed, which are the main impact assessment categories except for Global Warming Potential (GWP) Biogenic. The EPDs that are used in this study are based on EN 15804 + A2, and they publish data for all stages from

A1-A3 to end-of-life. Fig. 1 demonstrates the whole process and workflow from the selection of materials, 3D modelling, extracting the materials take-off, energy simulation, and performing the analysis. This process repeats for analysing each scenario. The focus of this study is a comparative analysis of facades, particularly in clarifying the role of insulation materials in sustainable design and the total CO₂ emissions of RBs. Therefore, the alternative materials considered in this study are insulation materials and main core blocks. The outcomes are not just GWP- Carbon Dioxide Equivalent (CO₂ e) emissions, but the main focus is on GWP, and the comparative analysis is based on the total carbon emissions of RBs in each scenario. As mentioned before in the section on “total building emissions,” the total carbon emissions include the initial ECE, emissions due to maintenance or replacement, which are also called recurring ECE, OCE, and emissions due to disposal and recycling. In this study, the total emissions are classified into two categories: embodied emissions, which include A1-A3, A4, A5, B4-B5, C2, C3, and C4, and operational emissions, which include only B6, energy for heating.

The goal of this study is to perform a variety of LCAs on a residential building with alternating designs of facades with a specific focus on insulation materials. Since insulation materials play an important role in energy efficiency and reduction of OCE. The insulation materials are selected from 3 categories: mineral, synthetic, and natural. In the first scenario, four types of walls are designed, which are designed

from a combination of lightweight blocks made of pumice with glass wool, PUR, and cork for the first three walls, and a traditional type of facade that is designed from a combination of clay brick blocks with glass wool, and all of these walls have a thermal resistance equal to $4 \text{ m}^2\text{K/W}$. In the second scenario, three types of walls are designed with the same stratigraphy as walls 1, 2, and 3 in the previous analysis. The only difference is that the amount of insulation materials is fixed and equal to 4 kg/m^2 , and the total mass of walls is equal to 227.21 kg/m^2 . In the third scenario, to find the optimal amount of insulation material, 49 walls are designed using 3 alternative materials: glass wool, plastic, and wool with a variation in thickness from 0 to 25 cm.

All material and environmental data are extracted from the verified Environmental Product Declarations (EPDs) available in the One Click LCA database. The database follows ISO 14025 [49] and EN 15804 standards [45] and is regularly updated to reflect the latest European datasets. In cases where manufacturer-specific EPDs are unavailable due to limited access to the student version, generic datasets internally validated by One Click LCA experts are used to maintain methodological consistency.

For materials without available thermal property data, thermal conductivity values are taken from the Italian standard UNI TR 11552:2014 [50], which is aligned with EN ISO 10456 [51]. As this study is a comparative analysis focused on insulation materials, the highest accuracy is ensured for insulation-related parameters by relying exclusively on verified EPDs and manufacturer data. Other materials are kept constant throughout all scenarios to isolate the effect of insulation performance on ECE and OCE.

2.1. BIM–LCA tool selection and integration workflow

One Click LCA was selected for this study due to its ability to directly integrate with BIM authoring tools such as Revit, enabling an automated connection between building models and life cycle inventory data. Unlike conventional LCA software tools, such as SimaPro and openLCA, which typically rely on manual quantity take-offs and data transfer, One Click LCA provides a dedicated BIM plugin that allows material quantities and environmental indicators to be synchronized dynamically. This automated BIM–LCA linkage supports the objective of the study, which is to investigate practical and design-oriented approaches for integrating environmental assessment into the building design process.

In addition to its BIM integration capabilities, One Click LCA provides access to an extensive construction-oriented life cycle database, covering a

wide range of building materials and systems commonly used in practice. Peer-reviewed LCA studies widely use datasets derived from well-established sources, such as GaBi and ecoinvent, which the platform incorporates. Compared to conventional LCA tools that are often applied at the level of individual material manufacturing processes, One Click LCA is specifically structured to support building-level and construction-phase assessments, making it particularly suitable for evaluating whole-building and envelope-related design alternatives. Furthermore, the platform includes an Environmental Product Declaration (EPD) generator, which enables the use of manufacturer-specific data where available. Although the student license imposes certain database and functionality limitations, the accessible datasets are sufficient to support a comparative research-oriented analysis, as undertaken in this study.

2.2. Building materials

The selection of an optimized design solution has considerable results in ECE and OCE. As it is clear, insulation materials have an important role in energy efficiency, which contributes to lower operational energy. OCE accounts for almost most total emissions, but this does not mean that the ECE is negligible. It is not reasonable to use huge amounts of insulation materials to improve thermal resistance and decrease energy consumption. Three types of insulation materials and two types of main core blocks are considered alternative materials for different design solutions, and the other materials remain unchanged. Since the project is in Italy, the materials are selected from the Italian market, except for two materials originating from Germany: the “Lightweight concrete block made from pumice” and the “Wooden Interior Door”. The materials are chosen from the database of One Click LCA software, which offers limited access in the student license version. Therefore, in cases where materials are unavailable, two German materials have been used. Another important reason for this selection is the need for precision in the results. It is essential to use materials with Environmental Product Declarations (EPDs) verified by third parties, particularly for key materials like insulation materials and main core blocks, which have a significant impact on the analysis. Other materials which are fixed during the analysis are chosen based on their availability in the database of software and their ranking performance.

Table 1 demonstrates the list of materials which are utilized during this research. The physical and thermal characteristics of materials are extracted from

Table 1. The list of materials.

No.	Building Elements	Material Description	Density [kg/m ³]	Mass per area [kg/m ²]	Thermal Conductivity λ [W/mK]	Reference
1	Foundation	Concrete C37	2330	932.00	1.91*	[52]
2	Foundation	Reinforcement steel- A615	7850	40.00	–	[53]
3	Foundation	Natural Stone (Available at site)	–	–	–	–
4	Column	Concrete C37	2330	93.20	1.91*	[52]
5	Column	Reinforcement steel- A615	7850	14.00	–	[53]
6	Beam	Concrete C37	2330	116.50	1.91*	[52]
7	Beam	Reinforcement steel- A615	7850	12.50	–	[53]
8	Floor	Concrete C37	2330	466.00	1.91*	[52]
9	Floor	Reinforcement steel	7850	27.00	–	[53]
10	Floor	Waterproofing	1143	7.20	0.17*	[54]
11	Floor	Insulation (Glass Wool)	21.5	1.72	0.034	[55]
12	Floor	Vapour barrier	–	0.121	–	[56]
13	Floor	Cement Mortar	2150	107.50	1.4*	[57]
14	Floor	Ceramic and Stone Adhesive	–	1.25	–	[58]
15	Floor	Ceramic tiles	2309	20.78	1.3*	[59]
16	Roof	Marble Stone	2700	81.00	2.4*	[60]
17	Roof	Ceramic and Stone Adhesive	–	1.25	–	[58]
18	Roof	Cement Mortar	2150	107.50	1.4*	[57]
19	Roof	Waterproofing	1143	7.20	0.17*	[54]
20	Roof	Insulation (Glass Wool)	21.5	1.72	0.034	[55]
21	Roof	Vapour barrier	–	0.12	–	[56]
22	Roof	Concrete C37	2330	582.50	1.91*	[52]
23	Roof	Reinforcement steel- A615	7850	33.75	–	[53]
24	Roof	Int. Plaster	1400	28.00	0.47	[61]
25	Roof	Painting	–	0.288	–	[62]
26	Int. Wall	Sandwich panel	–	29.43	–	[63]
27	En. Door	Alu-polyamide framed glass door	–	35.91	See Table 7.	[64]
28	Int. Door	Wooden interior doors	–	53.95	–	[65]
29	Window	Triple glazed with PVC-U frame	–	37.33	See Table 7.	[66]
30	Facade	Brick Cladding	2200	52.80	–	[67]
31	Facade	Ext. Plaster	1400	42.00	0.47	[61]
32	Facade	Insulation (Glass Wool)	21.5	–	0.034	[55]
33	Facade	Insulation (Natural Cork)	165	–	0.043	[68]
34	Facade	Insulation (PUR)	33	–	0.022	[69]
35	Facade	Vapour barrier	–	0.121	–	[56]
36	Facade	Concrete Block (Pumice)	500	100.00	0.26	[70]
37	Facade	Clay Brick Block	800	160.00	0.4*	[71]
38	Facade	Int. Plaster	1400	28.00	0.47	[61]
39	Facade	Wall Paint	–	0.288	–	[62]
40	Par. Wall	Brick Cladding	2200	52.80	–	[67]
41	Par. Wall	Ext. Plaster	1400	42.00	0.47	[61]
42	Par. Wall	Insulation (Glass Wool)	21.5	–	0.034	[55]
43	Par. Wall	Insulation (Natural Cork)	165	–	0.043	[68]
44	Par. Wall	Insulation (PUR)	33	–	0.022	[69]
45	Par. Wall	Concrete Block (Pumice)	500	100.00	0.26	[70]
46	Par. Wall	Clay Brick Block	800	160.00	0.4*	[71]
47	Par. Wall	Int. Plaster	1400	28.00	0.47	[61]
48	Par. Wall	Waterproofing	1143	7.20	0.17*	[54]
49	Par. Wall	Ceramic and Stone Adhesive	–	1.25	–	[58]
50	Par. Wall	Marble Stone	2700	81.00	2.4*	[60]

*UNI TR 11552 2014.

the One Click LCA database and EPD programs. In the lack of data for other materials, the values for thermal conductivities are extracted from UNI TR 11552 2014 [50]: concrete, waterproofing, cement mortar, ceramic tiles, marble stone, and clay brick block. However, they have little effect on thermal performance except for clay brick blocks, which are the main core of the wall, but in the case of precise

analysis, they are necessary. Windows and external doors are composite systems, and their thermal performance is expressed through overall R-values rather than material λ -values (see Table 7). The internal wooden door, being part of the interior partition, does not contribute to heat exchange with the external environment; hence, no thermal conductivity or resistance value is assigned.

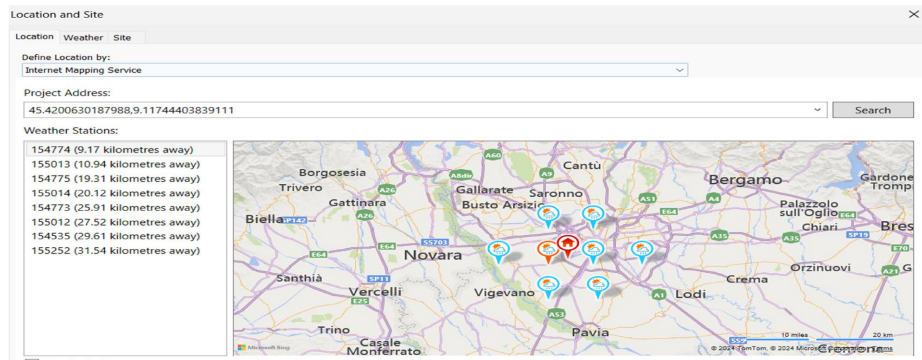


Fig. 2. The geographical location of the building- Revit 24.

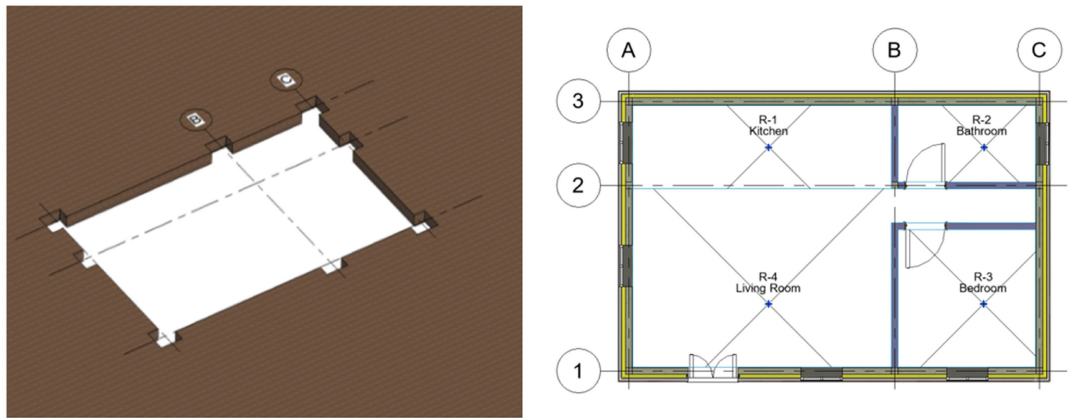


Fig. 3. The plan of residential building.

Table 2. Foundation.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Concrete C37	0.4	2330	932	1.91	0.21
2	Reinforcement steel		7850	40		
3	Natural Stone (Available at site)	0.4	–	–	–	–
Total		0.4		972		0.21

2.3. 3D modelling of the residential building

The residential building is a prototype case study that is in Milan, Via Emilia. Fig. 2 shows the geographical location of the building.

Its latitude and longitude are respectively, 45.42 and 9.117. The selected weather station number is 154774, and the distance from the building is 9.17 km with 100 m elevation. Fig. 3 shows the plan of the residential building, the gross area of the building is 101.68 m² (12.40 m * 8.20 m). It also includes the area occupied by internal and facades, except for the insulation and cladding layers, which are located over the finish layer.

The architectural and structural element design, dimensions, and other characteristics of the building, as well as the stratigraphy of the building elements,

are based on assumptions and empirical knowledge, not on a real case. Table 2 to Table 9 demonstrate the stratigraphy and material specifications of building elements. Fig. 4 shows the stratigraphy of the building elements used in this study, which are modelled with Revit 24.

Although the primary focus of this study is on the performance of external wall insulation materials, floor insulation is included to ensure thermal continuity across the building envelope. This approach minimizes heat losses and reduces thermal bridging at wall–floor junctions, thereby providing consistent and realistic boundary conditions for the energy analysis. All other building components, are kept constant across all design scenarios to isolate the influence of façade insulation on the building’s energy demand and carbon performance.

Table 3. Column and beam.

Layers No.	Material	Dimensions [m]	Density [kg/m ³]	Mass per length [kg/m]	λ [W/mK]	R [m ² K/W]
1	Column					
2	Concrete C37	0.20 × 0.20	2330	93.20	1.91	0.10
3	Reinforcement steel	–	7850	14.00	–	–
4	Total	–	–	107.20	1.91	0.10
5	Beam	–				–
6	Concrete C37	0.20 × 0.25	2330	116.50	1.91	0.10
7	Reinforcement steel	–	7850	12.50	–	–
8	Total	–	–	129.00	1.91	0.10

Table 4. Floor.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Concrete C37	0.2	2330	466	1.91	0.10
2	Reinforcement steel		7850	27		
3	Waterproofing	0.0063	1143	7.2	0.17	0.04
4	Insulation (Glass Wool)	0.08	21.5	1.72	0.034	2.35
5	Vapour barrier	–	–	0.121	–	–
6	Cement Mortar	0.05	2150	107.50	1.4	0.04
7	Ceramic and Stone Adhesive	–	–	1.25	–	–
8	Ceramic tiles	0.009	2309	20.78	1.3	0.01
Total		0.345		631.57		2.54

Table 5. Roof.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Marble Stone	0.03	2700	81	2.4	0.01
2	Ceramic and Stone Adhesive	–	–	1.25	–	–
3	Cement Mortar	0.05	2150	107.5	1.4	0.04
4	Waterproofing	0.0063	1143	7.2	0.17	0.04
5	Insulation (Glass Wool)	0.08	21.5	1.72	0.034	2.35
6	Vapour barrier	–	–	0.121	–	–
7	Concrete C37	0.25	2330	582.50	1.91	0.13
8	Reinforcement steel		7850	33.75		
9	Int. Plaster	0.02	1400	28	0.47	0.043
10	Painting	–	–	0.288	–	–
Total		0.436		843.33		2.61

Table 6. Internal wall.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Sandwich panel	0.2		29.43	–	5
Total		0.2		29.43		

There are four ways to transfer data from Revit to One Click LCA: By the One Click LCA plugin in Revit, extracting the materials take-off from Revit and importing an Excel file, or manually to One Click LCA, and by cloud-based data transfer. In this study, the cloud-based data transfer and importing data manually are utilized. The building area that includes the gross internal area of the building is equal to 92.80 m². This value is fixed for all the RBs since the variable elements, which are insulation materials, are placed on the external face of walls, and the changes

in the thickness of the insulation materials do not have any effect on the internal area.

2.4. Primary LCA parameters

The service life of materials is not based on the specific service life of the material since there is a wide range of materials with different service life and to have a consistent assessment, the service life of materials is considered to be 30 years, with some exceptions. For permanent elements such as

Table 7. Entrance door, internal door, window.

No.	Material	Dimensions [m]	Area [m ²]	Mass per area [kg/m ²]	Total Weight [kg]	R [m ² K/W]
1	Entrance Door	1.48 × 2.18	3.23	35.91	116.00	0.757
2	Internal Doors*	1.23 × 2.18	2.68	53.95	144.59	–
3	Windows	1.23 × 1.48	1.82	37.33	67.96	1.22

Table 8. Facade.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Brick Cladding	0.024	2200	52.8	–	–
2	Air	0.05	–	–	–	–
3	Ext. Plaster	0.03	1400	42	0.47	0.064
4	Insulation (Glass wool/PUR/Natural Cork)	–	21.5/165/33	–	0.034/0.043/0.022	–
5	Vapour barrier	–	–	0.121	–	–
6	Concrete Block (Pumice)/ Clay Brick Block	0.20	500/800	100/160	0.26/0.4	0.769/0.5
7	Int. Plaster	0.02	1400	28	0.47	0.043
8	Wall Paint	–	–	0.288	–	–
Total		0.324		223.21/283.21		0.879/0.609

Table 9. Parapet wall.

Layers No.	Material	Thickness [m]	Density [kg/m ³]	Mass per area [kg/m ²]	λ [W/mK]	R [m ² K/W]
1	Brick Cladding	0.024	2200	52.8	–	–
2	Air	0.05	–	–	–	–
3	Ext. Plaster	0.03	1400	42	0.47	0.064
4	Insulation (Glass wool/PUR/Natural Cork)	–	21.5/165/33	–	0.034/0.043/0.022	–
5	Concrete Block (Pumice)/ Clay Brick Block	0.2	500/800	100/160	0.26/0.4	0.769/0.5
6	Int. Plaster	0.02	1400	28	0.47	0.043
7	Waterproofing	0.0063	1143	7.20	0.17	0.037
8	Ceramic and Stone Adhesive	–	–	1.25	–	–
9	Marble Stone	0.03	2700	81	2.4	0.013
Total		0.360		312.25/372.25		0.929/0.659

foundations, columns, beams, and concrete slabs of roof and floor, the service life is permanent, or 60 years, since the calculation period is considered 60 years, and for painting, the service life is considered 10 years. Therefore, there is a stage of B4-B5 replacement and refurbishment for materials with a service life of less than 60 years. The transportation distance for materials is based on the European default values that the software considers, except in the case of pumice blocks and wooden internal doors, which have their origins in Germany, and the transportation distance is considered 1174 km. Localization is done automatically for all the materials, and the only required alterations are for the pumice block and wooden internal doors. For the End-of-Life section, the market scenario is selected.

2.5. Energy analysis

To perform the energy analysis, there are some plugins in Revit, and in this study, Open Studio is used. Open Studio performs the whole building en-

ergy modelling by using the Energy Plus engine. To perform energy analysis, the first step is defining the location of the building and selecting the weather station, since the energy analysis is performed based on the data from the weather station. After that, the parameters of the energy settings are modified. It is considered that the building type is single-family with an operation schedule of 24/7. Fig. 5 shows the HVAC zones according to the four spaces defined in the plan. The energy analysis is done by considering four spaces: the kitchen, bedroom, bathroom, and living room. Then it is necessary to assign the required data for HVAC zones. For all the zones, the heating set point is considered 20°C.

Then the energy model is created before running the energy simulation. Only the energy consumption of heating is considered. After that, the energy simulation is done for each scenario, and the results of energy consumption for heating are imported to the section of operational energy in the One Click LCA software tool. Energy sources have a considerable influence on the amount of operational emissions. In this study, the impact of energy for heating is based

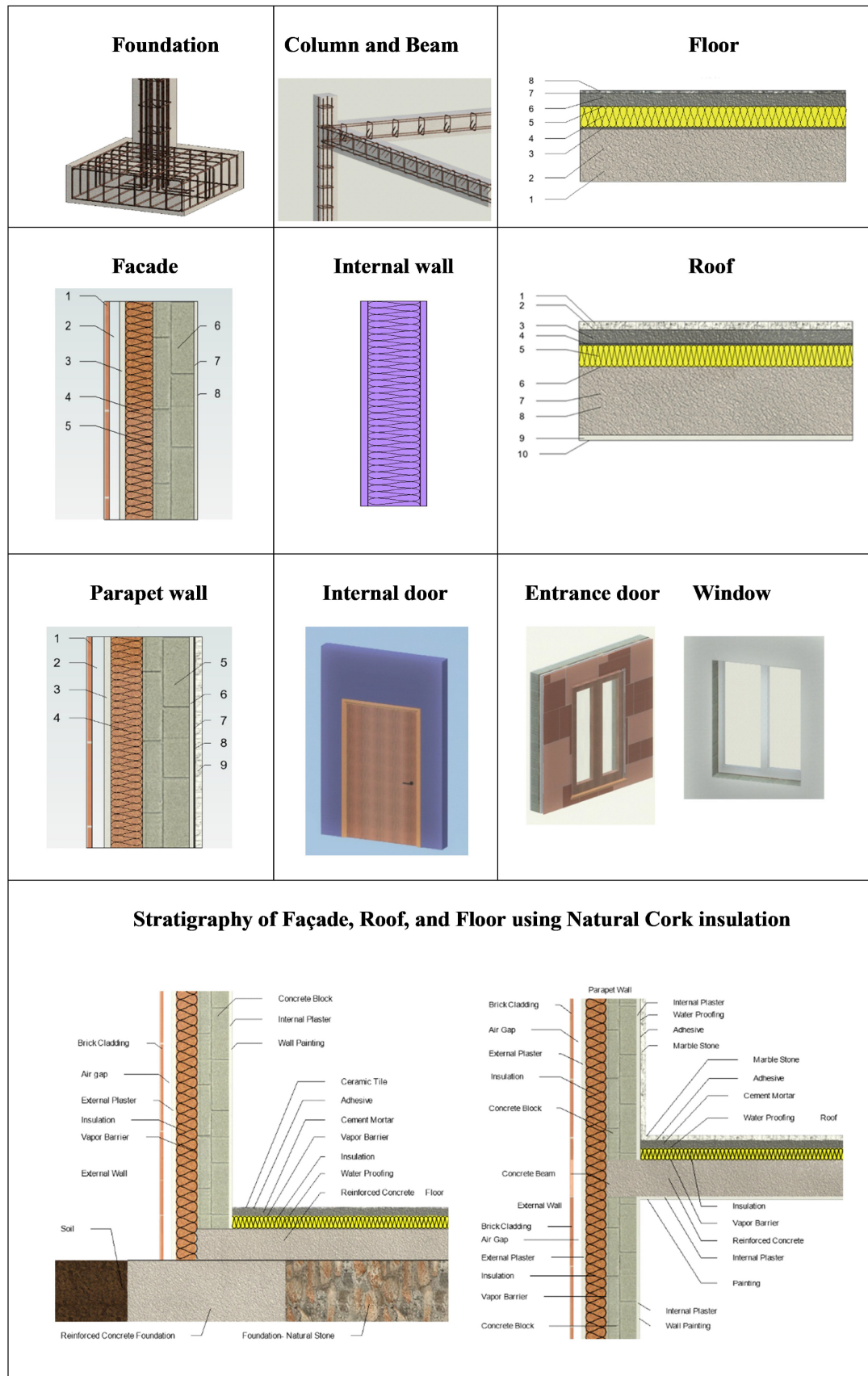


Fig. 4. Stratigraphy of building elements- Revit 24.

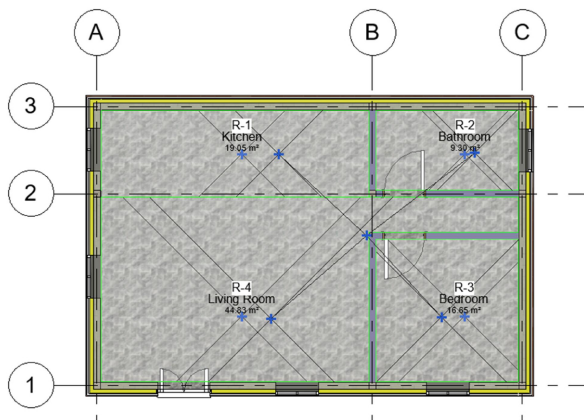


Fig. 5. Defining the HVAC zones- Revit 24.

on the district heating energy profile in Italy in the One Click LCA database. These impacts are calculated according to the energy LCA profile in the One Click LCA software tool, which considers that the production of district heating energy is through the mixed fuels that IEA provides for each country and a special energy production-modified version of the upstream life-cycle inventories [72].

2.6. Life-cycle assessment of RBs

As it was explained before, this section is divided into 3 parts to evaluate different assumptions and alternative designs for the facades of the building. During all the analyses, all the building elements, such as foundations, beams, columns, floor, roof, internal walls, doors, and windows, are fixed, and facades and parapet walls are the variables. The variations in energy consumption for district heating in the case of different designs are another important factor that has a great influence on the total carbon emissions of the buildings. Fig. 6 demonstrates the renderings of the final 3D model of the residential building in Revit 24 by Lumion tools.

2.6.1. First scenario- equal thermal resistance

In the first approach, four RBs are evaluated by applying four different external and parapet walls. Table 10 shows that all the facades have the same thermal resistance, equal to $4 \text{ m}^2\text{K/W}$, and all the parapet walls have a thermal resistance of $4.05 \text{ m}^2\text{K/W}$. Facade-1 is designed with pumice block and glass wool insulation with a weight of 225.49 kg/m^2 and a thickness of 43 cm, and Par. Wall-1 is designed with pumice block and glass wool with a weight of 314.53 kg/m^2 and 46.6 cm thickness. Facade-2 is made of pumice block and natural cork insulation with a weight of 245.35 kg/m^2 and a thickness of 45.8 cm, and Par. Wall-2 is made of pumice block and natural cork with a weight of 334.39 kg/m^2 and

a thickness of 49.5 cm. Facade-3 is modelled by a pumice block with PUR insulation with a weight of 225.48 kg/m^2 and a thickness of 39.3 cm, and Par. Wall-3 is designed with a pumice block and PUR with a weight of 314.52 kg/m^2 and a thickness of 42.9 cm. Facade-4 is made of clay brick block with glass wool insulation with a weight of 285.69 kg/m^2 and a thickness of 43.9 cm, and Par. Wall-4 is made of clay brick block and glass wool with a weight of 374.73 kg/m^2 and a 47.6 cm thickness.

The goal is to compare the total life-cycle stages of RBs with different designs for facades to investigate, in the case of the same thermal performance, which building has the best environmental performance and which one has the worst. It is feasible by evaluating the results of the ECE and OCE of different designs. The masses of materials and building elements shown in “results of GWP of building elements” and “the results of GWP - Resource types” represent the net values. This indicates that the quantities of materials wasted during construction (A5) and those replaced or refurbished (B4-B5) after 30 years, which is the service life of the materials over the 60-year calculation period, are not considered. Rather than comparing the overall mass of material used for the whole calculation period, the aim is to compare the masses of the resource types or the construction elements.

2.6.2. Second scenario- equal insulation mass

In the second approach, three RBs are evaluated by applying three different external and parapet walls. Table 11 demonstrates that all the facades have the same mass of 227.21 kg/m^2 , and all the parapet walls have a mass of 316.25 kg/m^2 . Facade-5 is designed with pumice block and glass wool insulation with a thermal resistance of $6.35 \text{ m}^2\text{K/W}$ and a 51 cm thickness, and Par. Wall-5 is designed with pumice block and glass wool with $R = 6.40 \text{ m}^2\text{K/W}$ and a 54.6 cm thickness. Facade-6 is made by pumice block and natural cork insulation with $R = 1.44 \text{ m}^2\text{K/W}$ and 34.8 cm thickness, and Par. Wall-6 is made by pumice block and natural cork with $R = 1.49 \text{ m}^2\text{K/W}$ and a thickness equal to 38.5 cm. Facade-7 is modelled by a pumice block with PUR insulation with a thermal resistance equal to $6.39 \text{ m}^2\text{K/W}$ and a 44.5 cm thickness, and Par. Wall-7 is designed with a pumice block and PUR with $R = 6.44 \text{ m}^2\text{K/W}$ and a thickness equal to 48.2 cm.

The idea is to apply the same amount of insulation materials, equal to 4 kg/m^2 , to each façade since mass is an important factor for building elements. The thermal performances of facades are not the same, so the operational energy and, as a result, the OCE are very different. The total emissions of these RBs are compared to observe in the case of the same mass to



Fig. 6. The 3D model of the residential building- Revit 24- rendering by Lumion.

Table 10. Description of RBs 1-4 under scenario 1.

Description of Residential Building	
4.10.1.1.	RB-1- Facade-1 (Glass Wool Insulation)- $R_{\text{wall}} = 4.00 \text{ m}^2\text{K/W}$
4.10.1.2.	RB-2- Facade-2 (Natural Cork Insulation)- $R_{\text{wall}} = 4.00 \text{ m}^2\text{K/W}$
4.10.1.3.	RB-3- Facade-3 (PUR Insulation)- $R_{\text{wall}} = 4.00 \text{ m}^2\text{K/W}$
4.10.1.4.	RB-4- Facade-4 (Glass Wool Insulation)- $R_{\text{wall}} = 4.00 \text{ m}^2\text{K/W}$

Table 11. Description of RBs 5-7 under scenario 2.

Description of Residential Building	
4.10.2.1.	RB-5- Facade-5 (Glass Wool Insulation)- $R_{\text{wall}} = 6.35 \text{ m}^2\text{K/W}$
4.10.2.2.	RB-6- Facade-6 (Natural Cork Insulation)- $R_{\text{wall}} = 1.44 \text{ m}^2\text{K/W}$
4.10.2.3.	RB-7- Facade-7 (PUR Insulation)- $R_{\text{wall}} = 6.39 \text{ m}^2\text{K/W}$

determine which building performs better than the others and which one is worse.

2.6.3. Third scenario

By evaluating the results of previous parts and comparing the effect of insulation materials on the total CO₂ e of buildings, it is evident that the suitable thickness of insulation layers plays an important role in the environmental performance of the building. Therefore, the purpose of this section is to investigate the suitable range of thickness for three insulation materials by considering the total CO₂ e of the buildings. Table 12 shows that Facade-8 with glass wool, Facade-9 with natural cork, and Facade-10 with PUR are considered with the same stratigraphy as Facade-

1-2-3-5-6-7, and like the previous assessment, only the insulation layers are variables. The analysis starts with facades without insulation, and at each step, the thickness increases gradually to 25 cm. The results of ECE in this section include emissions of construction (A1 to A5), use (B4-B5), and all the end-of-life stages (C2 to C4). OCE includes the emissions due to energy consumption (B6). Tables 13 to 15 show in detail the facade characteristics for each residential building under investigation.

3. Results

As three scenarios are followed during this study, their results are presented in three sections. The

Table 12. Description of RBs 7–9 under scenario 3.

Description of Residential Building	
4.10.3.1.	RB-8- Facade-8 (Glass Wool Insulation)
4.10.3.2.	RB-9- Facade-9 (Natural Cork Insulation)
4.10.3.3.	RB-10- Facade-10 (PUR Insulation)

Table 13. Description of facades for RB-8.

Facade-8 Rev No.	Material	Thickness of Glass Wool [m]	Thickness of Facade [m]	Facade Mass per area [kg/m ²]	Facade R [m ² K/W]
Facade-8-Rev00	Glass Wool	0	0.324	223.21	0.88
Facade-8-Rev01	Glass Wool	0.01	0.334	223.42	1.17
Facade-8-Rev02	Glass Wool	0.02	0.344	223.64	1.46
Facade-8-Rev03	Glass Wool	0.03	0.354	223.85	1.76
Facade-8-Rev04	Glass Wool	0.04	0.364	224.07	2.05
Facade-8-Rev05	Glass Wool	0.05	0.374	224.28	2.35
Facade-8-Rev06	Glass Wool	0.06	0.384	224.50	2.64
Facade-8-Rev07	Glass Wool	0.07	0.394	224.71	2.93
Facade-8-Rev08	Glass Wool	0.08	0.404	224.93	3.23
Facade-8-Rev09	Glass Wool	0.09	0.414	225.14	3.52
Facade-8-Rev10	Glass Wool	0.1	0.424	225.36	3.82
Facade-8-Rev11	Glass Wool	0.12	0.444	225.79	4.41
Facade-8-Rev12	Glass Wool	0.14	0.464	226.22	4.99
Facade-8-Rev13	Glass Wool	0.16	0.484	226.65	5.58
Facade-8-Rev14	Glass Wool	0.18	0.504	227.08	6.17
Facade-8-Rev15	Glass Wool	0.2	0.524	227.51	6.76
Facade-8-Rev16	Glass Wool	0.25	0.574	228.58	8.23

Table 14. Description of facades for RB-9.

Facade-9 Rev No.	Material	Thickness of Natural Cork [m]	Thickness of Facade [m]	Facade Mass per area [kg/m ²]	Facade R [m ² K/W]
Facade-9-Rev00	Natural Cork	0	0.324	223.21	0.88
Facade-9-Rev01	Natural Cork	0.01	0.334	224.86	1.11
Facade-9-Rev02	Natural Cork	0.02	0.344	226.51	1.34
Facade-9-Rev03	Natural Cork	0.03	0.354	228.16	1.57
Facade-9-Rev04	Natural Cork	0.04	0.364	229.81	1.81
Facade-9-Rev05	Natural Cork	0.05	0.374	231.46	2.04
Facade-9-Rev06	Natural Cork	0.06	0.384	233.11	2.27
Facade-9-Rev07	Natural Cork	0.07	0.394	234.76	2.50
Facade-9-Rev08	Natural Cork	0.08	0.404	236.41	2.74
Facade-9-Rev09	Natural Cork	0.09	0.414	238.06	2.97
Facade-9-Rev10	Natural Cork	0.1	0.424	239.71	3.20
Facade-9-Rev11	Natural Cork	0.12	0.444	243.01	3.67
Facade-9-Rev12	Natural Cork	0.14	0.464	246.31	4.13
Facade-9-Rev13	Natural Cork	0.16	0.484	249.61	4.60
Facade-9-Rev14	Natural Cork	0.18	0.504	252.91	5.06
Facade-9-Rev15	Natural Cork	0.2	0.524	256.21	5.53
Facade-9-Rev16	Natural Cork	0.25	0.574	264.46	6.69

results of 12 impact assessment categories, all the LCA stages, and a comparison of mass ratio with total CO₂ e are presented. Table 16 shows the 12 impact assessment categories based on the EN15804 + A2. One of the most important impact assessment categories is GWP, which has an equivalent unit of kg CO₂ for all gases, which are called greenhouse gases. The results of total LCA stages only include the amount of total GWP (kg CO₂ e), other impact assessments are not considered.

3.1. Results of scenario 1- equal thermal resistance

In Scenario 1, all RB configurations are designed to achieve the same façade thermal resistance. Under this condition, differences in operational energy demand are minimized, and variations in environmental performance are primarily driven by material-related factors, particularly ECE. The results are therefore organized into three thematic categories: energy performance, environmental impact categories, CO₂ e

Table 15. Description of facades for RB-10.

Facade-10 Rev No.	Material	Thickness of PUR [m]	Thickness Facade [m]	Facade Mass per area [kg/m ²]	Facade R[m ² K/W]
Facade-10-Rev00	PUR	0	0.324	223.21	0.88
Facade-10-Rev01	PUR	0.01	0.334	223.54	1.33
Facade-10-Rev02	PUR	0.02	0.344	223.87	1.78
Facade-10-Rev03	PUR	0.03	0.354	224.20	2.24
Facade-10-Rev04	PUR	0.04	0.364	224.53	2.69
Facade-10-Rev05	PUR	0.05	0.374	224.86	3.15
Facade-10-Rev06	PUR	0.06	0.384	225.19	3.60
Facade-10-Rev07	PUR	0.07	0.394	225.52	4.06
Facade-10-Rev08	PUR	0.08	0.404	225.85	4.51
Facade-10-Rev09	PUR	0.09	0.414	226.18	4.97
Facade-10-Rev10	PUR	0.1	0.424	226.51	5.42
Facade-10-Rev11	PUR	0.12	0.444	227.17	6.33
Facade-10-Rev12	PUR	0.14	0.464	227.83	7.24
Facade-10-Rev13	PUR	0.16	0.484	228.49	8.15
Facade-10-Rev14	PUR	0.18	0.504	229.15	9.06
Facade-10-Rev15	PUR	0.2	0.524	229.81	9.97
Facade-10-Rev16	PUR	0.25	0.574	231.46	12.24

Table 16. Environmental impact categories based on the EN 15804+A2.

Environmental Impacts- EN 15804 + A2	
Impact category	Unit
GWP- Total	kg CO2 e
GWP- Fossil	kg CO2 e
GWP- Biogenic	kg CO2 e
GWP- LULUC	kg CO2 e
Depletion potential of the stratospheric ozone layer - (ODP)	kg CFC11 eq.
Acidification potential, Accumulated Exceedance	mol H+ eq.
Eutrophication aquatic freshwater	kg P eq.
Eutrophication aquatic marine	kg N eq.
Eutrophication terrestrial	mol N eq.
Formation potential of tropospheric ozone	kg NMVOC eq.
Abiotic depletion potential (ADP-elements) for non-fossil resources (+ A2)	kg Sb eq.
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+ A2)	MJ
Water use	m3 deprived

performance across different LCA stages, and optimal insulation thickness, evaluated in relation to material mass and carbon efficiency.

3.1.1. Energy performance

Table 17 demonstrates the results of the energy analysis for four RBs of scenario 1- Equal Thermal Resistance. The results are presented based on the yearly heating consumption and the comparative heating ratio. In the first scenario, the facades have the same thermal resistance, equal to 4 m²K/W.

3.1.2. Environmental impact categories

The evaluation of environmental impact categories in Fig. 7 provides some important hints. In the results of all the RBs, RB-4 has the highest emissions in 8 impact assessment categories, and in the case of “Eutrophication aquatic freshwater” and “Abiotic depletion potential for non-fossil resources,” RB-2 has the highest emissions. The other three RBs have a

performance that is almost the same, but RB-2 has a good overall performance.

3.1.3. CO2 e performance across LCA stages

According to Fig. 8, RB-2 has the lowest value of kg CO2 e in the A1-A3 stage and a considerably high value for balancing biogenic waste disposal, which is due to the presence of Natural Cork insulation materials. As a biogenic material, it emits the total amount of CO2 that has been stored at the final stage. Generally, the results show that the RB-2 has better environmental performance.

3.1.4. Optimal insulation thickness

As is evident from Fig. 9, the RB-4 is located at the top with a range of 5.77% to 7.83% more CO2 e emissions and 3.17% to 4.88% more mass in comparison to the other ones. R-B-2 is placed at the lowest level, with a small difference of about 0.35% from R-B-1. R-B-2 is 1.64% and 1.71% heavier than R-B-1 and 3.

Table 17. Results of heating consumption for scenario 1-equal thermal resistance.

Residential Building Description	Heating (kWh per year)	Heating Ratio (%)
RB-1 (Facade -Pumice Block + Glass Wool)	4454.6	99.75%
RB-2 (Facade -Pumice Block + Natural Cork)	4465.97	100.00%
RB-3 (Facade -Pumice Block + PUR)	4431.07	99.22%
RB-4 (Facade -Clay Brick Block + Glass Wool)	4454.35	99.74%

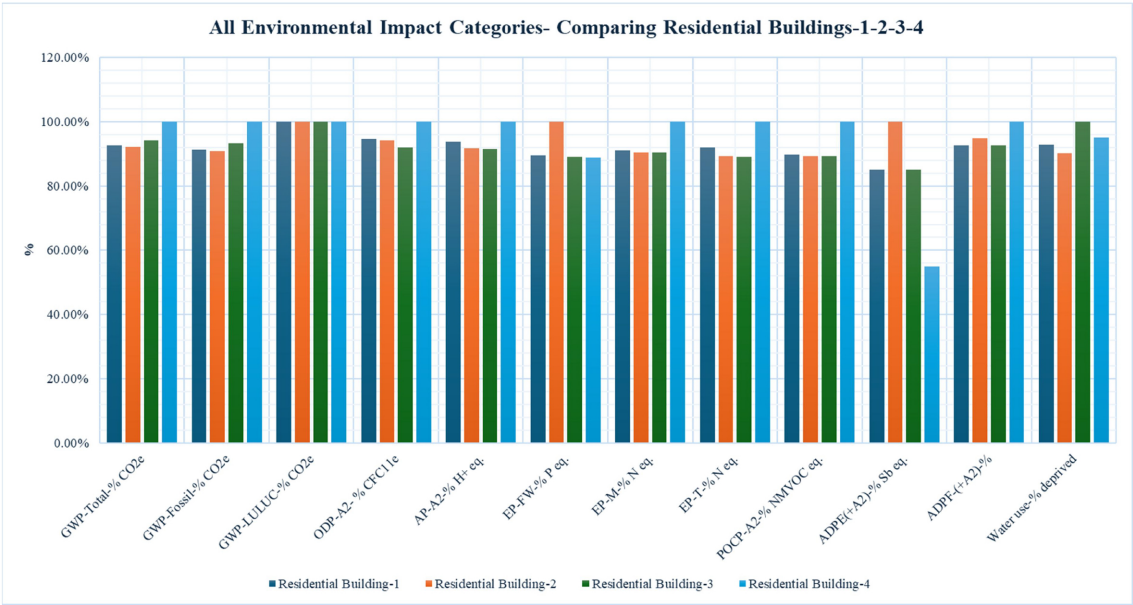


Fig. 7. Comparing the results of all environmental impact categories- RBs 1-4 under scenario 1.

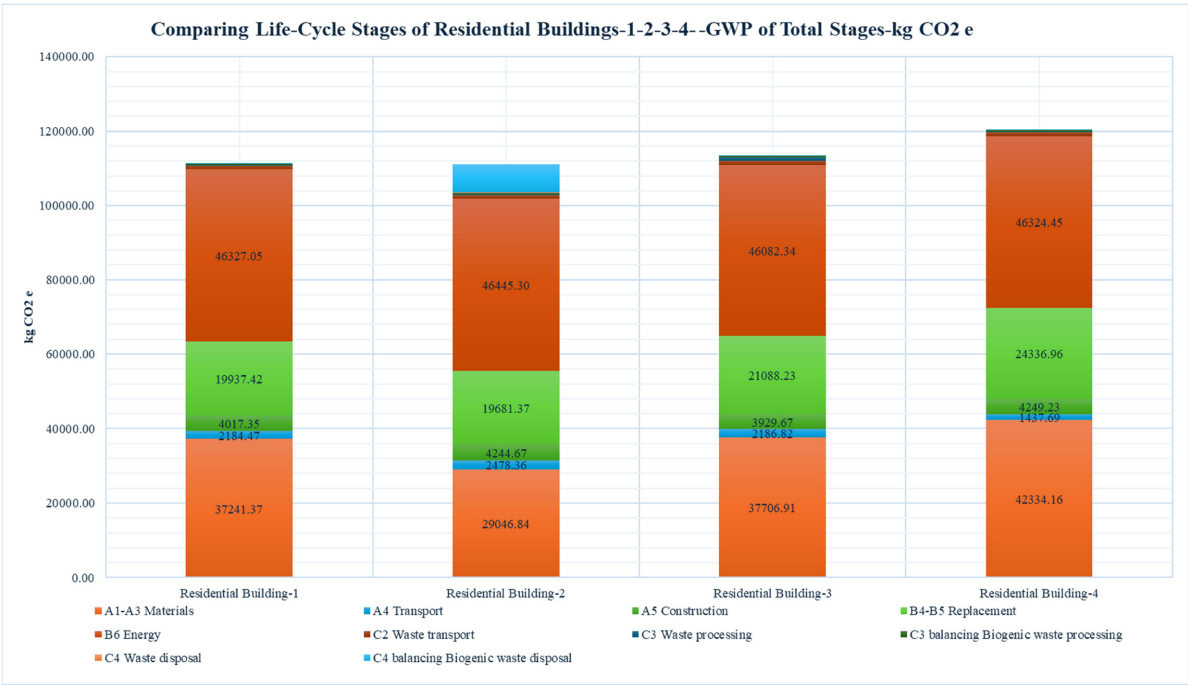


Fig. 8. Comparing the results of GWP of all life-cycle stages- RBs 1-4 under scenario 1.

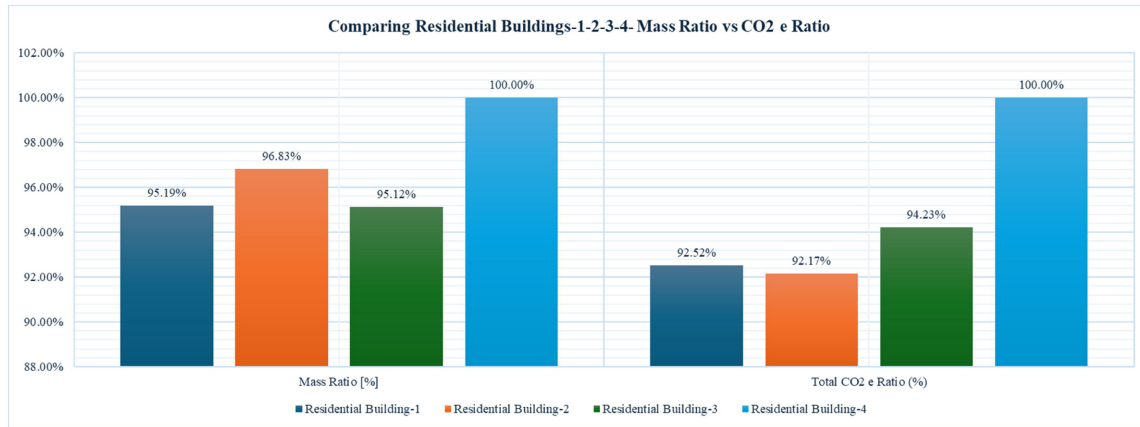


Fig. 9. Comparing the results of total GWP ratio with the total mass ratio of RBs 1-4 under scenario 1.

Therefore, in the case of applying the same thermal performance for the facade, the RB-2 with Natural Cork insulation material is much more eco-friendly, but with a precise investigation, it is visible that the facade of RB-2 is 20 kg/m² heavier and 6.5 cm thicker than the facade of RB-3, which are considerable values.

3.2. Results of scenario 2- equal insulation mass

In Scenario 2, the facade design alternatives are evaluated under the condition of fixed insulation mass, with all external wall assemblies standardized to a material mass of 227.21 kg/m². By controlling mass, this scenario isolates the influence of material properties, particularly thermal conductivity and density, on thermal resistance, operational energy demand, and associated life-cycle emissions. The results are therefore structured to highlight how identical material quantities can lead to substantially different energy and environmental performances due to variations in insulation efficiency. Accordingly, the results are discussed in terms of energy performance, environmental impact categories, CO₂ e performance across different LCA stages, and optimal insulation thickness.

3.2.1. Energy performance

Table 18 demonstrates the results of the energy analysis for four RBs of scenario 2- Equal Insulation Mass. The results are presented based on the yearly heating consumption and the comparative heating ratio. In the second scenario, the facades have the same mass. The quantity of insulation materials is 4 kg for each m² of facades. Due to significant distinctions in the density and thermal conductivity values for insulation materials, the thermal resistance of RB-5 and RB-7 is more than 400% higher than that of RB-

6. This means the operational energy for heating of RB-6 is considerably high, which causes much more operational emissions.

3.2.2. Environmental impact categories

According to Fig. 10, in all impact categories except ADPE and water use, R-B-6 is placed at the top of the categories with the highest values, and R-B-7 has the first place in ADPE and water use. Except for the categories related to GWP and the two mentioned ones, R-B-7 has the lowest values for the others. In the case of GWP categories, R-B-5 has the lowest emissions.

3.2.3. CO₂ e performance across LCA stages

By comparing the results of the LCA stages, as is visible in Fig. 11, the values of the A1-A3 stages for RB-5, and RB-7 are higher than expected due to the higher usage of insulation materials and also the eco-friendly content of natural cork in RB-6. In the case of operational energy, it is expected to observe approximately a 22% higher value for RB-6. By comparing the stages A1-A3 and B6 operational energy, it is clear that the difference between the values of these two stages is reduced in RB-5 and RB-7 by about 5.41% and 4.13% in comparison to RB-1 and 3, while it is increased in RB-6 by about 1.16%.

3.2.4. Optimal insulation thickness

The mass of the facades and all the other building elements are considered the same. The reason for the 0.35% difference in the total mass of buildings in Fig. 12 is due to a considerable difference in the thickness of walls, which leads to the different lengths of facades. RB-5 has lower CO₂ emissions values in comparison to RB-6 and RB-7, 6.81% and 3.72%, respectively. The thickness of facades in RB-5 is much higher than in RB-6 and 7, 16.2 cm and 6.5

Table 18. Results of heating consumption for scenario 2.

Residential Building Description	Heating (kWh per year)	Heating Ratio (%)
RB-5 (Facade -Pumice Block + Glass Wool)	4209.16	79.40%
RB-6 (Facade -Pumice Block + Natural Cork)	5301.21	100.00%
RB-7 (Facade -Pumice Block + PUR)	4167.02	78.61%

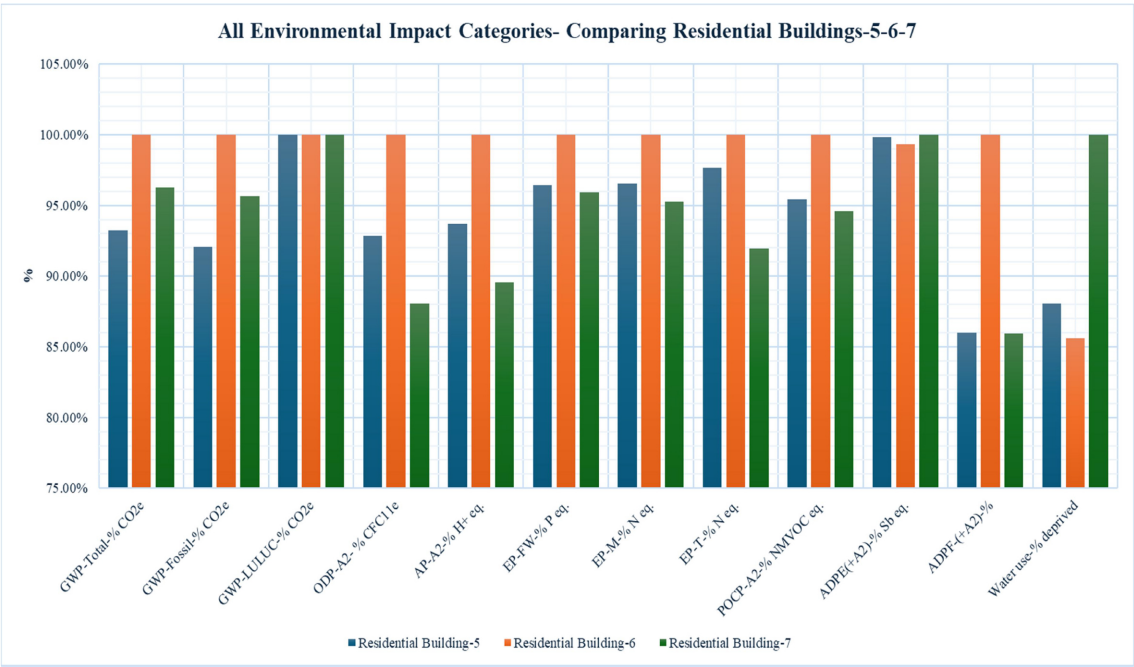


Fig. 10. Comparing the results of all environmental impact categories- RBs 5-7 under scenario 2.

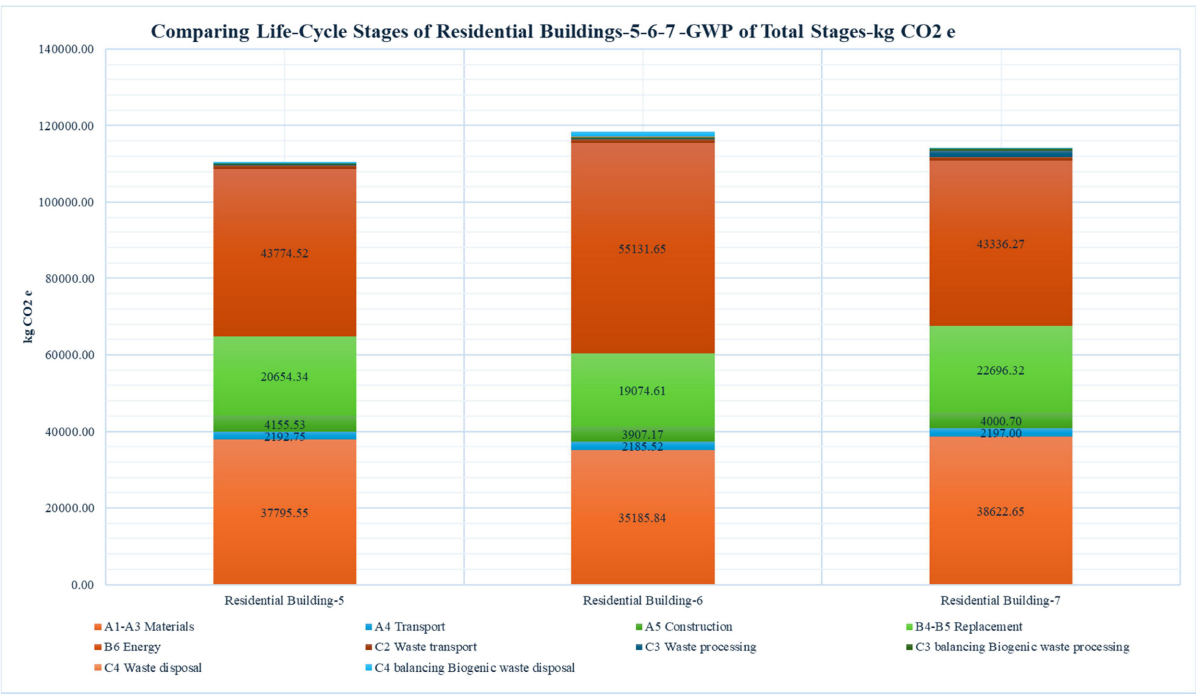


Fig. 11. Comparing the results of GWP of all life-cycle stages- RBs 5-7 under scenario 2.

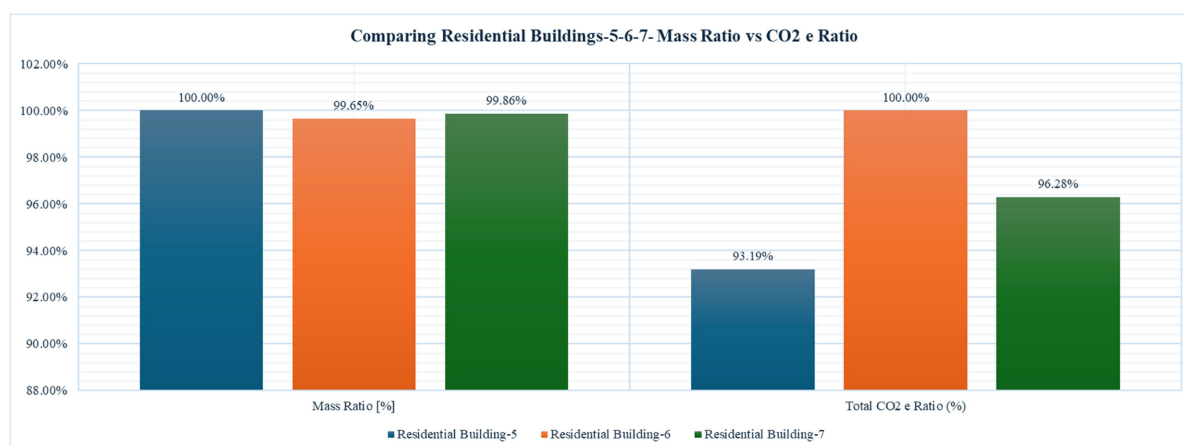


Fig. 12. Comparing the results of total GWP ratio with the total mass ratio of RBs 5-7 under scenario 2.

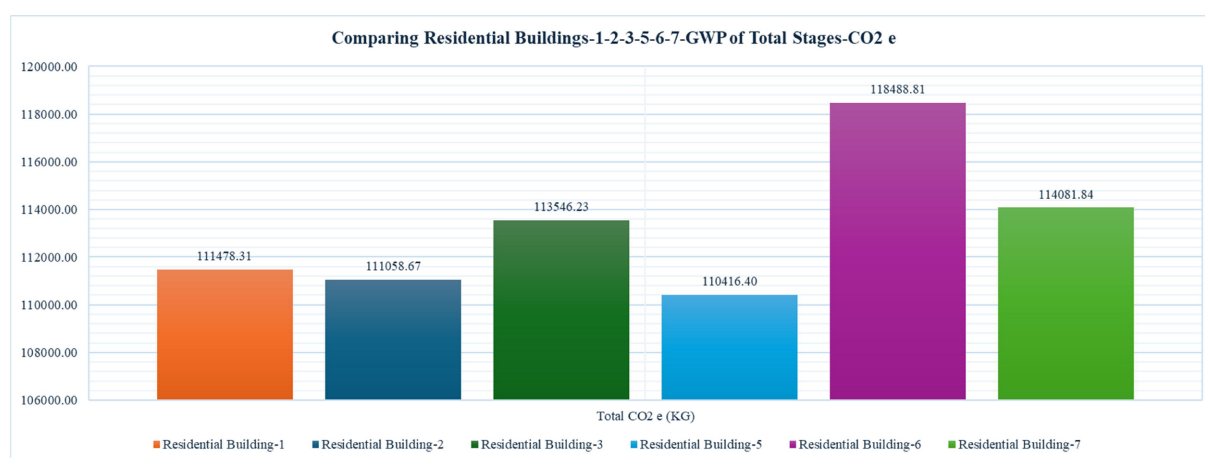


Fig. 13. Comparing the results of total GWP of RBs 1, 2, 3, 5, 6, 7.

cm, respectively, which should be considered as an important factor.

3.3. Comparative analysis of scenarios 1 and 2 and implications for insulation thickness optimization

By examining Fig. 13, the importance of insulation design choices becomes evident from the comparative evaluation of the seven residential building cases. RB-2 exhibits favourable environmental performance; however, this outcome is achieved through the application of 22.14 kg/m² of natural cork insulation, resulting in a substantially heavier façade system. Similarly, RB-5 achieves the lowest total GWP, but this performance requires a glass wool insulation layer with a thickness of 18.6 cm, which exceeds typical design values. In contrast, increasing the thickness of the PUR insulation layer from 6.9 cm in RB-3 to 12.1 cm in RB-7 leads to an increase in total carbon emissions, indicating that the rise in embodied carbon outweighs the reduction in operational carbon.

These results demonstrate that improved thermal performance does not necessarily correspond to lower total emissions when insulation thickness increases beyond certain thresholds, thereby motivating the investigation of insulation thickness optimization in Scenario 3.

3.4. Results of scenario 3- variable thickness

Scenario 3 investigates the influence of insulation thickness on the balance between operational and embodied carbon emissions. Building on the insights from Scenarios 1 and 2, this scenario aims to identify optimal insulation thickness ranges for different materials by explicitly capturing the trade-off between decreasing operational energy demand and increasing embodied carbon. To this end, a parametric analysis was conducted through 49 combined energy and LCA simulations on three residential building variants, each employing a different insulation material. Insulation thickness was systematically varied

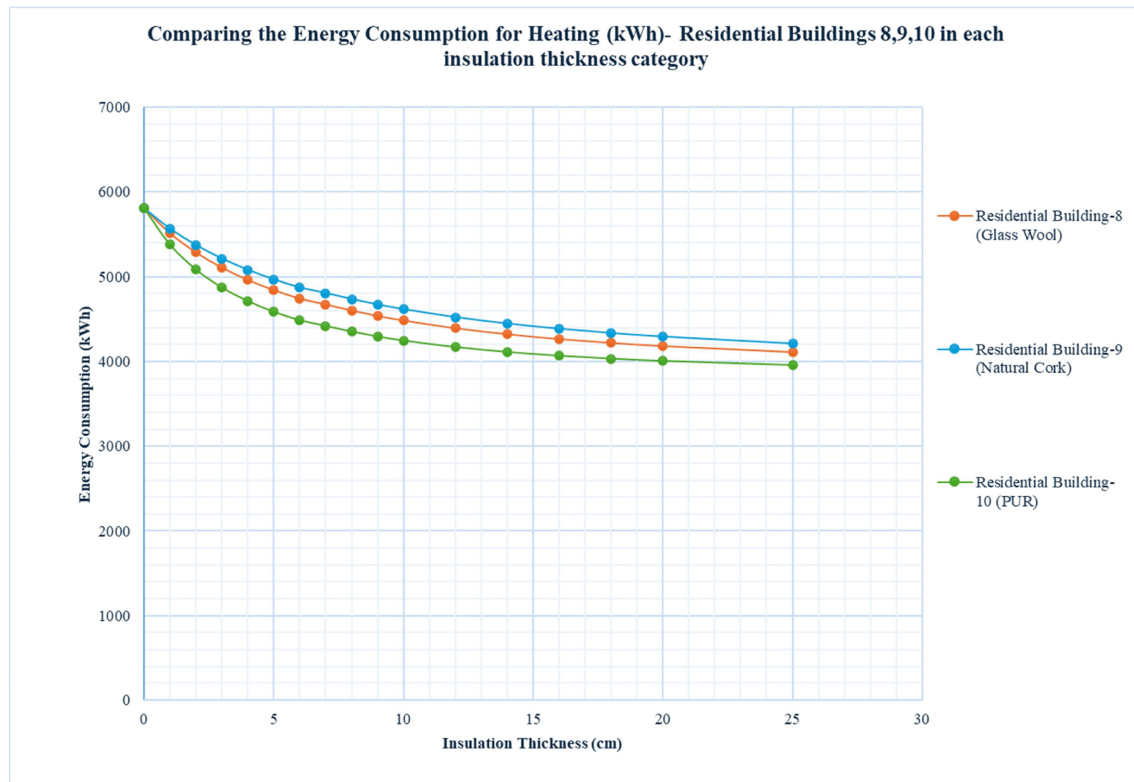


Fig. 14. Comparing the energy consumption results for RBs 8-10 under scenario 3.

over a wide range, enabling a detailed evaluation of energy performance, total CO₂ emissions, and material efficiency thresholds.

3.4.1. Energy performance

The energy performance analysis for the three considered buildings demonstrates the influence of insulation material and thickness on reducing energy demand. As shown in Fig. 14, each building exhibits a distinct energy reduction trend due to differences in thermal conductivity. RB-10, insulated with PUR, shows the most significant decrease in energy consumption, attributed to its low thermal conductivity. In contrast, RB-8 (Glass Wool) and RB-9 (Natural Cork) exhibit much shallower reductions due to higher thermal conductivity values.

3.4.2. Total CO₂ emissions

The total CO₂ emissions represent a trade-off between embodied and operational carbon, which is closely linked to the type and properties of the insulation material. Materials with low thermal conductivity reduce energy demand and, consequently, OCE but increase ECE. Fig. 15 highlights how different insulation materials balance these effects in distinct ways. Overall, the results demonstrate that total CO₂ performance is governed primarily by material properties rather than thickness alone.

3.4.3. Optimal insulation thickness

Based on the comparative analysis shown in Fig. 15, which presents the total CO₂ emissions of the buildings across different insulation thicknesses, PUR performs best at low thicknesses, maintaining its advantage up to approximately 6 cm. Beyond this point, glass wool begins to outperform PUR in terms of carbon efficiency. Interestingly, the CO₂ trend for RB-10 remains nearly stable between 6 and 8 cm, but at greater thicknesses, the emissions increase, so that at 25 cm, the total CO₂ exceeds the value at just 1 cm, indicating that PUR is not ideal for very thick layers. For RB-8, glass wool delivers better performance up to 11 cm, after which natural cork in RB-9 becomes the more effective option. Overall, the analysis suggests that moderate PUR thicknesses (up to 6 cm), thicker glass wool (6–11 cm), and thick natural cork (beyond 11 cm) provide the most efficient balance between insulation and carbon emissions.

In Scenario 3, the percentage changes in operational carbon emissions (OCE), embodied carbon emissions (ECE), and total carbon emissions are evaluated relative to a material-specific reference case without insulation. This approach allows the optimal insulation thickness range for each material to be identified by examining the balance between reductions in operational emissions and the additional embodied impacts associated with increasing

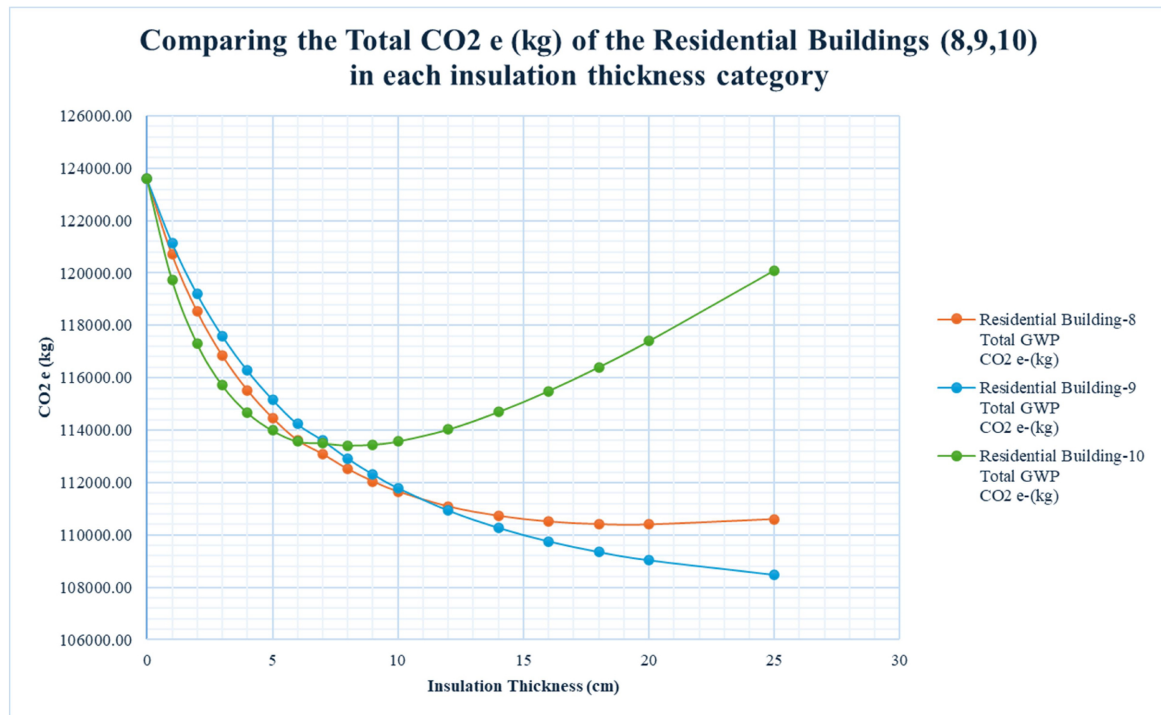


Fig. 15. Comparing the results of total CO2 e of RBs 8-10 in each insulation thickness category under scenario 3.

insulation thickness. Rather than comparing different materials at identical thickness levels, the analysis focuses on performance trends within each material. Table 19 summarizes the resulting optimal thickness ranges together with the corresponding changes in operational, embodied, and total carbon emissions for Scenario 3, referenced to the uninsulated baseline of each material.

It is important to note that the reported optimal thickness ranges should not be interpreted as strict performance limits. Insulation layers thinner or thicker than these ranges may still deliver meaningful thermal and environmental benefits when assessed independently. The identified ranges instead reflect the relative performance of the three insulation materials under the same boundary conditions, highlighting where the most favourable balance between operational carbon savings and embodied carbon impacts is achieved, rather than defining absolute minimum or maximum design values.

4. Discussion

This section interprets and contextualizes the results of the study by examining the role of insulation materials and the effectiveness of BIM–LCA integration in façade design optimization. The discussion is structured around scenario-based analyses, com-

parison with previous BIM–LCA studies, and an evaluation of practical limitations and constraints. Finally, the implications of BIM–LCA integration for design decision-making and sustainability assessment are outlined.

4.1. Role of insulation materials and BIM–LCA integration

The building industry plays an undeniable role in greenhouse gas emissions and global warming. LCA is a widely used method for evaluating the environmental impacts of materials, services, and processes across all life-cycle stages. In this study, building-related emissions are categorized into ECE and OCE. Insulation materials play a crucial role in improving energy efficiency and balancing total building emissions. Due to the wide range of available insulation materials and their differing properties, such as density and thermal conductivity, it is essential to assess each material individually. The objective of this study is to identify optimized façade design solutions for residential buildings through the integration of BIM and LCA. BIM provides substantial advantages for managing large datasets and detailed 3D models, enabling efficient handling of complex building information. This capability is particularly valuable when combined with LCA for real-time

Table 19. Summary of key findings results from scenario 3-variable thickness.

Scenario 3	Optimal Thickness (cm)	OCE Changes (%)	ECE (kg co2 e/m2)	ECE Changes (%)	Total Carbon Emissions Changes (%)
RB-8 (Façade- Glass Wool)	6 to 11	–18.33 to –23.57	636.5 to 645.6	+ 1.70 to + 3.08	–8.07 to –9.89
RB-9 (Façade- Natural Cork)	11 to 20	–21.34 to –26.10	632.2 to 637.66	+ 1.03 to + 1.88	–9.90 to –11.78
RB-10 (Façade- PUR)	6	–22.73	662.36	+ 5.54	–8.11

environmental assessment during design optimization processes.

4.2. Discussion of scenario-based results

This section discusses the results of the three investigated scenarios, focusing on the relationship between operational carbon savings, embodied carbon impacts, and total life-cycle emissions. The scenario-based analysis enables a consistent comparison of insulation materials and highlights material-specific trade-offs and optimal design ranges. In addition to scenario-based interpretation, the findings are positioned within the context of previous BIM–LCA studies to highlight methodological contributions and consistency with existing research.

4.2.1. Scenario 1: Equal thermal resistance

Under equal thermal resistance conditions ($R = 4 \text{ m}^2\text{K/W}$), annual heating demand varies marginally among the RBs, with differences below 1%. However, substantial differences emerge in embodied and total carbon performance. RB-2 exhibits an embodied carbon of $368.7 \text{ kg CO}_2 \text{ e/m}^2$ in the A1–A3 stages, whereas RB-4 reaches $419.15 \text{ kg CO}_2 \text{ e/m}^2$, corresponding to approximately 12% higher embodied emissions. In terms of total life-cycle emissions, RB-4 shows the highest impact, with total CO_2 emissions 7.83% greater than RB-2. Although RB-2 demonstrates the lowest carbon footprint, its façade is approximately 8% heavier than RB-1 and RB-3, while remaining 14% lighter than RB-4, highlighting the trade-off between embodied carbon efficiency and façade mass.

4.2.2. Scenario 2: Equal insulation mass

Under equal insulation mass conditions (4 kg/m^2), substantial differences are observed in both operational energy and carbon performance due to material properties. RB-6 (Natural Cork) exhibits the highest annual heating demand, 5301 kWh per year, which is 21.6% and 21.39% higher than RB-5 (Glass Wool) and RB-7 (PUR), respectively. In terms of embodied carbon (A1–A3), RB-7 records $382.40 \text{ kg CO}_2 \text{ e/m}^2$, which is 8.9% higher than RB-6 ($348.37 \text{ kg CO}_2 \text{ e/m}^2$) and 2% higher than RB-5 ($374.2 \text{ kg CO}_2 \text{ e/m}^2$). Despite this, total life-cycle emissions are highest for

RB-6, exceeding RB-5 by 6.81% and RB-7 by 3.72%, due to its significantly higher operational energy emissions. Although all façades share the same mass, RB-5 achieves the lowest total emissions with a much thicker façade of 51 cm, 16.2 cm, and 6.5 cm more than the façades of RB-6 and RB-7, highlighting the strong influence of insulation efficiency on overall building carbon performance.

4.2.3. Scenario 3: Variable insulation thickness

For Scenario 3, operational carbon reductions ranged from approximately 18% to 26%, depending on the insulation material and thickness, while embodied carbon emissions increased by about 1–6% as insulation thickness increased. Glass wool achieved a balanced reduction in total carbon emissions of up to approximately 10% at thicknesses between 6 and 11 cm. PUR insulation resulted in a total carbon reduction of around 8%, with diminishing returns observed beyond 6 cm due to the rapid increase in embodied carbon. Natural cork exhibited total carbon reductions in the range of approximately 9–12%, particularly at higher thicknesses, reflecting its lower operational emissions but higher material intensity. It should be noted that the identified thickness ranges represent comparative optima derived from the relative performance of the three materials under identical boundary conditions, rather than absolute performance thresholds. Thicknesses below these ranges may still provide effective thermal and environmental benefits when evaluated independently. The reported ranges, therefore, highlight the thickness intervals where each material most effectively balances operational carbon savings against additional embodied impacts in comparison with the other insulation options considered.

4.2.4. Comparison with previous BIM–LCA studies

Previous studies have extensively explored BIM–LCA integration to support sustainable building design; however, their scope, level of automation, and focus differ substantially. Several works, including [38, 40, 41] primarily address whole-building or system-level sustainability assessment, whereas the present study specifically targets façade-level insulation strategies and their role in balancing embodied and operational carbon emissions.

[73] demonstrates that increasing insulation thickness can reduce heating energy demand by up to 50%, while also emphasizing that unlimited thickness increase is not optimal due to rising material-related impacts and costs. The present results confirm the strong influence of insulation on reducing operational carbon emissions (OCE) but further show that excessive insulation thickness may lead to higher embodied carbon emissions (ECE), thereby reducing overall environmental benefits. Unlike [73], where cork exhibited low eco-efficiency mainly due to economic factors, this study demonstrates that cork can achieve competitive environmental performance when evaluated from a carbon-based perspective within a BIM–LCA framework, highlighting the importance of assessment scope and performance indicators in material ranking.

[37] critically discusses the limitations of BIM-based LCA tools and recommends their use primarily for early-stage comparative decision-making rather than final impact quantification. The present study aligns with this position by employing BIM–LCA as a design-support methodology focused on relative performance comparison under consistent assumptions, rather than absolute impact prediction.

Consistent with [38, 41], the results confirm that the operational phase dominates total life-cycle emissions, reinforcing the importance of envelope design and insulation strategies in long-term carbon mitigation. While [38] integrates BIM, LCA, and Building Sustainability Assessment to broaden sustainability evaluation, it requires extensive database harmonization and partial manual data handling. In contrast, the present research adopts a direct BIM–LCA integration that enables real-time synchronization between the BIM model and environmental data, improving workflow efficiency and reproducibility.

At the material-system scale, [40] shows that substituting conventional structural materials with recycled steel or timber significantly reduces ECE at the building level. Although that study focuses on structural systems rather than envelope insulation, its conclusions are consistent with the present findings in demonstrating that material selection should be evaluated through life-cycle performance rather than isolated properties.

Finally, [42] identifies the product stage (A1–A3) as the dominant contributor to embodied carbon emissions, largely driven by material mass and carbon intensity. This observation aligns with the present study, where increased insulation thickness leads to higher ECE that can outweigh operational carbon savings, emphasizing the necessity of optimized, material-specific insulation design.

4.3. Limitations and practical constraints

This study does not cover certain LCA phases, including repair (B3), demolition (C1), water use (B7), and routine maintenance (B2). In addition, construction-stage results (A5) are incomplete due to limited data availability. Material selection was constrained by database availability within the One Click LCA software. While materials with third-party verified EPDs are prioritized, particularly for insulation and façade core materials, some materials rely on generic EPDs, which represent market averages and reduce the precision of the results, but since the study focuses on comparative analysis, it does not pose considerable issues. In some cases, key material properties such as density or thermal conductivity are unavailable, and a supplementary resource is required. Furthermore, the student version of One Click LCA was used due to licensing limitations, which restrict access to certain databases and advanced functionalities.

Despite its favourable environmental performance, RB-2 employing natural cork insulation results in relatively heavy wall assemblies, requiring 22.14 kg/m² of insulation to achieve the targeted thermal resistance. Therefore, the limitations associated with cork are not primarily linked to local availability or transportation distance. Instead, they are mainly associated with higher initial material costs and the increased mass and thickness required to reach comparable thermal performance, which may constrain large-scale applications.

Furthermore, while cork is a biogenic material with substantial carbon storage potential during its service life, the end-of-life scenarios assumed in this study result in the release of the stored carbon, thereby limiting its net long-term carbon benefit. Different ways to end its life, like reusing materials or delaying the release of carbon, could greatly improve its overall environmental performance. In this context, hybrid insulation systems combining cork with materials with higher thermal resistance, like PUR, or lower-density materials may offer a promising compromise between carbon performance, structural feasibility, and cost. However, such configurations would require further detailed analysis and experimental validation before practical implementation can be recommended.

This study primarily aimed to develop and demonstrate a methodological framework for integrating BIM models within a LCA environment to support comparative environmental evaluation of building envelope design alternatives. The results are based on manufacturer-provided data and verified

Environmental Product Declarations and are therefore intended for comparative analysis rather than the derivation of absolute performance values. Future research could extend this work by incorporating laboratory testing or field-measured data to further validate and refine the simulation-based outcomes.

4.4. Implications of BIM–LCA integration

The integration of BIM and LCA demonstrates substantial advantages for sustainability assessment, particularly in complex and iterative design processes. BIM enables efficient management of large datasets and detailed geometric models, which is essential for conducting rapid and reliable comparative LCA analyses. In the third scenario, which required 49 energy and LCA simulations, the BIM–LCA workflow enabled real-time assessment and efficient evaluation of multiple design alternatives. Such analyses would be impractical without BIM-based data management. This integration improves efficiency in terms of time, cost, and analytical precision, especially for large-scale or complex projects.

5. Conclusion

This study discovered how an integrated BIM–LCA approach can help design façade insulation strategies that balance operational and embodied carbon emissions throughout a building's life cycle. By comparing different insulation materials under controlled scenarios, it is explored that insulation material choices can significantly influence a building's total carbon emissions—not just its energy use.

The results show that while insulation is highly effective in mitigating operational emissions, increasing material amounts or thickness does not necessarily result in proportional environmental benefits. The characteristics of materials, with emphasis on their efficiency and mass value in particular, play a critical role in determining this trade-off effect between operational savings and embodied impacts. Hence, optimal insulation design would be material-dependent and would require finding balanced design ranges rather than maximizing thermal resistance or insulation thickness.

From a methodological perspective, this research highlights the importance of the integration of BIM and LCA as a comparative method of decision-making in early stages of the design process. The framework enables consistent evaluation of alternative façade configurations under unified assumptions, supporting informed design choices aimed at reducing life-cycle carbon emissions.

Several limitations were discovered during the study, which demonstrate that the analysis is based

on the available EPDs, and some LCA stages are excluded due to a lack of data availability. Therefore, the results are intended for relative comparison rather than absolute impact quantification. Future research could improve robustness by incorporating measured performance data, alternative end-of-life scenarios, economic indicators, and a hybrid insulation system to further optimize environmental performance.

Overall, this study contributes to the growing body of knowledge on low-carbon building design, the increasingly fruitful area of low-carbon building design, showing that effective insulation design strategies should include whole LCA, and the approach should be life-cycle-based, material-by-material, and optimization-oriented. The proposed approach presents a certain platform for helping design facades in accordance with sustainability and carbon-reduction goals.

Statements and declarations

Ethics

There are no ethical issues with the publication of this manuscript.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author's contributions

The author is solely responsible for the conceptualization, methodology, data analysis, and writing of this manuscript.

Data availability statement

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