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LCA-Based Low-Carbon Retrofit of an Industrial Heritage Warehouse: Building No.7 of Scalo Ravone, Bologna

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LCA-Based Low-Carbon Retrofit of an Industrial Heritage Warehouse: Building No.7 of Scalo Ravone, Bologna

Abstract. This thesis investigates low-carbon retrofit strategies for Building No. 7, an early-twentieth-century reinforced-concrete warehouse at Scalo Ravone (Bologna) slated for adaptive reuse as a university innovation hub. The baseline was documented with construction and energy profiling using Honeybee, and preliminary embodied-carbon accounting with Tally; before specifying upgrades, a reuse design reorganized functions and space, setting heritage and performance constraints. Envelope measures were then developed and assessed at component level—external walls, windows, skylights, and roof—and synthesized into a whole-envelope low-carbon package. Energy performance was simulated in Rhino/Grasshopper (Honeybee), and life-cycle carbon quantified with One Click LCA over a 50-year period (A1–A5, B4–B5, C1–C4, B6; D excluded). Results show operational emissions dominate; triple-glazed windows and skylights and a PIR-insulated roof yield the largest operational reductions, while a double-wall external wall balances performance with embodied impacts. The combined package cuts total EUI by ~40% and total life cycle GWP by ~35–40%, despite a moderate rise in embodied carbon. The study highlights envelop performance as a primary lever for decarbonizing industrial heritage and supports adaptive reuse as a pathway to climate-aligned urban regeneration.

Keywords: Industrial heritage, adaptive reuse, envelope upgrade, Scalo Ravone, life cycle carbon assessment (LCA), low-carbon retrofit, BIM, energy simulation.

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1. Introduction

1.1 Research Background and Significance

In recent years, there has been a growing global emphasis on reducing carbon emissions across various sectors to address the challenges of climate change. The European Union, through the European Green Deal, has committed to achieving climate neutrality by 2050, positioning itself as a leader in sustainable development (European Commission, 2019). Other major economies have also reinforced their climate commitments, contributing to a shared global momentum.

In 2023, the buildings and construction sector accounted for about 34% of global energy-related CO_2 emissions (UNEP and GlobalABC, 2025). Recent assessments also confirm that both building operations and the embodied impacts of materials/construction are significant contributors to the sector's total footprint (UNEP and GlobalABC, 2025). A significant share of these emissions comes from existing buildings, which are often characterized by outdated systems, poor thermal performance, and high energy consumption. In the EU, about 85% of buildings were built before 2000 and roughly 75% have poor energy performance; the annual energy renovation rate is about 1% (European Commission, 2025).

Unlike rapidly urbanizing regions, Europe faces the unique challenge of modernizing an aging building stock, much of which holds historical and cultural value. This includes industrial heritage building structures that may not always be formally protected but are often embedded with collective memory and urban identity. Although typically inefficient in energy use, these buildings offer substantial potential for carbon reduction through adaptive reuse and targeted refurbishment.

Industrial heritage buildings are particularly significant due to their distinct spatial typologies and construction methods. Their transformation supports both cultural preservation and the goals of sustainable urban regeneration. Rather than demolishing and rebuilding, retrofitting these structures allows for the conservation of embodied energy and material resources, aligning with circular economic principles and long-term climate goals.

Consequently, low-carbon refurbishment of existing buildings has become a key strategy in Europe's carbon-neutrality roadmap. Compared to constructing new low-carbon buildings, renovating existing ones, especially those with heritage value, can achieve meaningful emissions reductions while enhancing architectural continuity. The European Union's Renovation Wave strategy aims to at least double the annual renovation rate by 2030, placing strong emphasis on deep, energy-efficient, and sustainable retrofits (European Commission, 2020).

1.2 Research Object and Scope

The subject of this study is Building No. 7 in Scalo Ravone, Bologna— a former warehouse with masonry walls and a steel roof, currently used as a car depot (based on author's field investigation). Scalo Ravone was historically a railway freight yard, integral to Bologna's industrial logistics system. Today, it is undergoing urban regeneration and has been incorporated into the DumBO (Distretto urbano multifunzionale di Bologna) initiative, a broader temporary urban regeneration project managed by Open Group and Eventeria. (Open Group, 2023).

This type of industrial building is common across Italy. Many similar structures, especially those from the former industrial or railway-related stock, have been abandoned due to deindustrialization, changing logistics systems, and urban spatial transformations. Although often lacking formal heritage protection, these buildings retain considerable industrial memory and architectural potential. Their simple structural elements and large open-plan interiors are often observed to allow relatively adaptable reuse and retrofitting.

Studying such buildings holds dual significance, supporting both conservation of local identity and cultural continuity via adaptive reuse, and enabling targeted refurbishment to reduce embodied emissions and improve operational performance. This is especially relevant in the context of the European Union's Renovation Wave strategy and Italy's National Recovery and Resilience Plan (NRRP), which prioritize the sustainable renewal of existing assets and climate-targeted investments (Commission, European, 2020; Italy's National Recovery and Resilience Plan (NRRP), 2021).

This research focuses on the low-carbon retrofit of the building envelope of Building No. 7, with an emphasis on life-cycle carbon emissions—covering both embodied carbon and operational carbon. Preserving the primary structural system, the project aims to repurpose the building as an innovation and incubation hub affiliated with the University of Bologna. Three refurbishment scenarios for the envelope will be proposed and compared using LCA methodology, to evaluate their carbon emission performance and provide strategic insights for similar industrial heritage transformations.

1.3 Research Objectives and Key Questions

This research aims to explore how to optimize low-carbon refurbishment strategies for industrial heritage buildings through the application of Life Cycle Carbon Assessment (LCA). The goal is to balance the conservation and adaptive reuse of these historical structures with contemporary requirements for carbon reduction and environmental performance. Using Building No.7 in Scalo Ravone, Bologna, as a case study, the project will propose a new functional layout, transforming the warehouse into an innovative hub for the University of Bologna. On this basis, three refurbishment scenarios for the building envelope will be developed and compared in terms of life cycle carbon emissions and carbon payback periods, to identify more reasonable and effective strategies for low-carbon transformation.

Based on the research objectives, this thesis seeks to address the following key questions:

(1) How can carbon emissions be reduced in industrial heritage buildings through functional renewal and optimized envelope refurbishment?

(2) How can Life Cycle Carbon Assessment (LCA) be applied effectively to evaluate carbon performance in adaptive reuse projects?

(3) How do the three proposed envelope renovation scenarios compare in terms of embodied and operational carbon emissions, and which offers the most carbon-efficient solution?

1.4 Methodology and Technical Approach

This study primarily adopts a Life Cycle Assessment (LCA) approach (GWP, $kgCO_2e$), covering both embodied and operational phases. At the component level, retrofit options were developed and assessed for the external walls, windows, skylights, and roof, and then synthesized into a whole-envelope low-carbon package.

Tools and data. BIM modeling in Revit was used to extract geometry and assemblies. The baseline embodied impacts were preliminarily inventoried with Tally® for Revit, while the 50-year LCA for all components and the whole-envelope package was conducted in One Click LCA, in accordance with ISO 14040/14044, EN 15804, and EN 15978. Operational carbon (B6) was derived from Honeybee (Rhino/Grasshopper) annual energy results and integrated into One Click LCA using consistent emission factors.

System boundaries and assumptions. A 50-year reference period including A1–A5, B4–B5, C1–C4, and B6 (Module D excluded). Building use, schedules, HVAC settings, and internal loads were held constant across scenarios. A previously developed reuse design defined functional and heritage constraints before specifying envelope upgrades.

Methodological steps:

1. Baseline status analysis: on-site/literature data collection; baseline energy model (Honeybee); preliminary embodied inventory (Tally).
2. Reuse design: functional reprogramming as the basis for envelope interventions.

3. Scenario development: component-level options for walls, windows, skylights, and roof.
4. LCA modeling: Revit assemblies mapped to One Click LCA datasets/EPDs; life-cycle stages assigned.
5. Analysis & comparison: calculate embodied, operational (Honeybee → One Click LCA), and total life cycle GWP.
6. Interpretation: discuss trade-offs and recommend low-carbon envelope strategies.

1.5 Thesis Structure

This thesis is structured into six main chapters:

1. Chapter 1 – Introduction
   Background, research gap, questions, scope, objectives, methods, and thesis structure.
2. Chapter 2 – Literature Review and Theoretical Foundation
   LCA for buildings (GWP focus), industrial-heritage retrofit strategies, envelope performance, and the study's theoretical framework.
3. Chapter 3 – Site and Building Analysis: Building No.7, Scalo Ravone
   A baseline energy model was first built in Honeybee to obtain operational energy use; these results were then linked in Tally® for Revit to calculate a preliminary LCA of the existing building, covering embodied impacts (A1–A5, B4–B5, C1–C4) and operational carbon (B6) derived from the Honeybee baseline energy results.
4. Chapter 4 – Adaptive Reuse Design for Building No.7
   Reuse design (functional reprogramming, spatial reorganization, light-touch interventions) setting heritage/performance constraints and targets for envelope upgrades.
5. Chapter 5 – Comparative Analysis of Envelope Retrofit Scenarios
   Following the reuse design, a new Honeybee energy model was developed for the adapted scheme. The 50-year LCA of component options and the whole-envelope package was then performed in One Click LCA, with B6 calculated from the reuse Honeybee results and embodied impacts mapped to OCL datasets (A1–A5, B4–B5, C1–C4; Module D excluded).
6. Chapter 6 – Conclusions
   Key findings (operational carbon dominance; selected package), limitations (datasets/assumptions, airtightness fixed, no cost/payback, Module D excluded), and future work (BIPV evaluation, airtightness & controls, cost–benefit, comfort/moisture, conservation detailing).

2. Literature Review and Theoretical Foundations

2.1 Overview of Carbon Emissions and Carbon Neutrality in Buildings

The building sector is one of the largest contributors to global greenhouse gas emissions. In 2021 it accounted for around 37% of energy- and process-related CO_2 emissions (International Energy Agency, 2022). Emissions are commonly distinguished as operational carbon—from energy use during a building's life—and embodied carbon—from the extraction, manufacturing, transport, construction, maintenance and end-of-life building materials and products. As countries pursue climate targets under the European Green Deal, buildings are a strategic focus because of their high emissions intensity and long service life (European Commission, 2019). Decarbonizing buildings delivers multiple co-benefits, including energy savings, improved comfort and resilience, and wider economic benefits (United Nations Environment Programme, 2022).

2.2 Life Cycle Carbon Assessment (LCA) in Buildings

Life Cycle Assessment (LCA) is a standardized method for evaluating environmental impacts across the full life cycle of a product or system (International Organization for Standardization, 2006). For buildings, Life Cycle Carbon Assessment (LCCA) focuses on greenhouse-gas emissions over all life-cycle stages as structured in EN 15978: product and construction (A1–A5), use (B1–B7), end-of-life (C1–C4) and beyond-system benefits (D). In this framing, embodied carbon covers A1–A5, component replacement in B4–B5, and C1–C4; operational carbon refers primarily to B6 (operational energy) and, where included, B7 (operational water) (Royal Institution of Chartered Surveyors (RICS), 2017; European Committee for Standardization (CEN), 2011).

The adoption of LCA in the building sector has grown because it enables evidence-based choices in design, renovation and material selection (Cabeza, 2014). Unlike traditional approaches that consider only operational energy, LCA makes visible the trade-offs between operational and embodied emissions—crucial in retrofit projects where retaining existing structures can substantially reduce embodied impacts (Pomponi & Moncaster, 2016). Standardized frameworks such as EN 15978 guide LCA application in buildings, defining system boundaries in modules A–D:

A1–A3: Product stage

A4–A5: Construction process stage

B1–B7: Use stage (including energy and water use)

C1–C4: End-of-life stage

D: Benefits and loads beyond the system boundary (e.g., reuse, recycling)

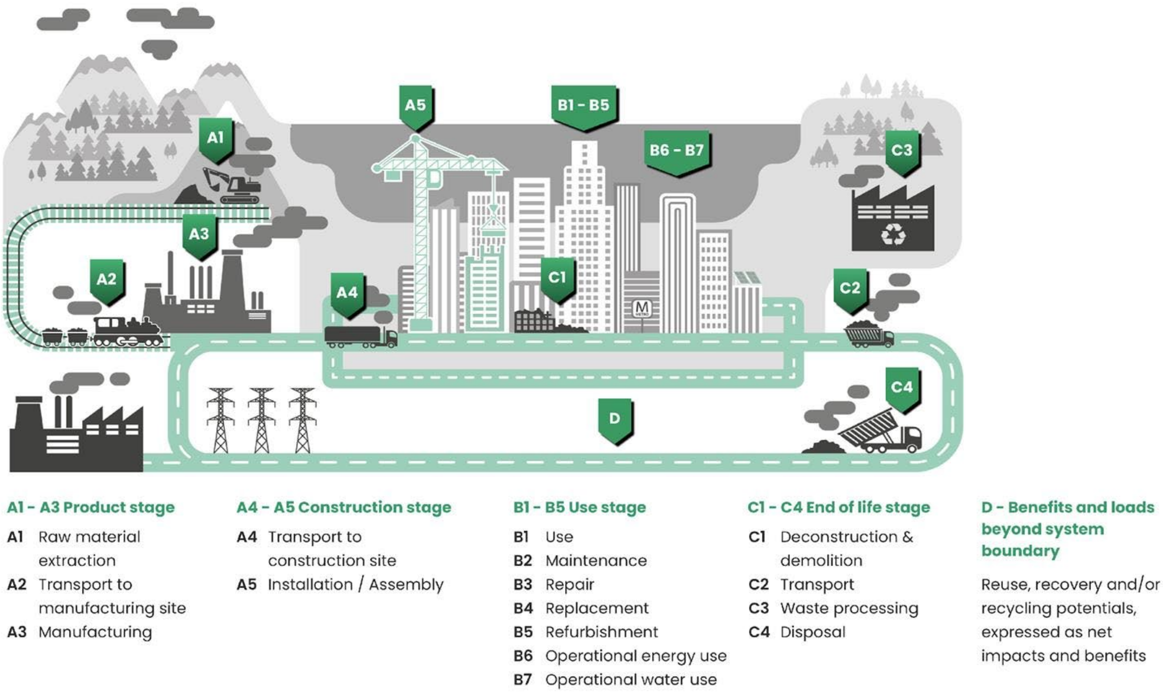


Figure 2.1 Life cycle assessment stages (One Click LCA, 2024).

2.3 Carbon Optimization Pathways in the Renewal of Industrial Heritage Buildings

The adaptive reuse of industrial heritage buildings offers significant opportunities to cut carbon emissions while preserving cultural identity. Compared with new construction, refurbishment avoids a large share of embodied emissions associated with producing new materials and components and is therefore a key pathway toward carbon neutrality (Royal Institution of Chartered Surveyors (RICS), 2017).

Many industrial buildings feature open structural grids, regular spans and limited interior finishes, which increase adaptability for energy retrofitting. From a life-cycle perspective, optimization couples embodied-carbon reduction—primarily by retaining and reusing existing elements—with operational-performance improvements via energy upgrades (European Committee for Standardization (CEN), 2011; Royal Institution of Chartered Surveyors (RICS), 2017).

European case studies show how heritage refurbishment integrates low-carbon principles. In Amsterdam's Westergasfabriek, a former gasworks, soil remediation was followed by the creation of a cultural park and the reuse of historic masonry structures for contemporary cultural and creative functions, demonstrating brownfield regeneration with building conservation.

In Italy, the National Recovery and Resilience Plan (PNRR) prioritize urban regeneration and building renovation within its green and digital missions, while national decrees (DM 560/2017, as amended by DM 312/2021) phase in mandatory BIM adoption for public works—often linked to PNRR funding incentives—thereby supporting digital tools in renovation programs. LCA is increasingly applied as a decision-support method in design practice and research, complementing BIM workflows (European Commission, 2021).

Typical carbon optimization strategies in industrial heritage renewal include:

1. Retaining structural elements to avoid demolition waste and reduce the need for new materials.
2. Upgrading the building envelope with high-performance, low-carbon materials to improve thermal performance.
3. Modernizing building systems and integrating Building-Integrated Photovoltaics (BIPV) to reduce operational emissions.
4. Using BIM and LCA tools to evaluate carbon trade-offs across different design scenarios and life cycle stages.

By applying these strategies holistically, it is possible to transform outdated industrial structures into low-carbon buildings without compromising their historical and architectural value.

2.4 Current Research on Retrofit Strategies for Building Envelopes

The building envelopes, including external walls, roofs, windows, and doors play a pivotal role in regulating energy flow between indoor and outdoor environments. Retrofit strategies targeting the envelope have been widely recognized for their potential to reduce both operational and embodied carbon emissions, particularly in existing and historic buildings.

Improving thermal insulation, enhancing airtightness, and upgrading glazing systems are among the most effective interventions to reduce heat loss and improve energy performance. However, in heritage contexts, these modifications must be carefully balanced with the need to preserve architectural character, which often limits the use of conventional materials or systems.

Recent approaches have explored the integration of passive design techniques with selected active technologies, such as ventilated façades, sometimes combined with renewable-energy elements. These strategies offer multifunctional benefits—enhancing thermal comfort while maintaining aesthetic compatibility—yet their application in industrial heritage buildings remains underexplored.

Particularly in southern European contexts, such as Italy, retrofitting faces additional constraints due to diverse climatic zones, traditional construction methods, and the historical significance of many buildings. More targeted research is needed to develop retrofit models that are both carbon-efficient and context-sensitive, offering viable pathways for deep renovation without compromising cultural value. In this regard, industrial warehouses with large roof spans present both challenges and opportunities for such context-sensitive retrofits, highlighting the need for tailored strategies in industrial heritage contexts.

2.5 Theoretical Framework Construction and Research Innovation

This study builds on a multidisciplinary foundation combining life cycle assessment (LCA), enveloping retrofit strategies, and the design constraints of industrial heritage. While each theme is well studied in isolation, there is a gap in integrated frameworks tailored to heritage refurbishment, where historical constraints, material reuse, energy upgrades, and aesthetics must co-exist within a carbon-reduction strategy.

Framework pillars:

1. Life Cycle Assessment (LCA) as the quantitative foundation, reporting GWP ($kgCO_2e$) for both embodied and operational phases over A1–A5, B4–B5, C1–C4, and B6 (Module D excluded).
2. Envelope retrofit optimization at component level (external walls, windows, skylights, roof) and whole-envelope synthesis, respecting structural integrity and heritage expression.
3. Reuse-design constraints that set functional, conservation, and performance targets and define the feasible retrofit space.

Implementation: A scenario-based workflow: BIM (Revit) for geometry/assemblies; Honeybee for operational energy; One Click LCA for 50-year LCA under EN 15978 boundaries.

Research innovation: An adaptive, component-to-package carbon framework for industrial heritage that links reuse design with envelope LCA to support decisions where long-term operational reductions dominate while respecting heritage constraints. Economic analysis, airtightness/controls, and comfort–moisture evaluation are identified as future work.

3. Site and Current Building Analysis: Scalo Ravone Building No. 7

3.1 Historical Background and Urban Regeneration of Scalo Ravone

Located west of Bologna Centrale Station (Fig 3.1), Scalo Ravone was established in the early 20th century as the city's first freight marshalling yard, relieving congestion in the central station and supporting national logistics flows. Closely linked with the Officine Grandi Riparazioni (OGR), the site played a key role in servicing locomotives and facilitating connections between northern industrial hubs and southern agricultural regions. Despite being overshadowed by the larger San Donato yard in the 1930s, Ravone maintained strategic importance until the decline of rail freight in the early 2000s. In 2012, it was officially designated as disused industrial heritage and transferred to FS Sistemi Urbani for redevelopment.

The regeneration process formally began with the 2016 Implementing Urban Plan (PUA), framed by earlier territorial agreements. The proposal aimed to create a mixed-use innovation district focused on culture, community, and creative industries, supported by ecological restoration. However, the plan was stalled by

the 2017 regional planning reform, which reclassified the area within the high-density "Areale Saffi" housing priority zone—exposing a broader conflict between heritage conservation and housing demand.

Figure 3.1 Location of Scalo Ravone.

As an interim response, FS Sistemi Urbani initiated the DumBO project in 2019, temporarily repurposing 18,000 m² of industrial space for cultural programming and creative enterprise. While the original PUA remains unapproved, the 2025 Bologna Urban Regeneration Plan redefines the site as a “culture + housing” zone, allowing for selective retention of industrial structures and new hybrid uses.

This transition from rail infrastructure to socially inclusive urban space exemplifies Bologna’s adaptive reuse strategy, where industrial memory and contemporary innovation coalesce to address evolving urban challenges.

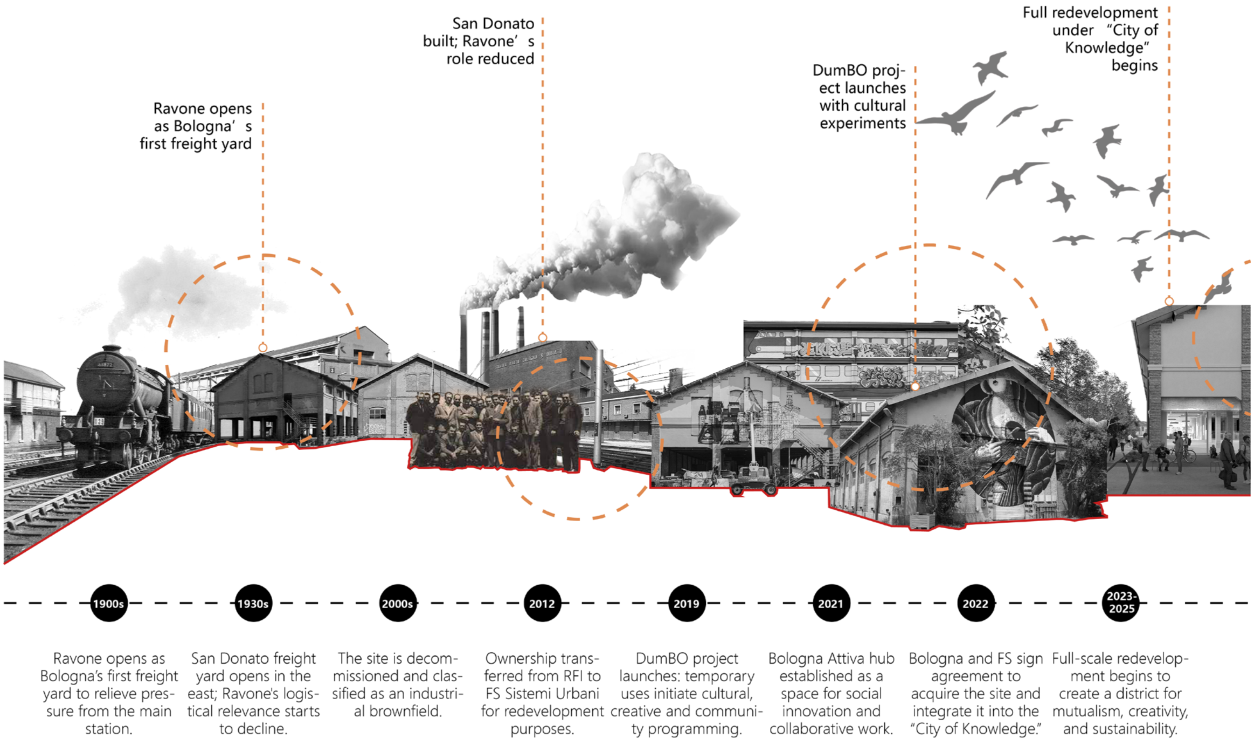


Figure 3.2 Scalo Ravone historical timeline diagram.

3.2 Site Analysis of Scalo Ravone Area

3.2.1 Location and Urban Context

Scalo Ravone is located in the northwestern sector of Bologna's urban core, as illustrated in (Fig 3.3), adjacent to both Bologna Centrale railway station and the Maggiore Hospital. This exceptional central position offers significant potential for multimodal connectivity and seamless integration into Bologna's broader framework of the Knowledge City.

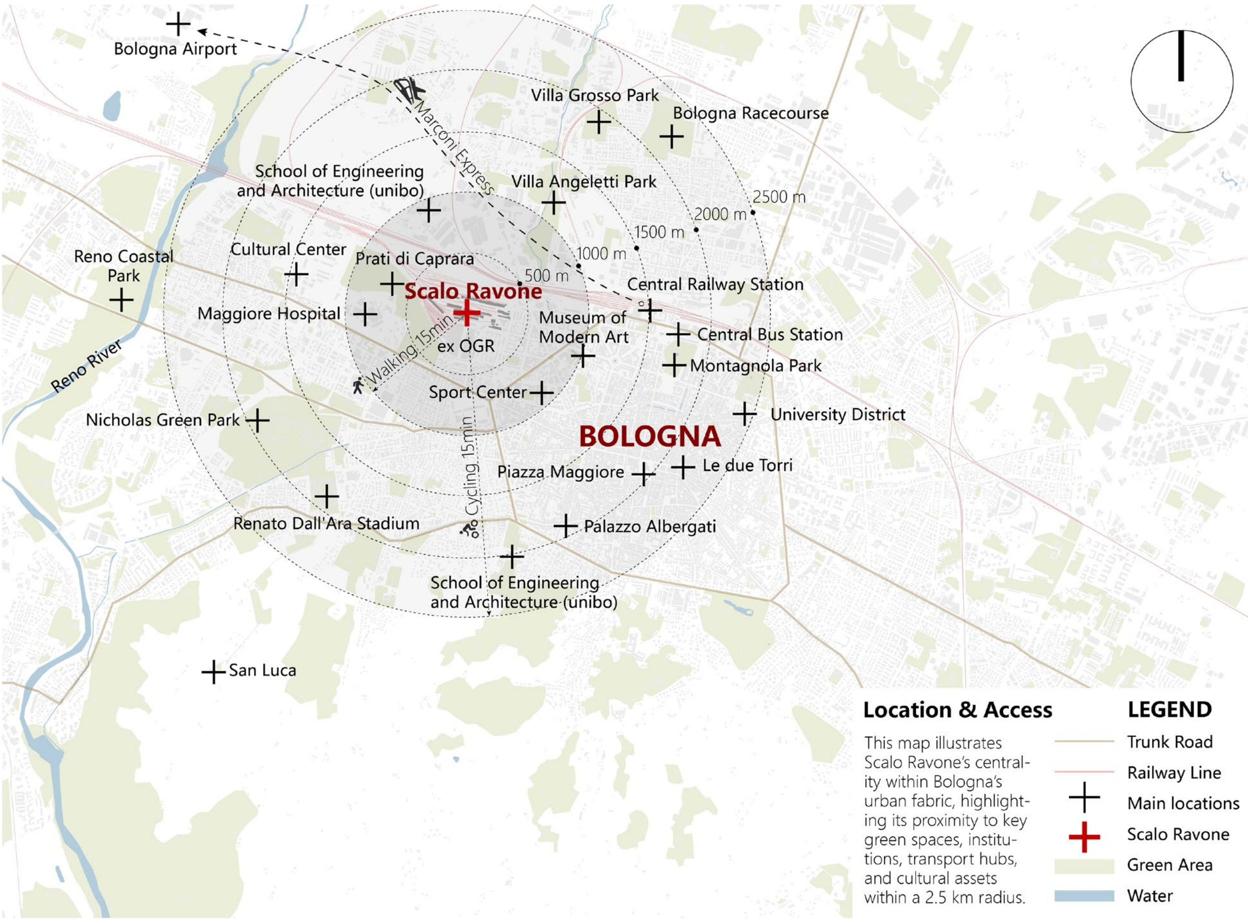


Figure 3.3 Location and access map.

3.2.2 Transportation Accessibility

Scalo Ravone benefits from partial multimodal access, though its connectivity varies depending on direction. As shown in (Fig 3.4), the eastern side is served by several bus lines (29 and 36), and future tram lines (red and yellow) are planned to run along the southern edge of the site. Multiple transit stops fall within both 400 m and 800 m walkable radio, supporting accessible east-side connections. However, north–south connectivity is limited by the railway infrastructure. Currently, a tunnel located on the northeastern edge of the site enables passage for pedestrians, cyclists, and vehicles, providing the only direct link between the two sides.

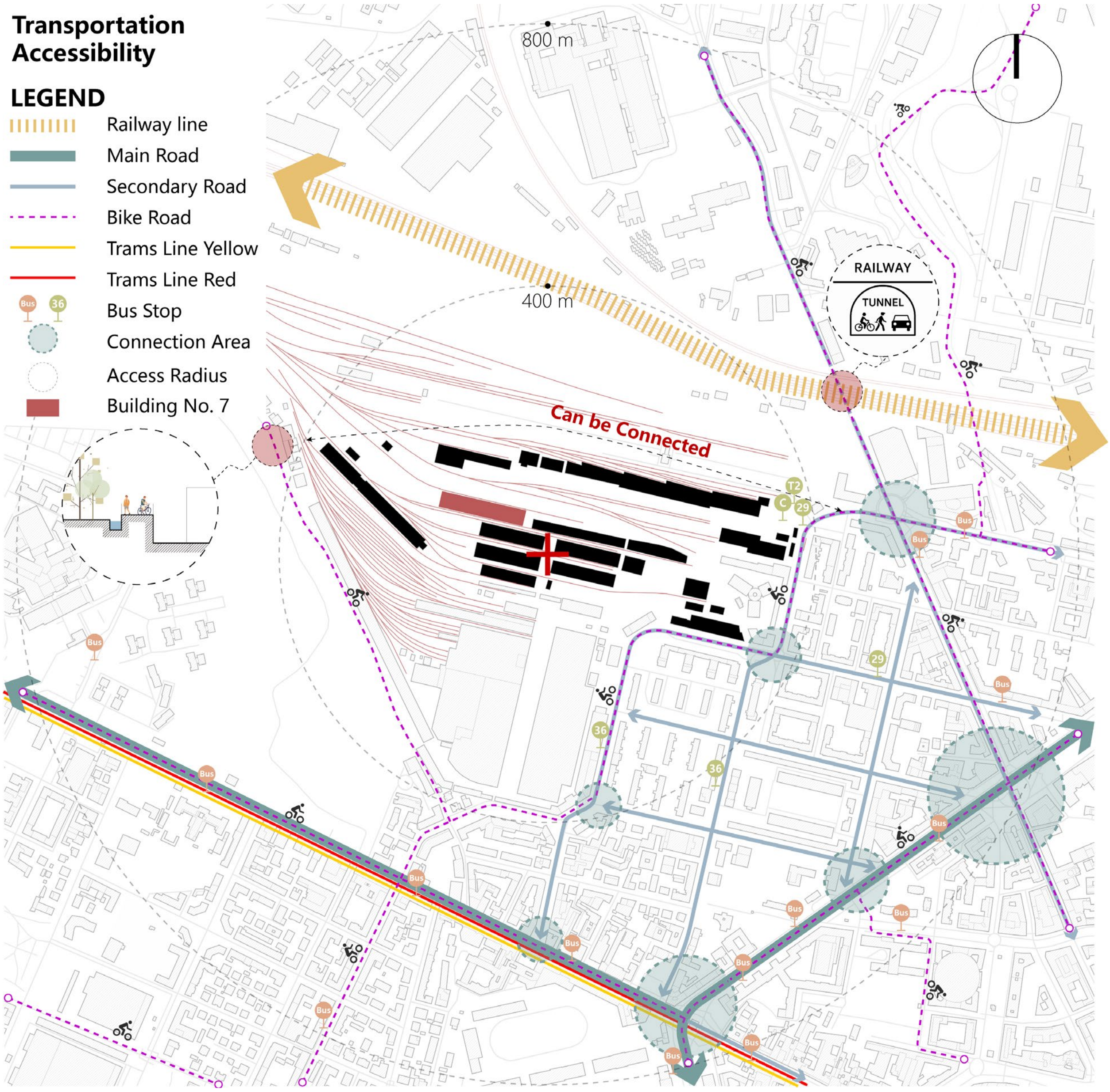


Figure 3.4 Transportation analysis map.

3.2.3 Green Open Space and Environmental Value

According to the LEED v4 SS open space standard, an impact radius of 400 meters was used to assess accessibility to eligible green spaces. (Fig 3.5) shows that the site is directly connected to one of Bologna's largest ecological assets, Prati di Caprara, offering the potential for the site to form a green corridor with this green space. Several neighborhood gardens (e.g., Mons. Enelio Franzoni Garden) are adjacent to the eastern side, but the green spaces are small and dispersed.

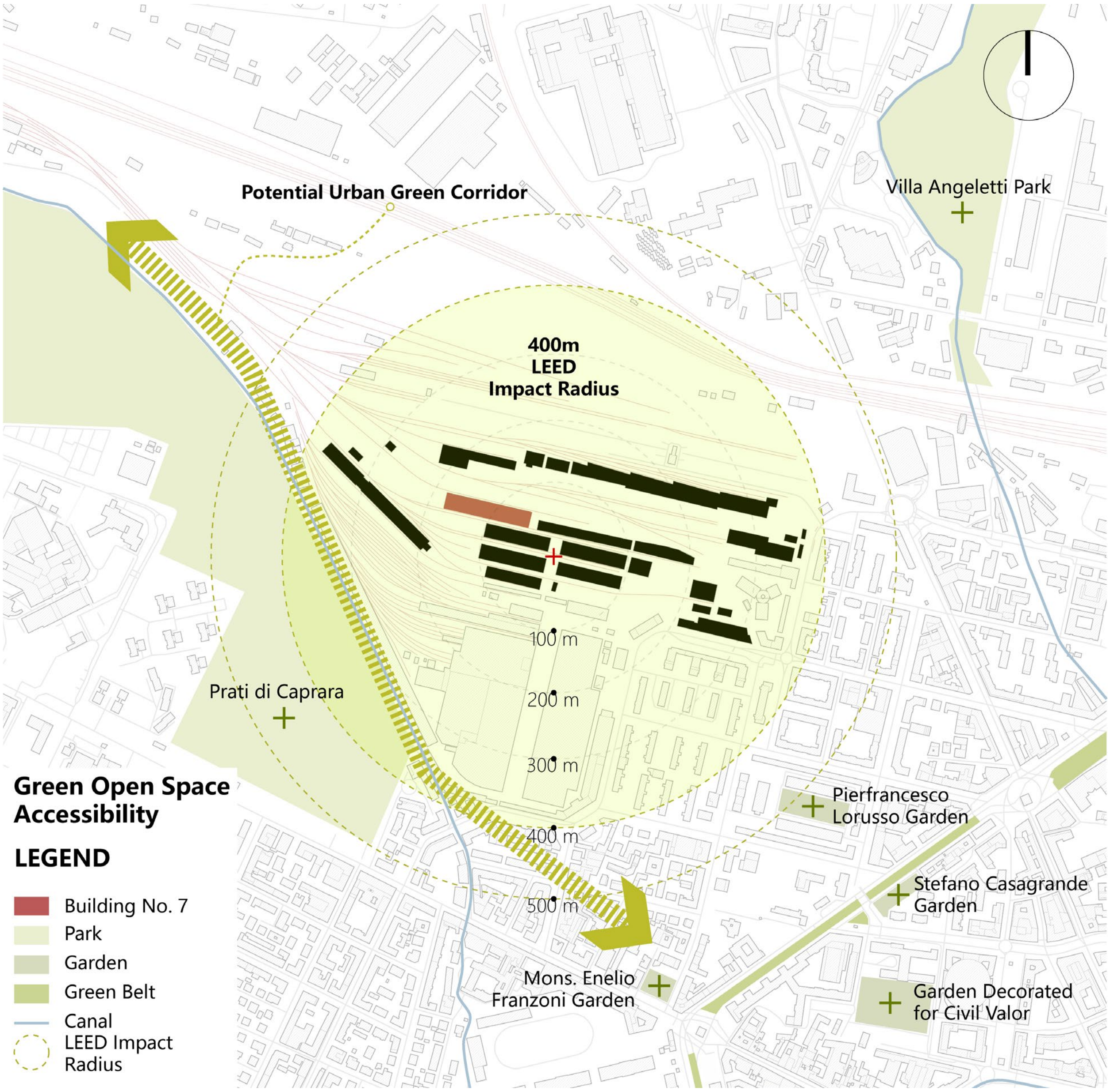


Figure 3.5 Green open space access.

3.2.4 Functional Accessibility and Social Infrastructure

A diverse range of public services is concentrated within an 800 m radius of the site, as depicted in (Fig 3.6). These include supermarkets, schools, government offices, health centers, and libraries, particularly toward the southeast quadrant. The Maggiore Hospital, Bologna's major healthcare hub, lies just across the railway. The dense and diverse social infrastructure indicates strong potential for mixed-use integration and supports walkable urbanism principles. However, the rail corridor still acts as a physical divider, reinforcing the need for spatial stitching strategies.

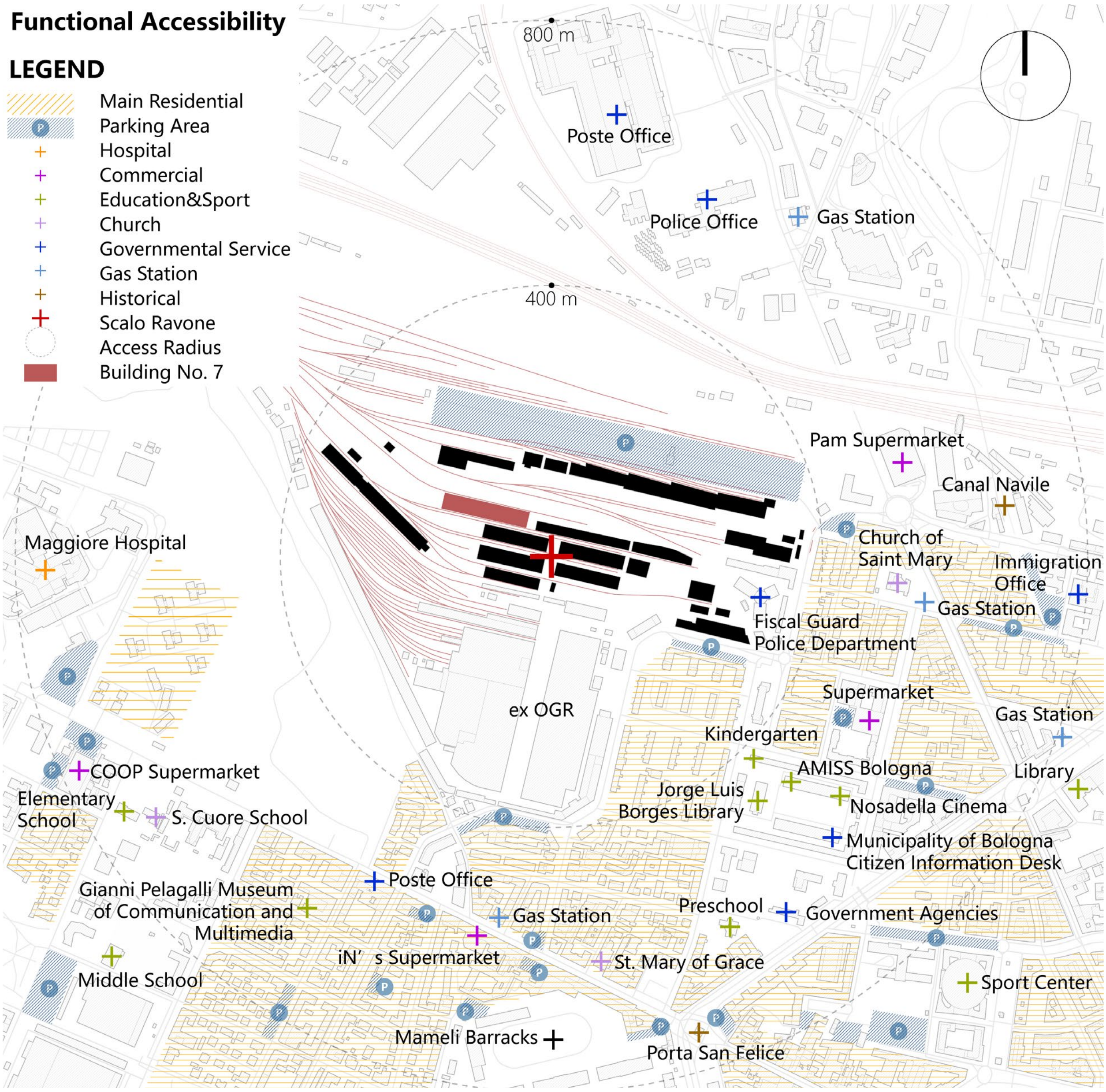


Figure 3.6 Functional accessibility map.

3.3 Weather conditions

3.3.1 Temperature Distribution and Thermal Comfort

Bologna's climate features a wide annual temperature range with pronounced diurnal variation. As illustrated in Fig 3.7, temperatures fall below 18 °C for a large portion of the year, especially during winter and transitional months, indicating a strong need for thermal insulation and heating strategies in building design. Temperatures above 26 °C occur primarily during the summer daytime hours, signaling the necessity of shading and passive cooling strategies. The thermally comfortable range (18–26 °C), suitable for natural ventilation, is mainly concentrated in spring and fall. These conditions support the use of mixed passive design strategies to improve indoor comfort and reduce energy consumption.

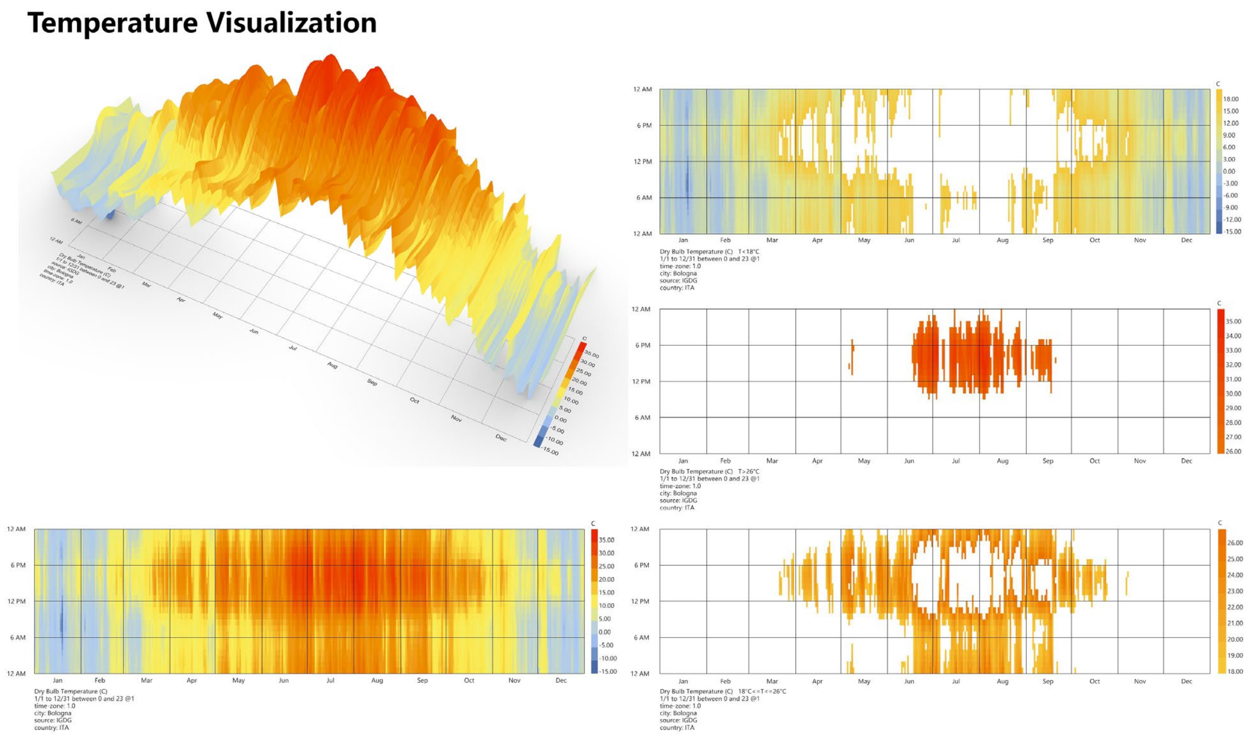


Figure 3.7 Annual temperature distribution and thermal zones.

3.3.2 Wind Patterns and Natural Ventilation Potential

As shown in Fig 3.8, summer winds in Bologna mainly come from the southeast and northeast, with higher speeds that support natural ventilation. In winter, winds shift to southeast, southwest, and northeast, but are weaker, with calm conditions exceeding 50%, reducing passive cooling or ventilation potential. This highlights the need for wind protection and insulation, while outdoor or semi-open spaces are best located on the northwest side to limit cold-season exposure.

3.3.3 Solar Access and Sun Path Implications

The site receives high levels of solar radiation year-round, particularly on rooftops and south-facing façades (Fig 3.9). In summer, high sun paths necessitate shading and cross-ventilation to prevent overheating, while in winter, low angles emphasize the need for passive solar gain. Building 7's orientation and large roof surface make it suitable for solar panels, green roofs, and sun-responsive outdoor spaces. Overall, the layout should optimize solar access while integrating efficient envelopes to ensure comfort, sustainability, and seasonal adaptability.

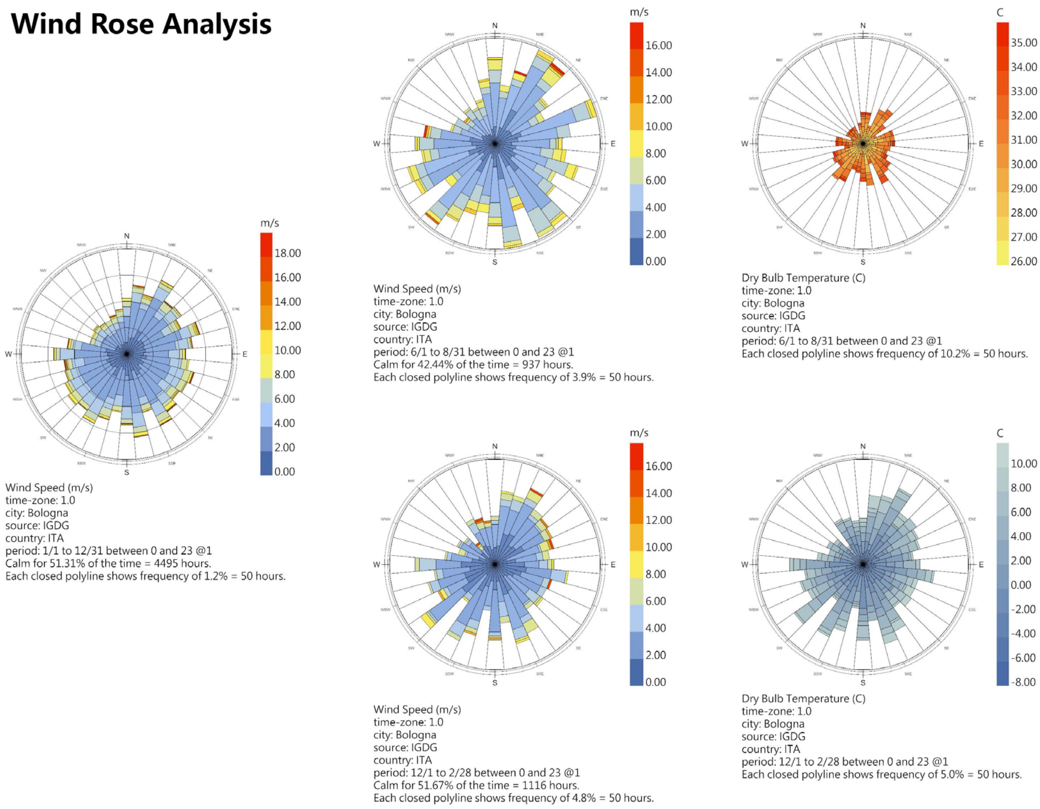


Figure 3.8 Seasonal wind rose diagrams.

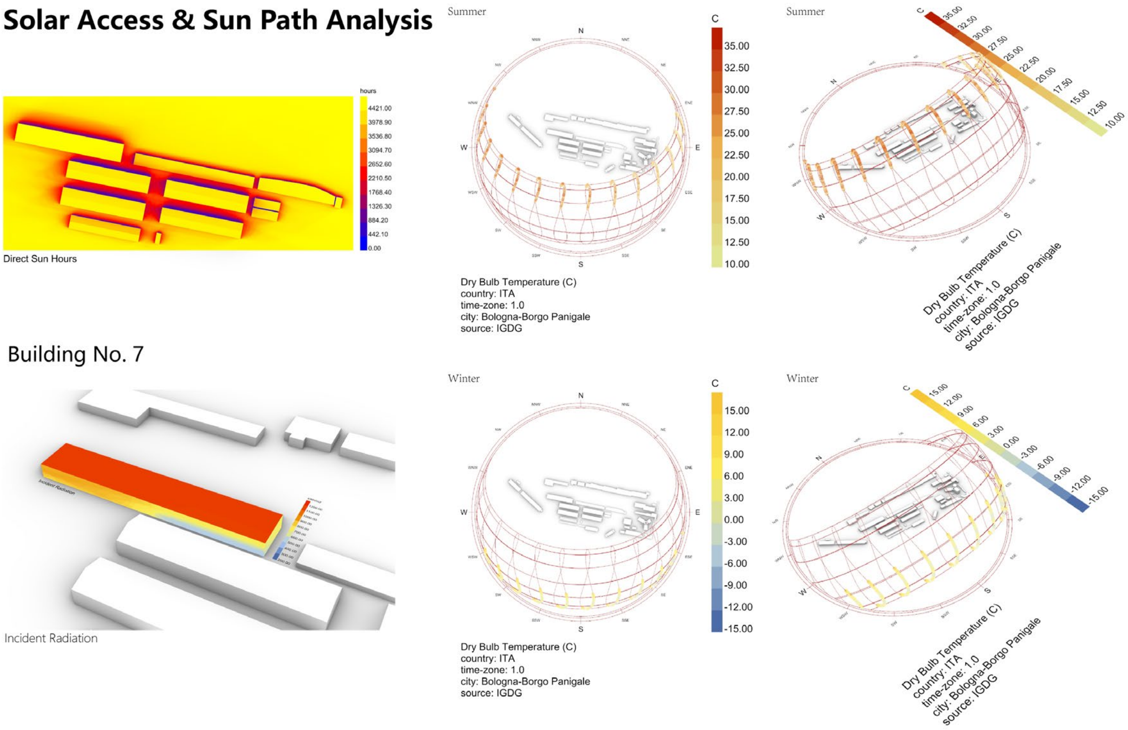


Figure 3.9 Solar access and sun path.

3.4 Master Plan of Scalo Ravone

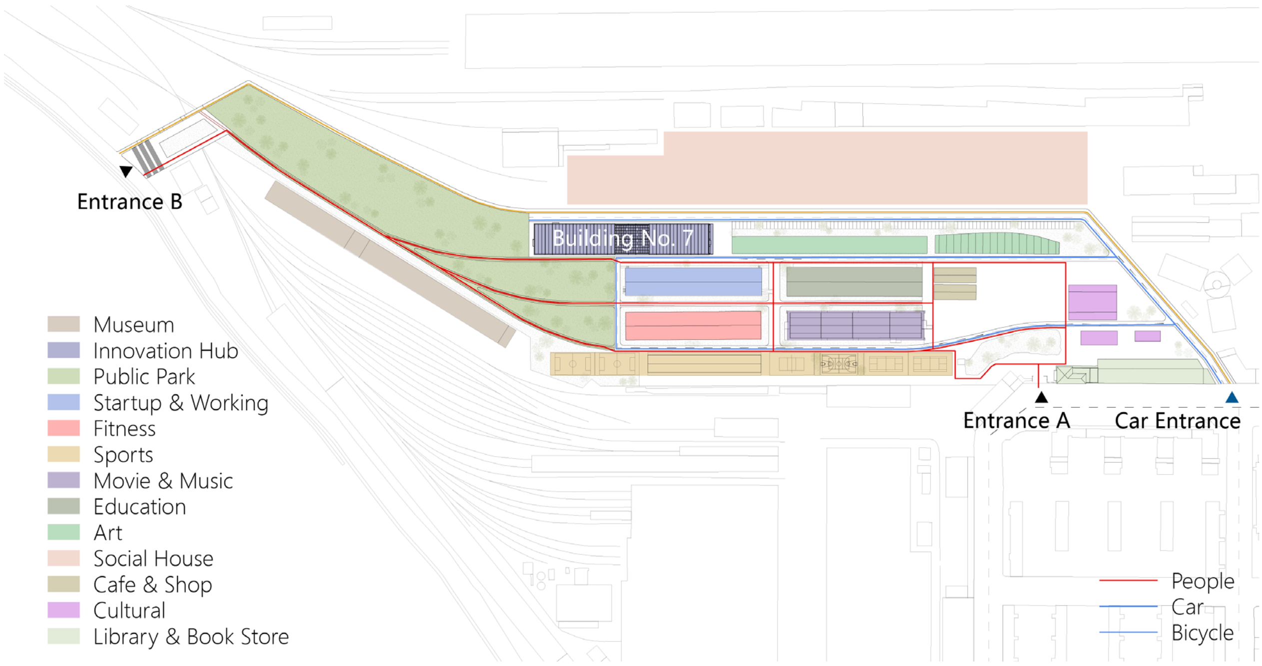


Figure 3.10 Master plan of Scalo Ravone.

The site is organized by an east–west pedestrian spine that links open spaces with the warehouse volumes. Along the northern edge, this spine runs in parallel with a dedicated bicycle path, tying seamlessly into the urban cycling network at Entrance B (west) and the eastern connection. Pedestrian and vehicular flows are clearly separated: Entrance B serves people on foot and bikes and opens a potential green interface with Prati di Caprara; Entrance A is the main eastern pedestrian access; the adjacent Car Entrance handles vehicles, giving direct access to parking and to Building No. 7.

The intervention adopts a minimal-intervention approach that follows the existing industrial grid and railway morphology, establishing a legible circulation system and coherent spatial order. The overall objective is to provide a flexible, recognizable, and expandable framework that preserves the industrial heritage while enabling the long-term growth of knowledge- and innovation-based activities.

3.5 Condition Assessment of Building No. 7

3.5.1 Master plan of building No. 7

From the masterplan, Building No.7 is a long east–west volume located on the northern band of the site, parallel to the rail corridor. Visitor access is primarily from the east: people enter the site at the eastern main entrance and reach the main door on the east gable of No.7 along the internal route shown. A continuous access track (red dashed line) runs along the south side of the building, linking the eastern approach to the west and serving secondary doors indicated on the plan. To the south of No.7 lie the elongated volumes No.12 and No.16, positioned parallel to it and together forming a linear court in between; vacant lots (hatched) are visible to the north and locally to the south, acting as open margins around the building.

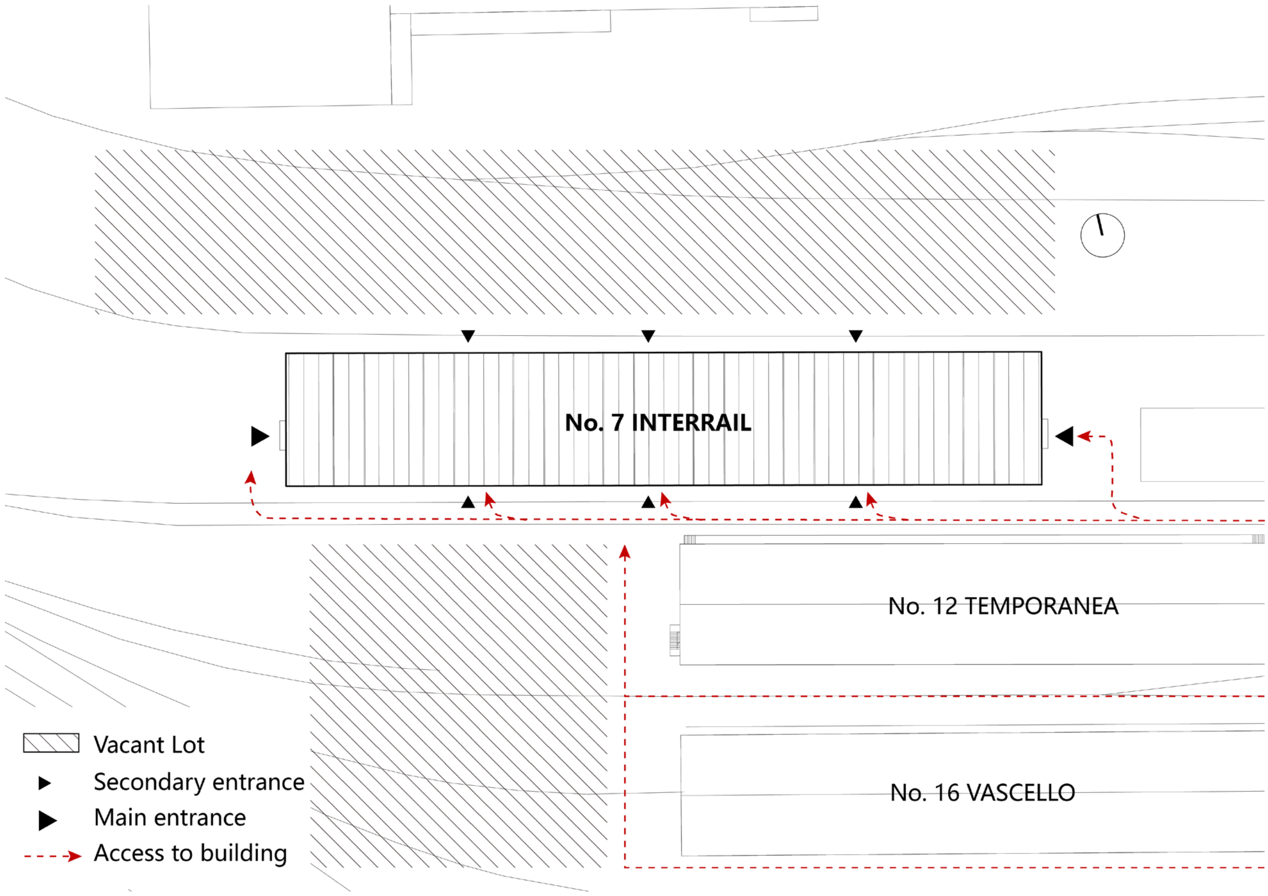


Figure 3.11 Master plan of building No. 7.

3.5.2 Structural and Material Conditions

As part of the status assessment of the Scalo Ravone site, Building No. 7 exemplifies an early-twentieth-century medium-to-large industrial warehouse. Its structural system consists of long-span reinforced concrete frames supporting a roof of continuously arranged precast U-shaped concrete panels, integrated with extensive strip skylights to maximize natural daylight. The façades combine exposed concrete frames with red brick infill, while the north–south elevations are symmetrically equipped with large industrial rolling doors surmounted by horizontal steel strip windows. These features not only reflect the functionalist character of the era's industrial architecture but also provide generous spatial flexibility that facilitates adaptive reuse. In particular, the clear-span interior creates a robust foundation for accommodating new programs without major structural alterations.

The building remains structurally sound, with no visible cracks or signs of deterioration, and its well-preserved envelope provides a solid foundation for adaptive reuse. The precast concrete roof panels are intact, though the skylight glazing shows aging and should be replaced with energy-efficient alternatives during future renovations. The basic electrical, heating, and water supply systems remain operational but require upgrading to meet the demands of future multifunctional use. The two existing restrooms are in good serviceable condition, although their layout and accessibility will likely need to be adapted to comply with contemporary standards. Overall, the building's current condition offers a reliable basis for low carbon retrofit interventions.

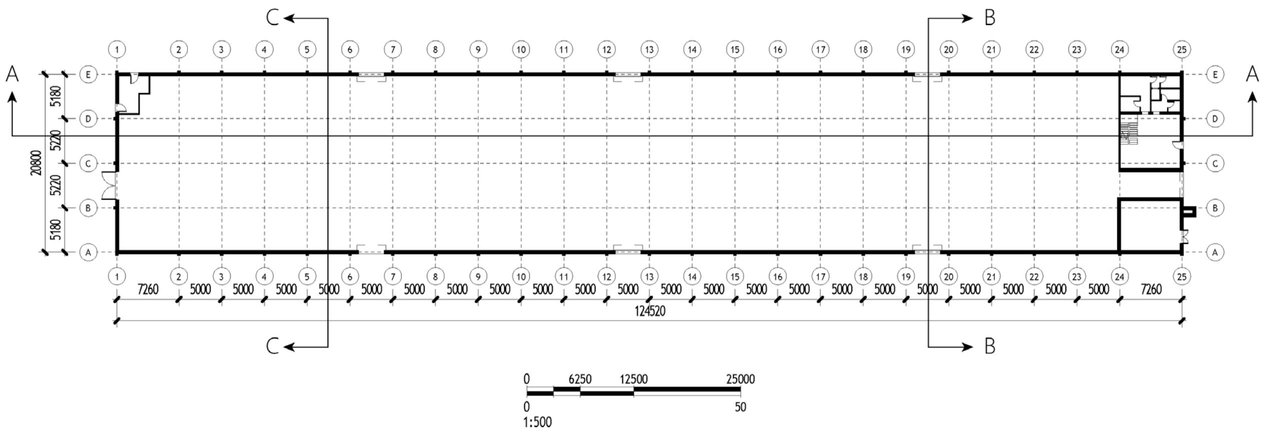


Figure 3.12 Plan of building No.7.

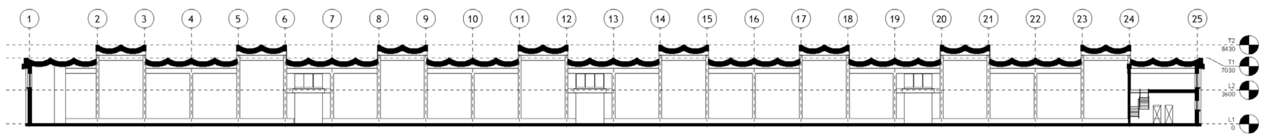


Figure 3.13 Building section A-A

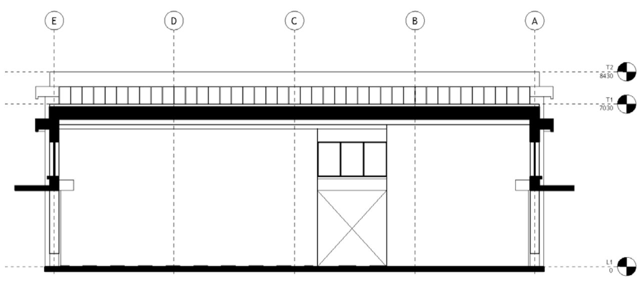


Figure 3.14 Building section B-B

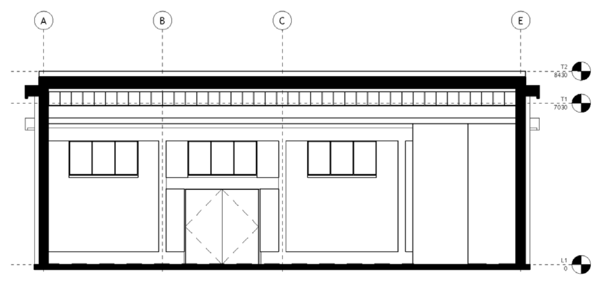


Figure 3.15 Building section C-C

Table 3.1 Basic data of building No.7, Scalo Ravone

Parameter	Value
Building Name	Scalo Ravone – Building No.7
Location	Bologna, Italy
Year of Construction	1920s
Building Type	Industrial warehouse
Gross Floor Area	~2646 m²
Max Height	8.43 m
Structural System	Reinforced concrete frame
Roof Type	Precast U-panels with strip skylights
Envelope	Brick infill + exposed concrete
Current Use	Car warehouse

3.5.3 Current Use and Future Plans

Currently, Building No. 7 functions as a car warehouse for storing second-hand vehicles and temporary fleets. It's clear-span structure facilitates circulation but lacks facilities for offices, services, or public use. Under the urban regeneration plan, it falls within "Zone A – Unconventional Maintenance Projects" and will be managed by the University of Bologna. The building is set to become a multifunctional innovation hub, combining startup incubation, entrepreneurial training, and temporary exhibitions, as part of the broader City of Knowledge strategy to reactivate underused assets and foster an academic–social innovation ecosystem.

Figure 3.16 Current outdoor image.

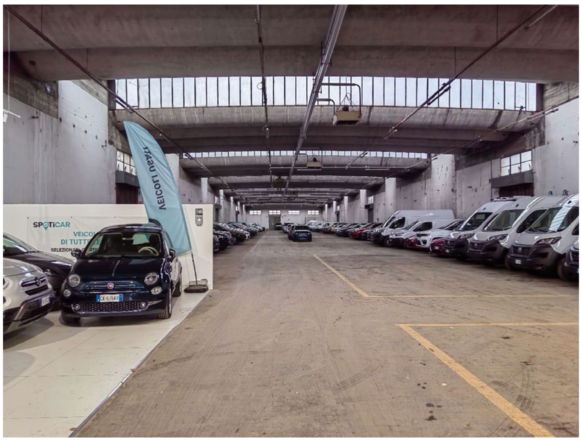


Figure 3.17 Current indoor image.

3.5.4 Building Physics Performance Overview (Envelope, Ventilation, Solar Access)

From a building physics perspective, Building No. 7 features a traditional brick-concrete envelope with no thermal insulation layer, resulting in poor thermal performance. The roof and walls lack thermal stratification, causing heat loss in winter and overheating in summer. The large rooftop skylights provide ample daylighting during the day but also contribute to increased solar gain during hot periods, requiring shading and insulation strategies for improved indoor comfort.

In terms of ventilation, the continuous high-level skylights on the roof enable some degree of natural heat exhaust. However, the limited number of operable windows on the façades—mainly on the east wall—combined with the nearly sealed north and south elevations (except for narrow strip windows above the rolling doors), restrict effective cross-ventilation. Overall, the building was originally designed for industrial storage use with minimal consideration for thermal comfort or energy efficiency. Future retrofits should prioritize improving the thermal performance of the envelope, optimizing ventilation paths, and enhancing the solar and thermal environment to support intensive and sustainable future use.

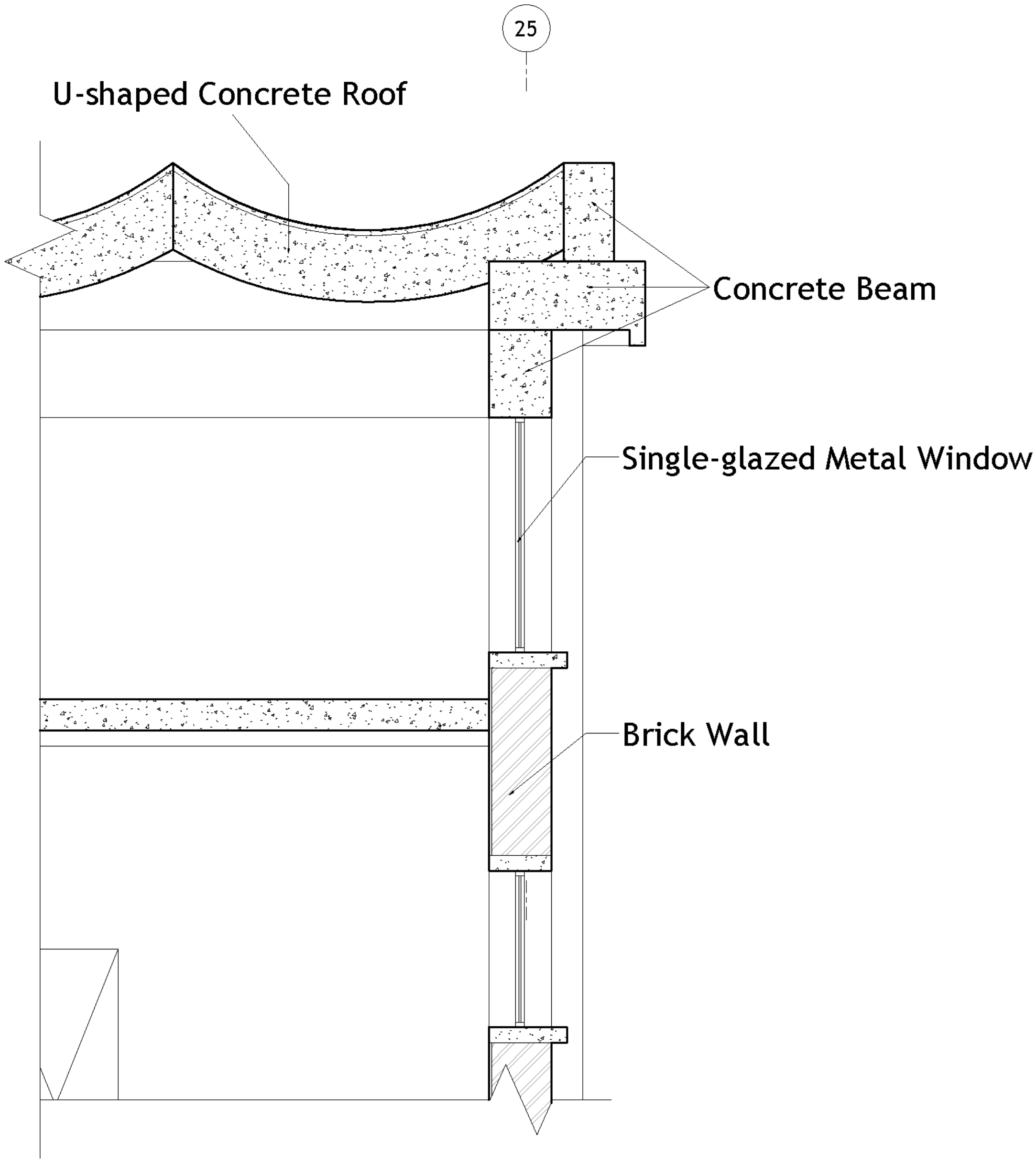


Figure 3.18 Current section details 01.

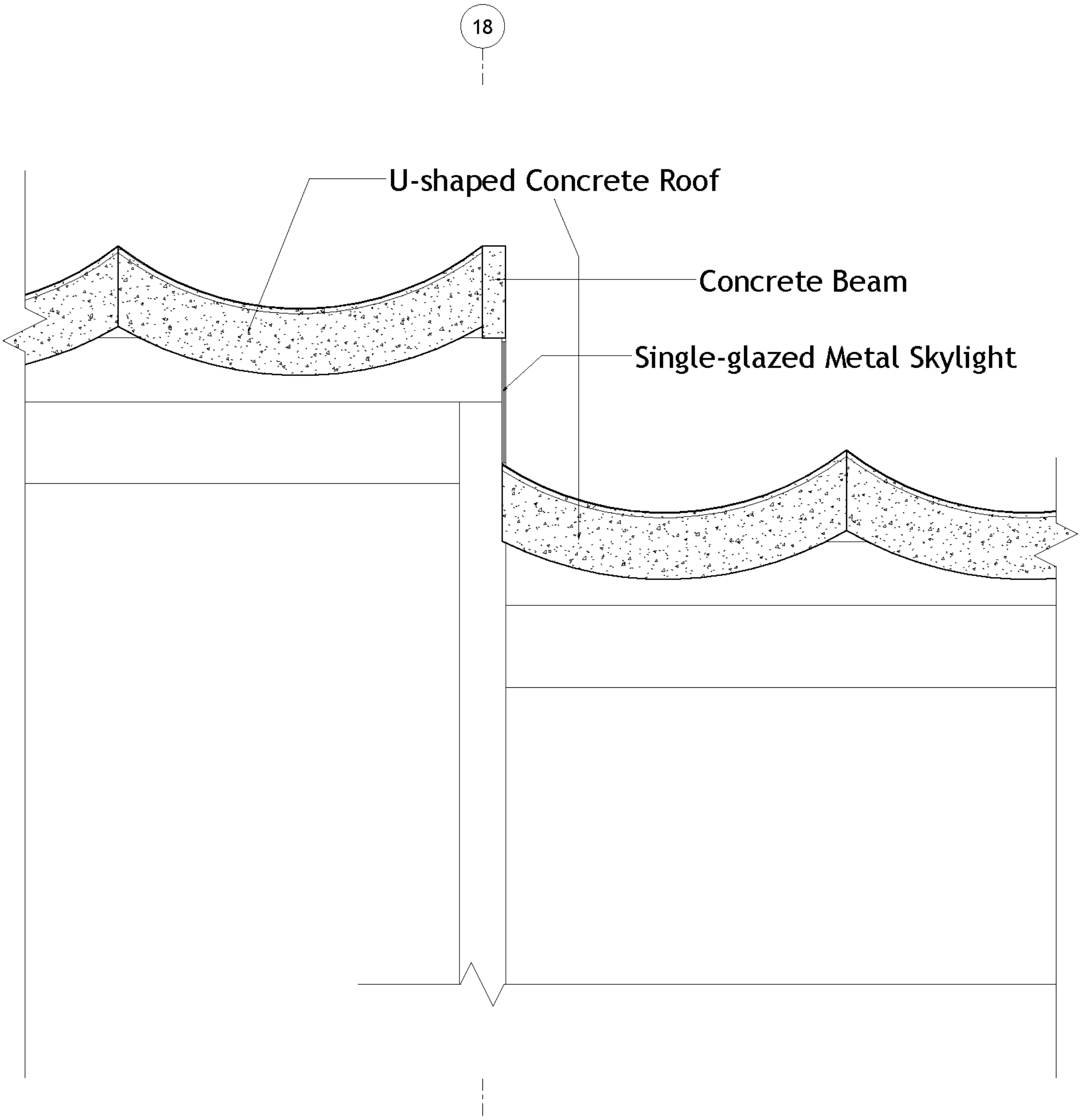


Figure 3.19 Current section details 02.

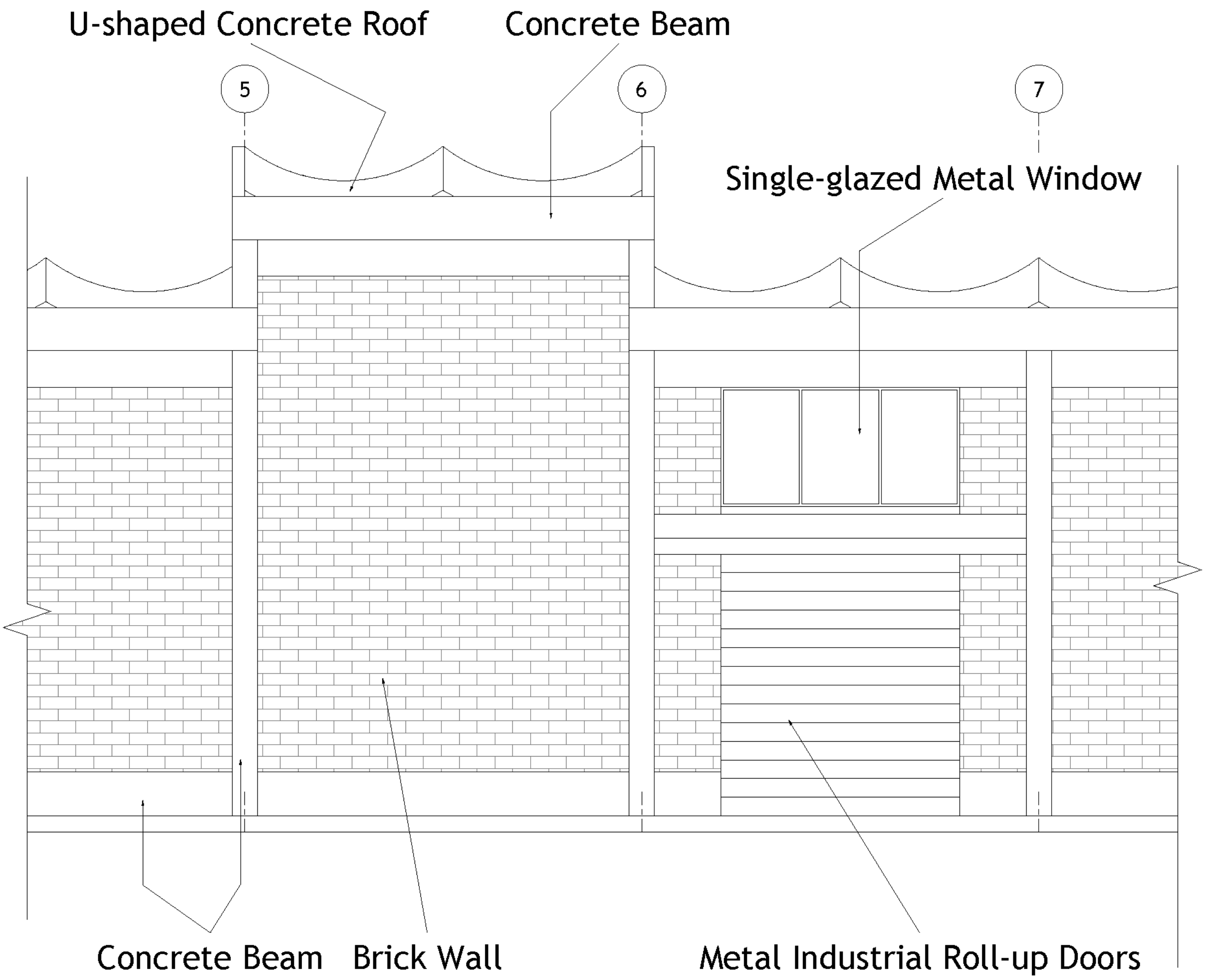


Figure 3.20 Current facade details.

In terms of ventilation, the continuous high-level skylights on the roof enable some degree of natural heat exhaust. However, the limited number of operable windows on the façades—mainly on the east wall—combined with the nearly sealed north and south elevations (except for narrow strip windows above the rolling doors), restrict effective cross-ventilation. Overall, the building was originally designed for industrial storage use with minimal consideration for thermal comfort or energy efficiency. Future retrofits should prioritize improving the thermal performance of the envelope, optimizing ventilation paths, and enhancing the solar and thermal environment to support intensive and sustainable future use.

3.6 Baseline Operational Energy Simulation (Existing Condition, Honeybee)

3.6.1 Energy Model and Simulation Flowchart

To evaluate the baseline energy performance of Building No. 7 prior to any retrofit interventions, an energy consumption simulation was carried out using the Grasshopper Honeybee plugin, which integrates Energy Plus as the simulation engine. The building geometry, envelope construction parameters, and operational schedules were modelled based on field measurements, historical construction data of 1920s Italian industrial warehouses, and site-specific climate conditions for Bologna (EPW weather file).

Annual energy end-uses, peak heating and cooling loads, monthly load profiles, and thermal load balance breakdowns were obtained from the same simulation run, ensuring consistent boundary conditions. These results form the baseline reference for assessing potential retrofit strategies in the subsequent sections.

The energy simulation workflow for Building No. 7 was developed in Grasshopper using the Honeybee plugin, as illustrated in Fig 3.22. The process begins with defining the building geometry and rooms (HB Rooms / Solve Adjacency) and assigning construction assemblies (HB Opaque / No Mass ⟶ HB Construction; HB Apply Construction / Construction Set), program types and schedules (HB Program Type / HB Apply Room Schedules), and HVAC system parameters (HB Ideal Air / Set Conditioned). Door and window definitions were added using the HB Door and HB Add Subface components, with corresponding Energy Plus construction assignments.

Weather data and simulation parameters (LB EPW / DDY, HB Simulation Parameter) were specified based on the Bologna climate file, ensuring location-specific thermal conditions. Once all inputs were assembled into the HB Model, the Model Validation step (HB Validate / Check Model) was carried out. If validation failed, model inputs—geometry, constructions, schedules, HVAC, weather, or doors—were revised before re-validation.

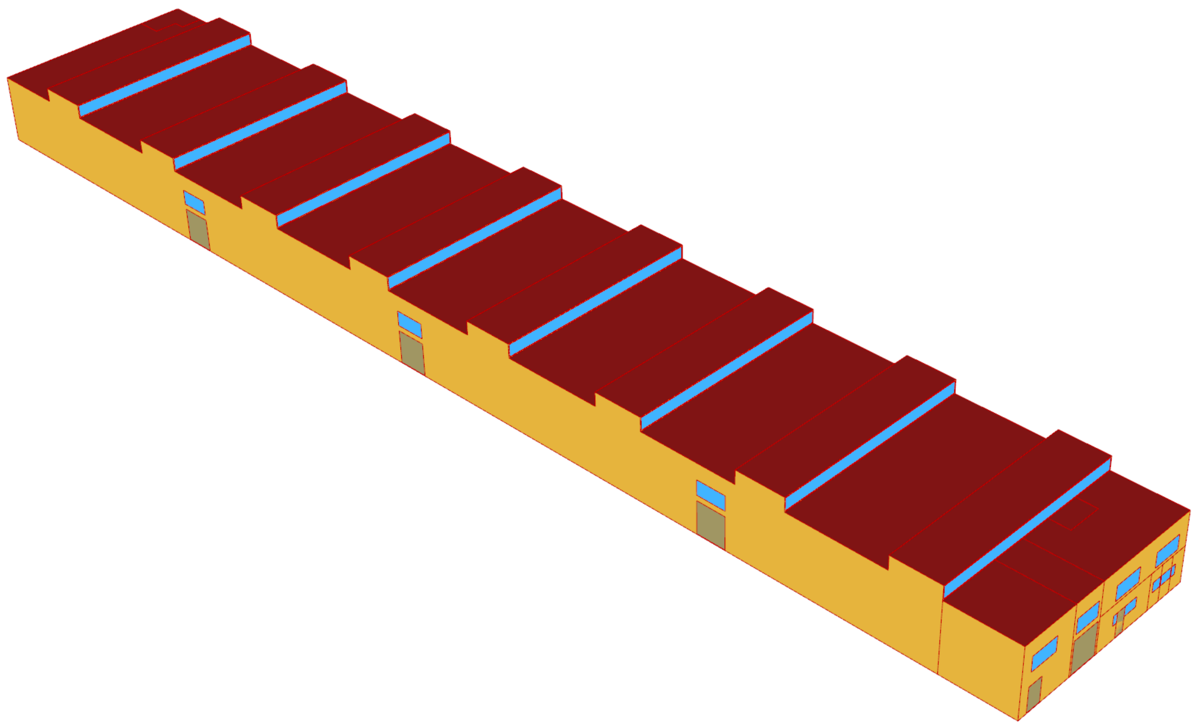


Figure 3.21 Grasshopper honeybee energy model image.

Upon successful validation, three types of simulation outputs were generated:

Annual End Uses (HB Annual Loads) with an EUI and end-use breakdown (kWh/m²·yr).

Peak Loads (HB Peak Loads, based on DDY files) with corresponding peak heating/cooling loads (W or W/m²).

Full simulation runs (HB Model to OSM + HB Run OSM), from which SQL results were read (HB Read Room Energy Result) and thermal load balance (HB Thermal Load Balance) calculated.

This structured workflow ensured a transparent, replicable, and location-specific simulation process, providing a reliable baseline for assessing retrofit strategies.

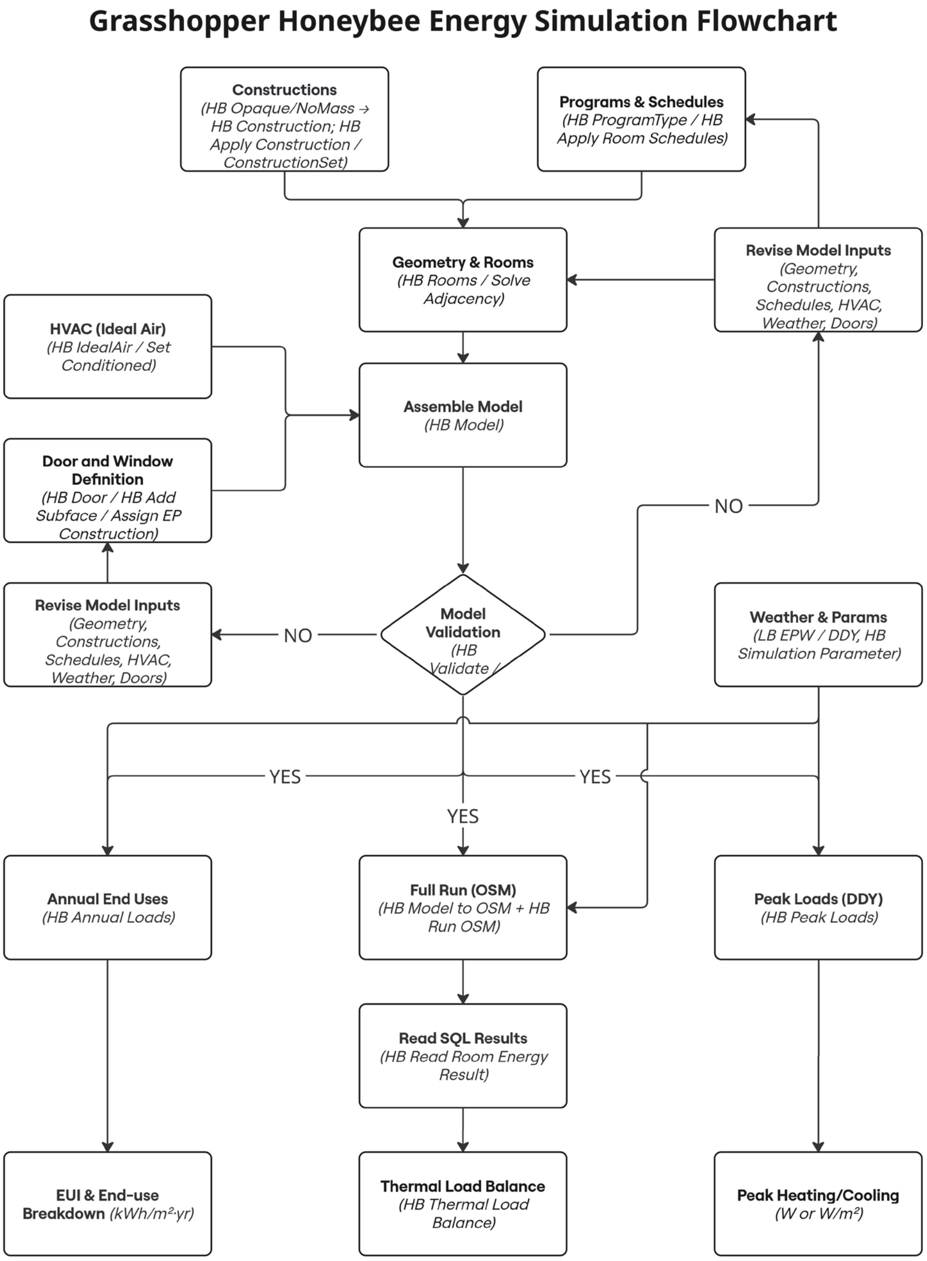


Figure 3.22 Grasshopper honeybee energy simulation flowchart.

3.6.2 Energy Use Intensity (EUI) of The Existing Warehouse

The baseline simulation (Honeybee/Energy Plus; Bologna EPW; warehouse business-hour schedules; Ideal-Air heating-only; no mechanical cooling/ventilation; uninsulated 1920s masonry with infiltration) yields an

EUI of 73.9 kWh/m²·yr. End-use contributions are Heating 46.07 kWh/m²·yr (62%), Lighting 20.22 kWh/m²·yr (28%), Electric equipment 7.62 kWh/m²·yr (10%), and Cooling 0%. The bar chart reports absolute EUI values, while the pie chart shows their relative shares. Results indicate a heating-dominated profile driven by a poorly insulated envelope and air leakage; lighting is the second contributor due to large-volume illumination demands; equipment is minor, and there is effectively no cooling demand under current use. Priority retrofit actions should therefore focus on envelope insulation and airtightness, followed by LED lighting upgrades with daylight/occupancy controls; any future program introducing summer operation should be accompanied by a separate assessment of cooling and ventilation impacts.

Energy use breakdown of the existing warehouse (EUI = 73.9 kWh/m²·yr). (a) Absolute end-use intensities (kWh/m²·yr). (b) Relative shares: Heating 62%, Lighting 28%, Equipment 10%, Cooling 0%.

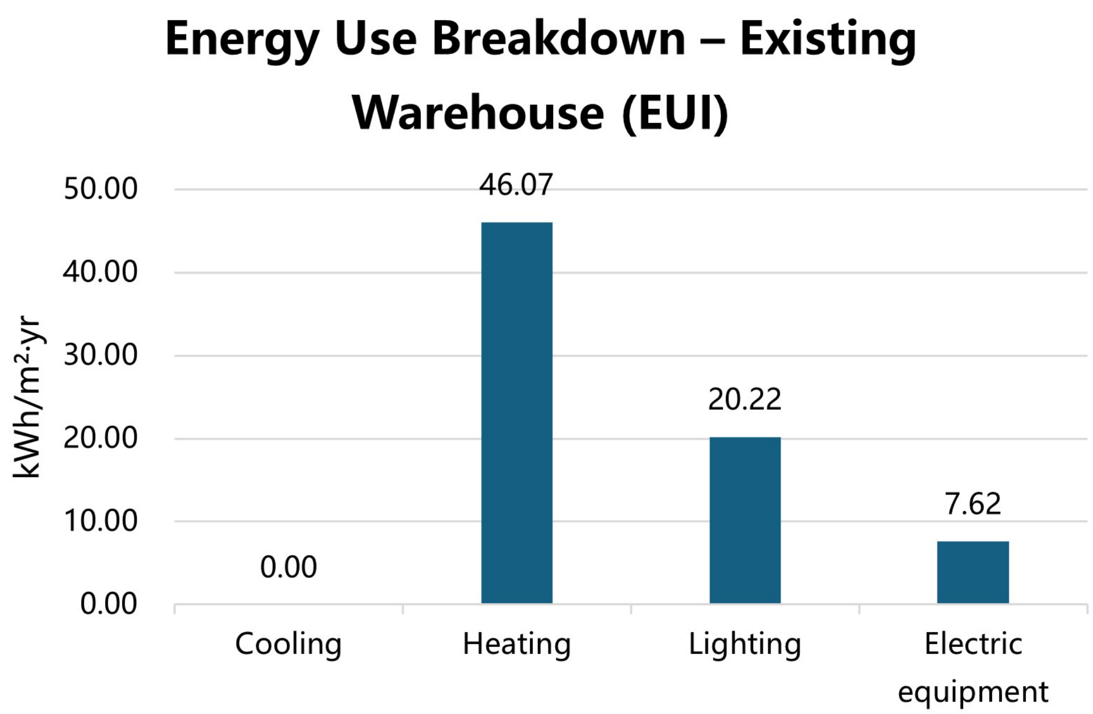


Figure 3.23 Existing warehouse EUI bar chart.

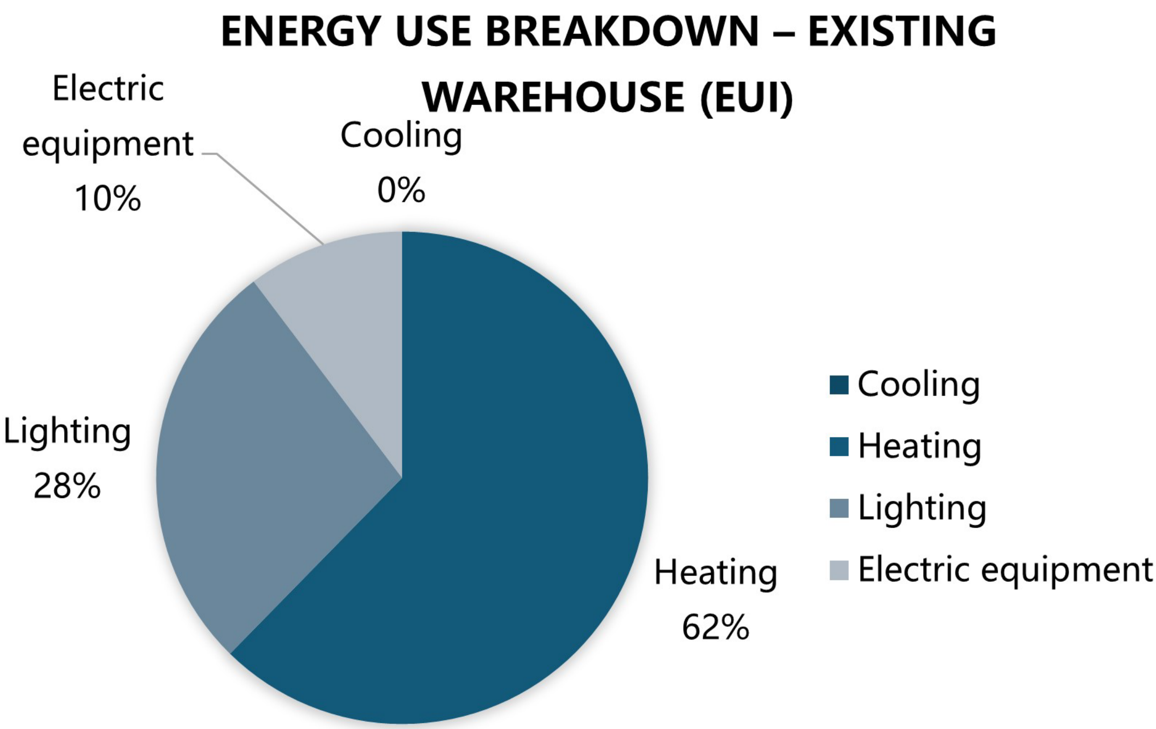


Figure 3.24 Existing warehouse EUI pie chart.

3.6.3 Energy Peak Loads

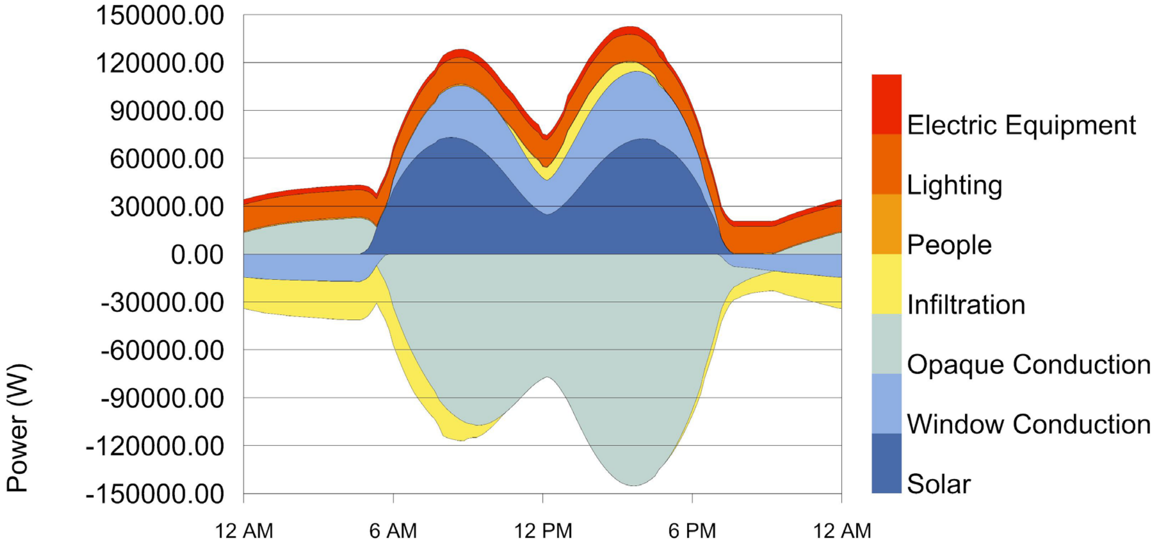


Figure 3.25 Cooling load balance chart.

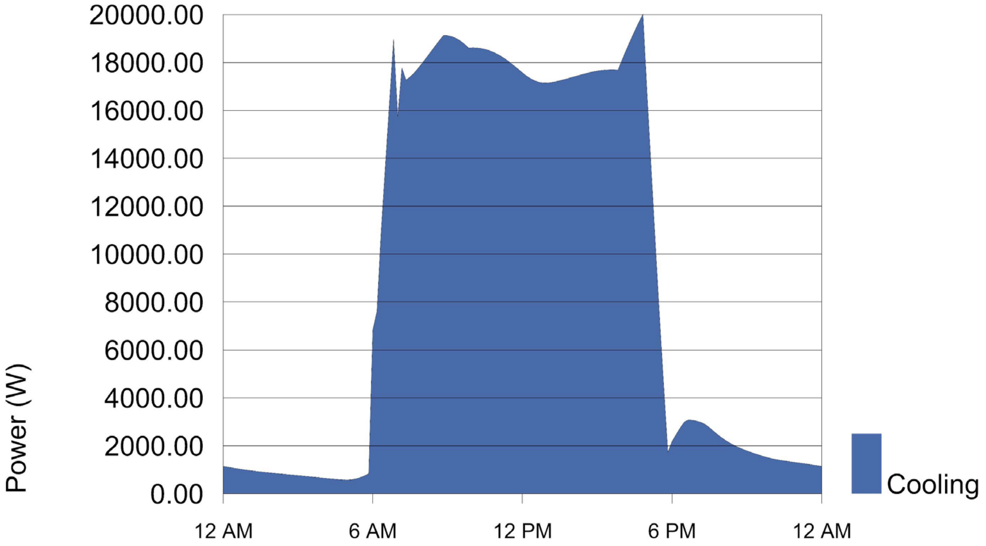


Figure 3.26 Potential cooling demand chart.

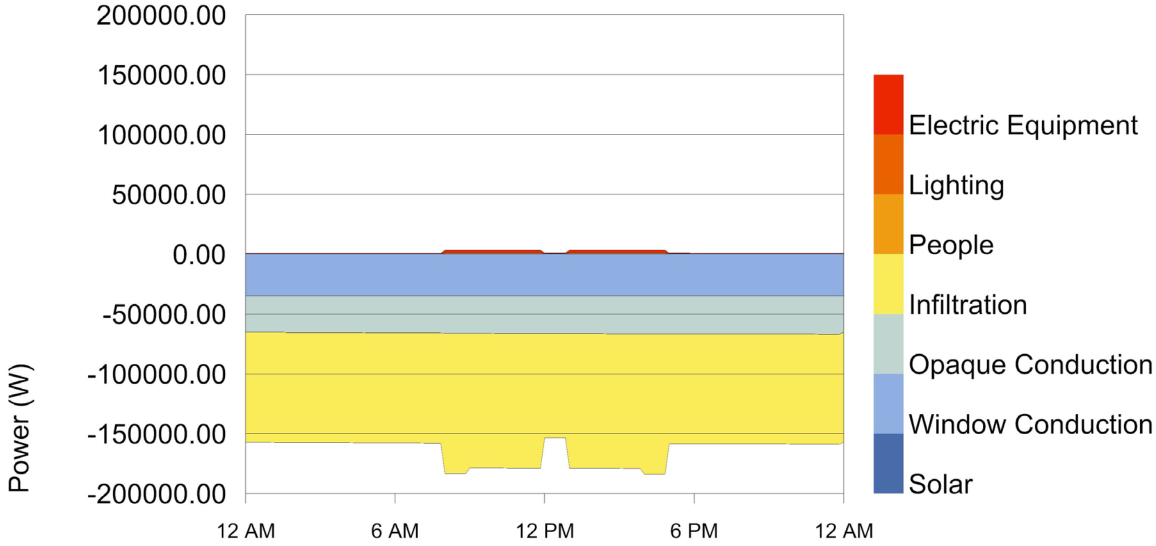


Figure 3.27 Heating load balance chart.

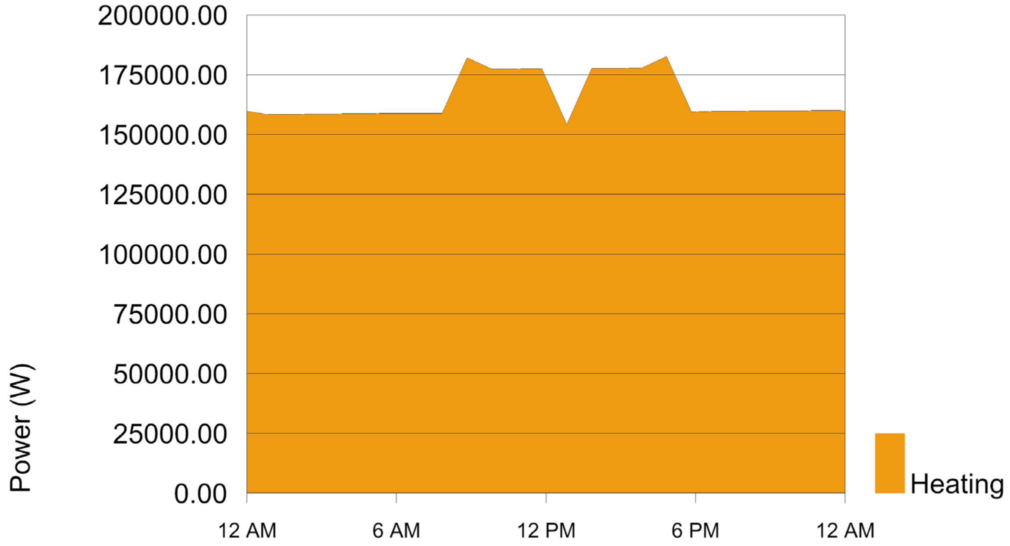


Figure 3.28 Heating demand chart.

Cooling peak loads (Fig 3.25-3.26) are driven by envelope conduction and infiltration, and the building exhibits a potential cooling demand (with no installed system) during periods of high solar gain and occupancy. Therefore, retrofits should prioritize airtightness and roof/wall insulation, complemented by external shading, lighting controls, and passive ventilation; if active cooling is needed in the future, it should be localized to critical spaces only. These measures will both depress heating peaks and curb daytime heat gains, improving comfort with minimal mechanical intervention. They also preserve the historic fabric while creating a scalable path for future multifunctional use.

Heating demand (Fig 3.27-3.28) is dominated by envelope conduction and infiltration; the design-day heating profile is almost flat, indicating that steady fabric and air-leakage losses set the peak rather than transient internal gains. Accordingly, retrofits should prioritize airtightness and roof/wall insulation, complemented by night setback, zonal control, and destratification/HRV, to reduce both peak capacity and annual consumption.

3.6.4 Monthly Thermal Load Balance

The chart (Fig 3.29) confirms the typical behavior of an old masonry warehouse: winter energy use is dominated by envelope conduction and infiltration, whereas non-winter months are governed by internal and solar gains. Accordingly, retrofit measures should prioritize airtightness and envelope upgrades (roof and walls), complemented by solar shading, lighting controls, and ventilation strategies.

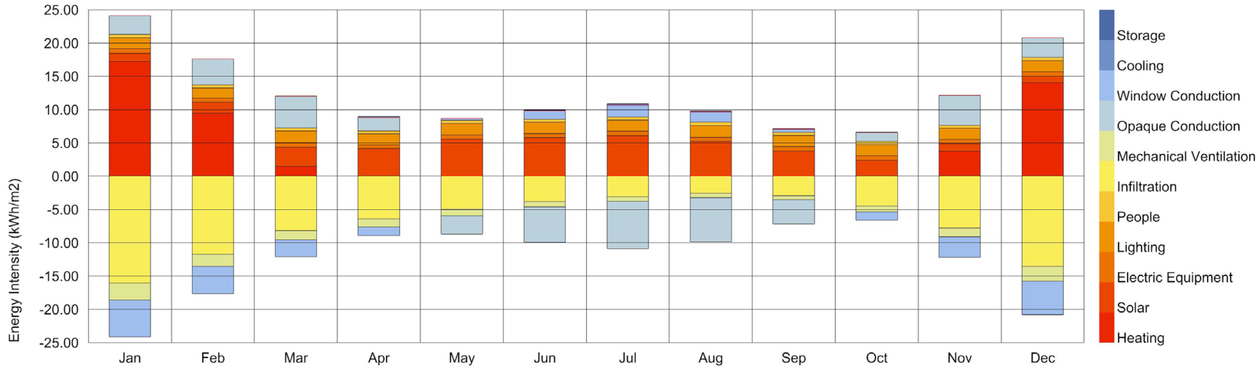


Figure 3.29 Monthly thermal load balance chart.

3.7 Baseline Life-Cycle Carbon Assessment (Existing Condition)

Method notes: Results in this section are produced with Tally®, aligned with ISO 14040/14044 and the building-sector standards ISO 21930, ISO 21931, EN 15804, and EN 15978.

3.7.1 Results per Life Cycle Stage

The Results per Life Cycle Stage chart (Fig 3.30) maps carbon emissions across life - cycle stages (Product, Transportation, Maintenance, Operational Energy, End of Life). For global warming potential, the Product (27%), Maintenance (37%), and Operational Energy (33%) stages dominate. Similar patterns hold for acidification, eutrophication, and smog formation, identifying these as key hotspots. This breakdown pinpoints where interventions (e.g., material optimization, energy - efficient upgrades) can target maximum carbon reduction.

3.7.2 Results per Revit Category

In Revit, building elements are organized into standardized categories (e.g., Walls, Floors, Roofs, Curtain Walls, and Doors), which form the basis for material quantification and life cycle assessment. The Results per Revit Category chart (Fig 3.31) show that Curtain Wall Mullions — representing the skylight components — account for 74% of the global warming potential, due to the intensive material production of metal and glass elements. Roofs (12%), Floors (6%), and Walls (5%) also contribute, but skylight-related mullions clearly emerge as the main carbon hotspot, directly linking emissions to architectural design and guiding retrofit priorities such as material upgrades and sub-design optimization.

3.7.3 Results per Division, itemized by Material

The Results per Division, itemized by Material chart (Fig 3.32) drills into material - level emissions. High - impact materials like cold - formed structural steel (Metals division) and structural concrete (Concrete division) emerge as carbon hotspots. By exposing material - specific footprints, it enables targeted substitutions (e.g., recycled metals, low - carbon concrete) to reduce life - cycle emissions.

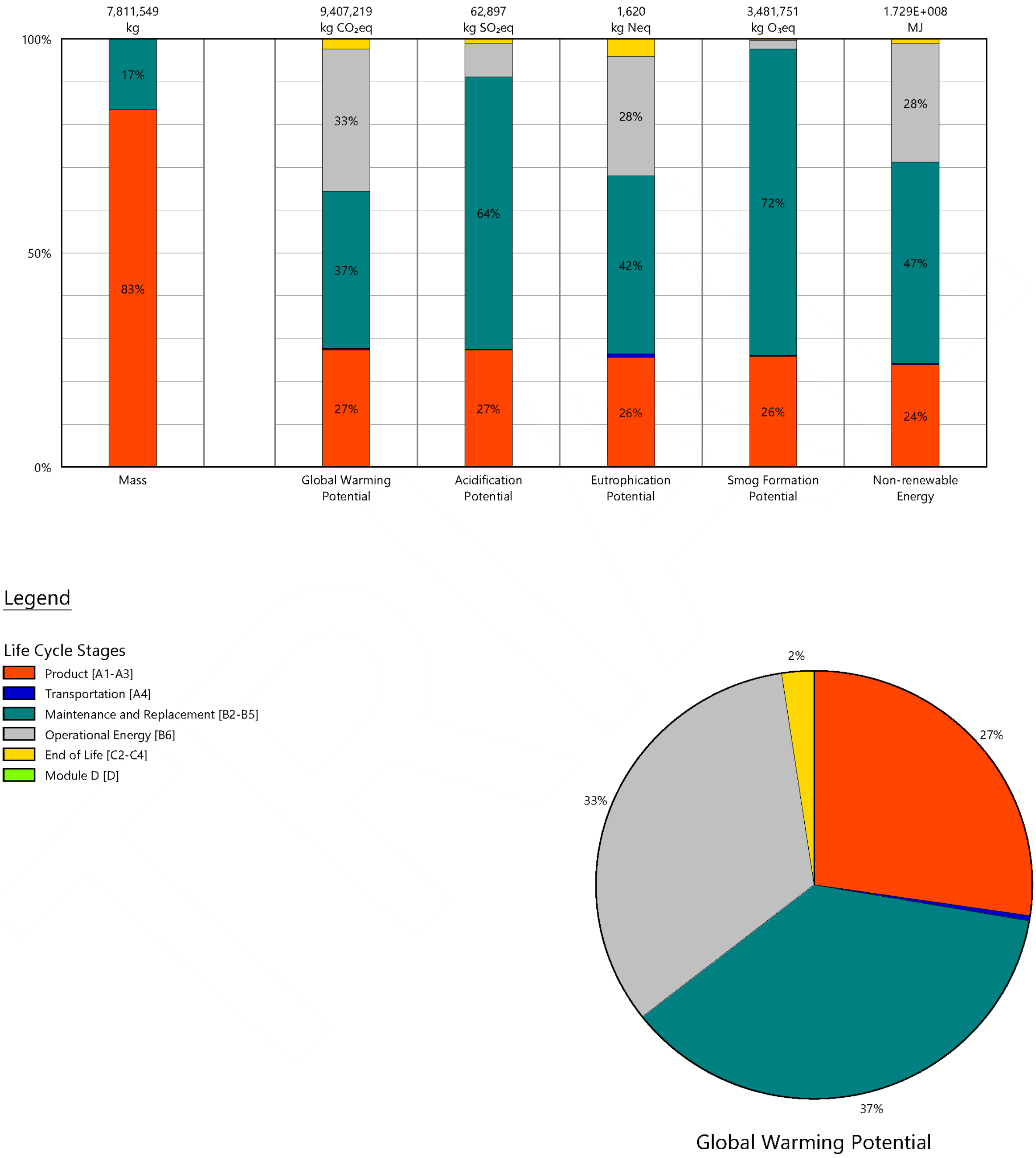


Figure 3.30 Results per life cycle stage.

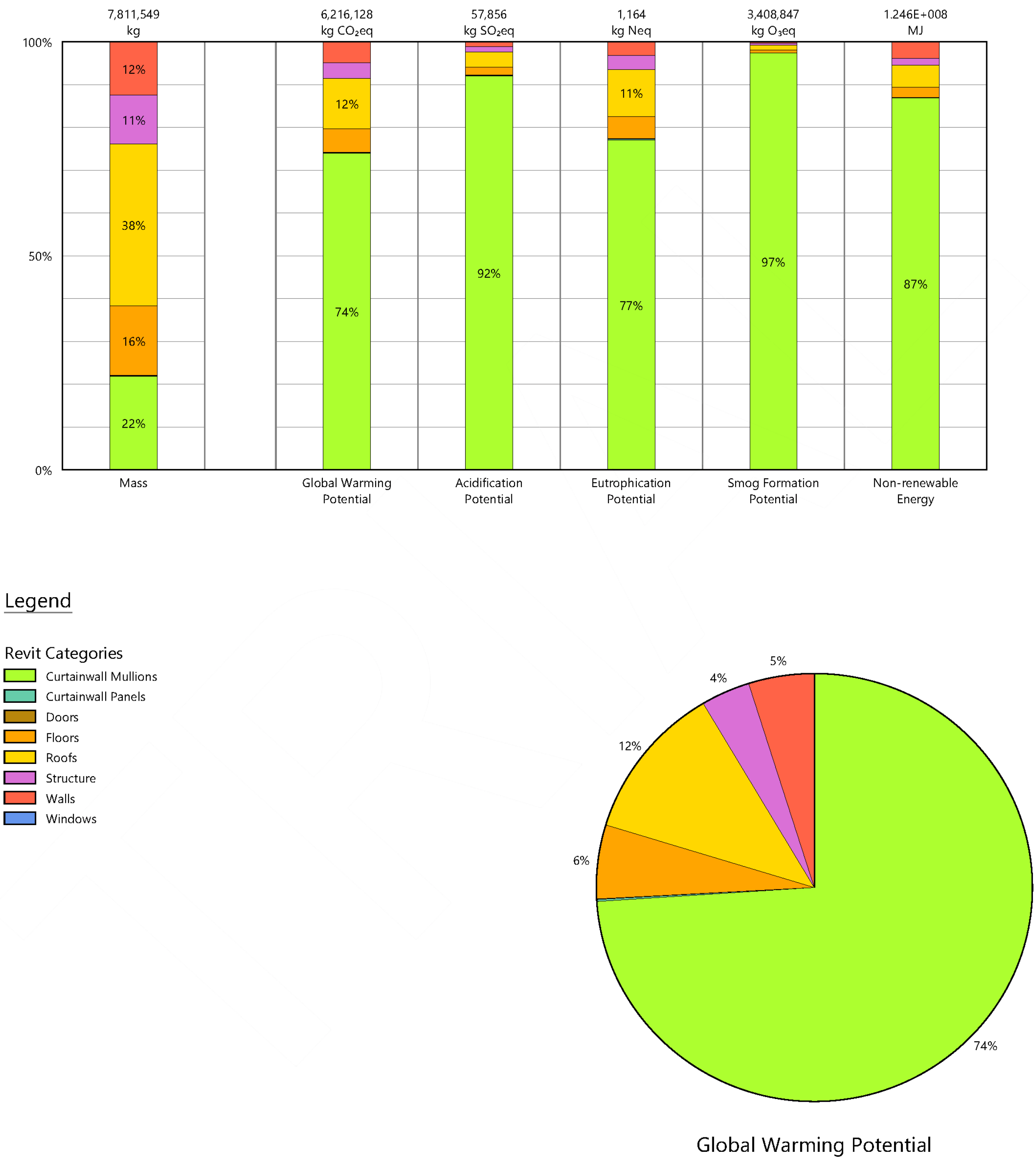


Figure 3.31 Results per Revit category.

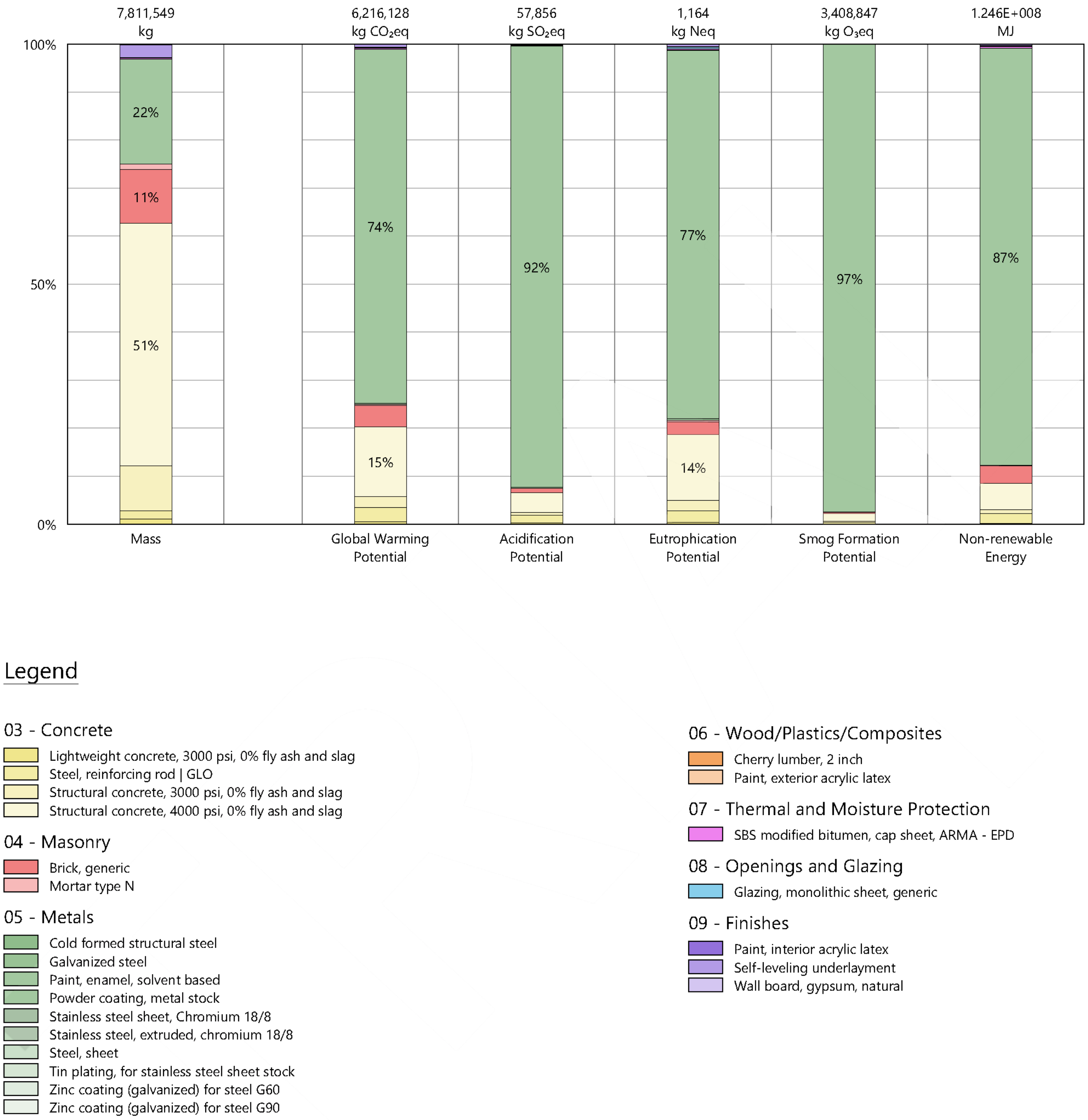


Figure 3.32 Results itemized by material.

3.7.4 Summary and Design Guidance

Collectively, these charts establish the warehouse's baseline carbon profile, clearly showing that the skylight system (Curtainwall Mullions in Revit) is a critical carbon hotspot, while the concrete structure and external walls, though having their own emissions, are relatively more stable in the existing condition and likely to be retained.

For the follow-up renovation design and carbon reduction efforts, first, focus on the skylight system. Consider using more sustainable materials, such as recycled metals for the mullions and low - emissive (Low - E) double - glazed glass instead of single - layer glass, to reduce the carbon emissions from the product stage and improve energy efficiency during the operational stage. Second, for the material - intensive stages like the product stage and maintenance stage, when replacing or maintaining components, prioritize low - carbon and recycled materials, such as using recycled steel and concrete with high fly - ash content. Third, in terms of operational energy, optimize the lighting and ventilation systems related to the skylight and the whole warehouse, introducing intelligent control systems to reduce unnecessary energy consumption. By targeting these key areas based on the life - cycle carbon assessment results, the carbon emissions of the warehouse can be effectively reduced while retaining the main structural features.

4. Adaptive Reuse Design for Building No.7

4.1 Preliminary Retrofit Concept: Functional Reprogramming and Window Optimization (Baseline Foundation)

Based on the development orientation of the site and the structural characteristics of Building No. 7, the preliminary retrofit concept centers on two core objectives: functional reprogramming and window system optimization.

From a functional perspective, the original use of the building as a single-purpose car depot resulted in low spatial efficiency and a lack of social engagement or mixed-use value. Its planned transformation into a university innovation hub offers the opportunity to introduce diverse programs such as maker studios, exhibition halls, training classrooms, co-working zones, and social lounges. A central courtyard is envisioned to act as a “Breath Point,” strengthening natural ventilation, daylight, and social interaction. By organizing circulation and spatial subdivisions rationally, it is possible to enhance flexibility and accessibility while preserving the main structural system. This reprogramming strategy will help activate the building’s public potential and support the construction of a knowledge-driven urban ecosystem.

Regarding window system optimization, the current building suffers from insufficient openings, resulting in limited natural ventilation and daylighting—particularly along the nearly sealed north and south façades, which contain only narrow clerestory strips. To meet future functional demands for daylight and thermal comfort, it is recommended to introduce large vertical window bands on the south façade, integrated with external operable shading systems to mitigate overheating. The east façade could feature horizontal ventilation strips to promote cross-ventilation. The existing roof skylights should be retained but upgraded to high-performance Low-E glass, combined with internal shading and thermally responsive opening mechanisms to enhance passive airflow and reduce energy consumption.

Overall, the retrofit strategy should respect the industrial identity of the original structure while embedding high-performance building envelopes, flexible space logic, and green design principles, achieving a synergy of cultural value, functional innovation, and environmental sustainability.

4.2 Conceptual design

4.2.1 Conceptual development

The conceptual design development of the warehouse retrofit is structured as a six-step process (Fig 4.1). The starting point is the existing linear warehouse, whose elongated form and reinforced concrete frame provides a robust spatial foundation. In the second step, the building volume is subdivided into functional bands, placing the lobby and exhibition hall towards the eastern entrance side, while positioning the Maker Studio and Co-working areas on the western side. A central courtyard is inserted as a “Breath Point” that connects the two ends.

In the third step, the courtyard is opened by removing its roof and walls, transforming it into an open-air void that enhances daylight, ventilation, and social interaction. To preserve and reinterpret the building’s industrial identity, the fourth step extracts the typology of the U-shaped precast roof modules as a key design element. This typology inspires the fifth step, in which a fabric canopy with a wavy geometry is introduced above the courtyard, echoing the rhythm of the original roof structure while generating a new layer of spatial quality. Finally, the sixth step brings together all interventions into a cohesive design integration, combining structural preservation, passive environmental strategies, and contemporary spatial interventions to establish an open, ecological, and socially engaging innovation hub.

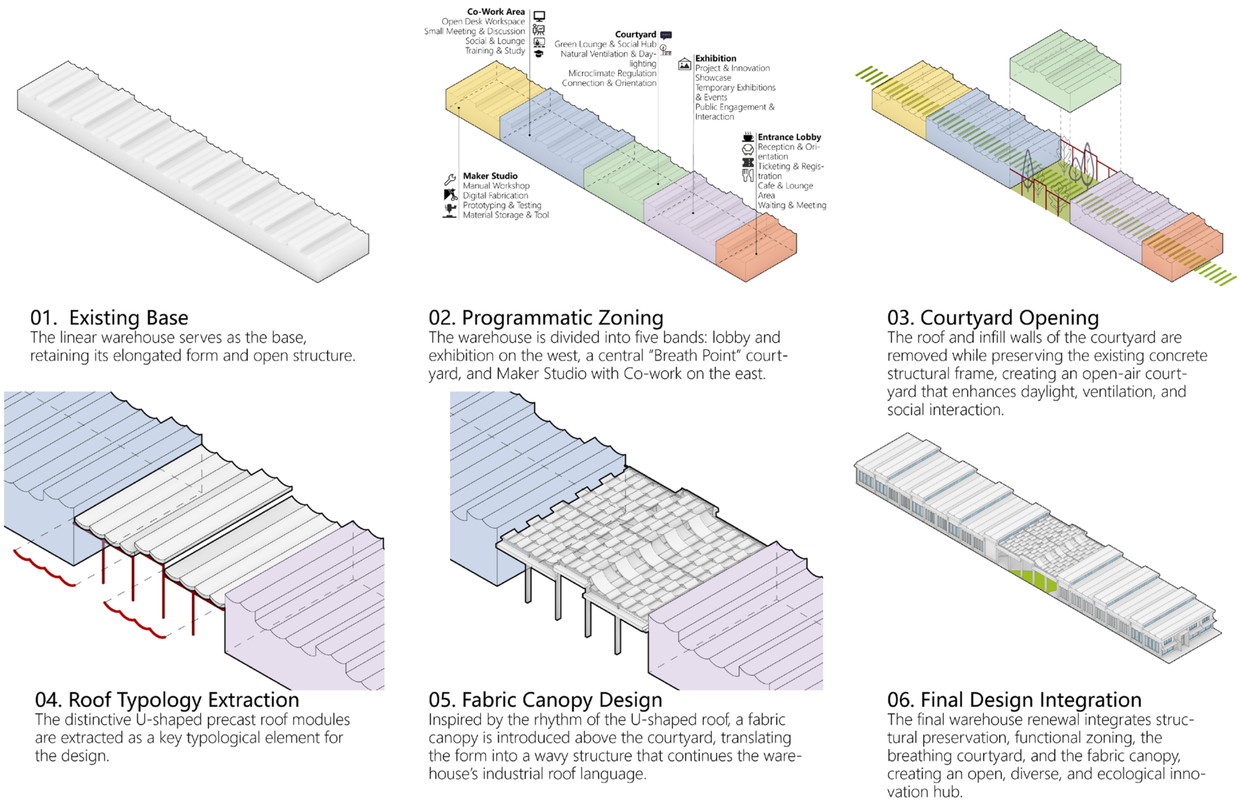


Figure 4.1 Conceptual design diagram.

4.2.2 *Functional zoning design*

The zoning diagram illustrates the spatial distribution of functions within the renovated warehouse (Fig 4.2). The overall layout follows a linear sequence from west to east, ensuring clarity of circulation and a balanced relationship between productive, social, and public functions.

On the western side, the Maker Studio and Co-work Area are placed in proximity, supporting innovation and collaboration. The Maker Studio accommodates digital fabrication, manual workshop, and prototyping activities, complemented by material storage and adjacent service facilities. The Co-work Area provides open desk workspaces, meeting rooms, and social lounges, fostering flexible collaboration and knowledge exchange.

At the center of the building, a Green Garden functions as a "Breath Point." This courtyard acts as a connective social hub, enhancing natural ventilation, daylight, and informal interactions. It establishes a transition between productive spaces in the west and public-oriented spaces in the east.

On the eastern side, the program opens towards the public with the Exhibition Hall and Entrance Hall. The Exhibition Hall is designed for project showcases, temporary events, and public engagement, while the Entrance Hall accommodates registration, ticketing, and service areas such as a café and restrooms. Together, they form the primary interface between the innovation hub and the wider community.

Overall, zoning ensures a clear gradient from productive innovation (west), through a green social connector (center), to public interaction (east), reflecting both functional efficiency and openness to community engagement.

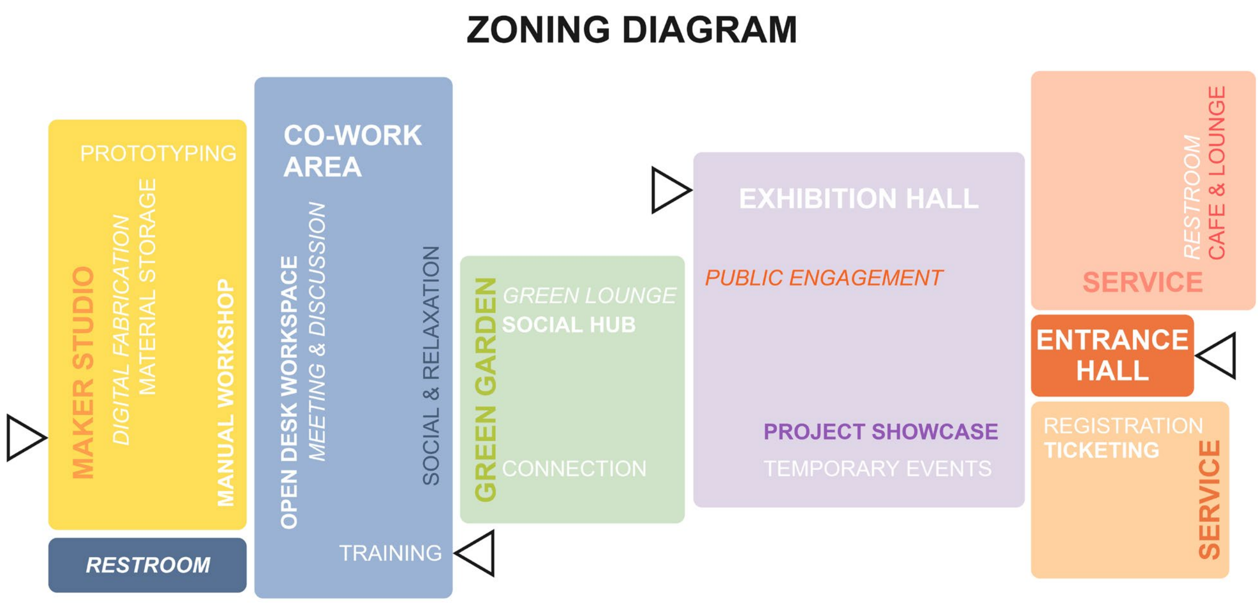
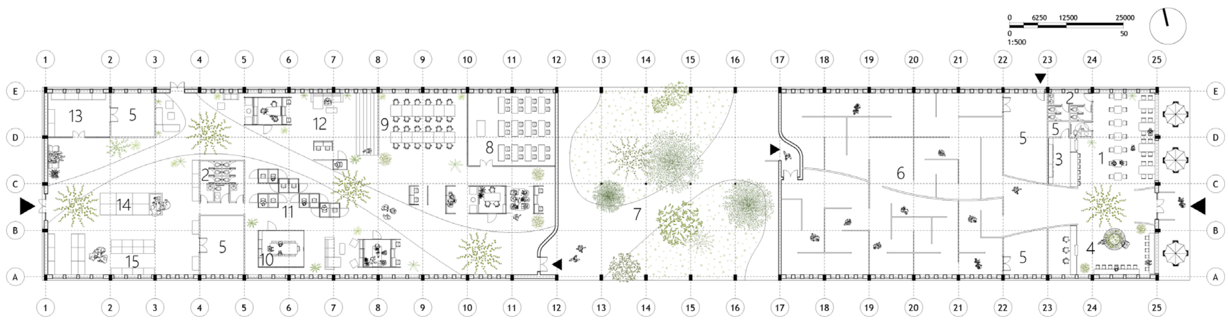


Figure 4.2 Zoning diagram.

4.3 Architectural Design Representation

4.3.1 Ground floor plan



1. Cafe
2. Washroom
3. Operating Area
4. Service & Registration
5. Storage Room
6. Exhibition Hall
7. Courtyard
8. Classroom
9. Open Work Area
10. Meeting Room
11. Study Area
12. Rest Area
13. Woodworking Area
14. Manual Area
15. 3D Printing Area

Figure 4.3 Ground floor plan.

The ground floor plan translates the adaptive reuse strategy into a coherent spatial configuration. The linear warehouse footprint is subdivided into distinct yet interconnected zones, with the entrance, service, and public functions positioned on the eastern side, providing direct accessibility for visitors. Adjacent to this entry sequence, the exhibition hall occupies a central position on the eastern half of the building, accompanied by dedicated storage rooms that support the flexible operation of the display space.

At the heart of the building, a courtyard garden forms a breathing space that introduces natural light and ventilation, while simultaneously serving as an informal gathering zone. Towards the west, the plan accommodates productive functions including the woodworking and manual workshops, the 3D printing area, and an open co-working space. These areas are complemented by meeting rooms to encourage collaboration, while a dedicated storage room adjacent to the woodworking area specifically supports the operation of the Maker Studio.

The circulation strategy follows a linear progression punctuated by transversal connections, guiding visitors from public-oriented functions in the east, through the central courtyard, to collaborative and productive spaces in the west. This arrangement enhances both the clarity of spatial organization and the functional synergy of the adaptive reuse proposal.

4.3.2 Building sections

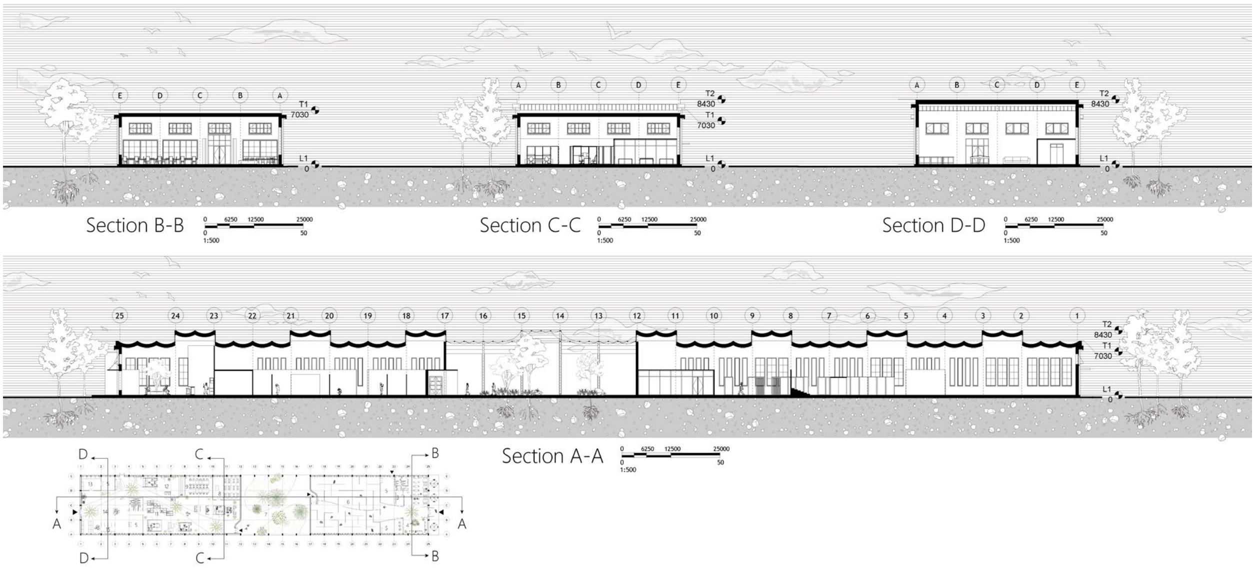


Figure 4.4 Building sections.

The sectional drawings reveal the spatial depth and vertical articulation of the adaptive reuse proposal. Section A–A, which cuts longitudinally through the building, highlights the rhythm of the precast U-shaped roof structure and demonstrates how the newly introduced courtyard transforms the linear warehouse into a porous and light-filled environment. The courtyard interrupts the continuity of the roof to create an open-air void, introducing daylight and natural ventilation while serving as a social connector between public and productive functions.

The transversal sections (B–B, C–C, and D–D) emphasize the interplay between the original clerestory windows and newly introduced openings, showing how daylight penetrates deep into the interior spaces. In particular, the sections through the entrance and exhibition hall illustrate a greater openness, while the western workshop areas maintain a more controlled light environment suited to making activities.

Overall, the sections demonstrate how the adaptive reuse strategy negotiates between the heritage structure and the new spatial interventions, creating an architectural language that balances functional performance with experiential quality.

4.3.3 Building elevations

The building elevations illustrate how the adaptive reuse proposal retains the industrial character of the warehouse while introducing new openings to enhance daylight and natural ventilation. The north and south façades are characterized by a regular rhythm of vertical window bands, replacing the original narrow clerestory strips. This intervention improves visual permeability and interior comfort while maintaining the modular order of the concrete frame.

On the east elevation, where the main entrance and public foyer are located, the façade design emphasizes accessibility and openness. While the original clerestory strip windows are retained as a reference to the industrial typology, larger openings are introduced at the entrance zone to accommodate the new public functions and improve visual connectivity with the exterior. Conversely, the west elevation adopts a more restrained language by largely maintaining the original clerestory strip windows, reflecting its role as the functional rear of the Maker Studio. This approach ensures adequate daylight and ventilation for workshop use while preserving the building's historic façade rhythm.

Overall, the elevations demonstrate a balance between heritage preservation and contemporary performance upgrades. The brick infill walls, and exposed concrete frames are retained as key industrial elements, while new fenestration strategies integrate environmental performance and spatial identity into the renewed architectural expression.

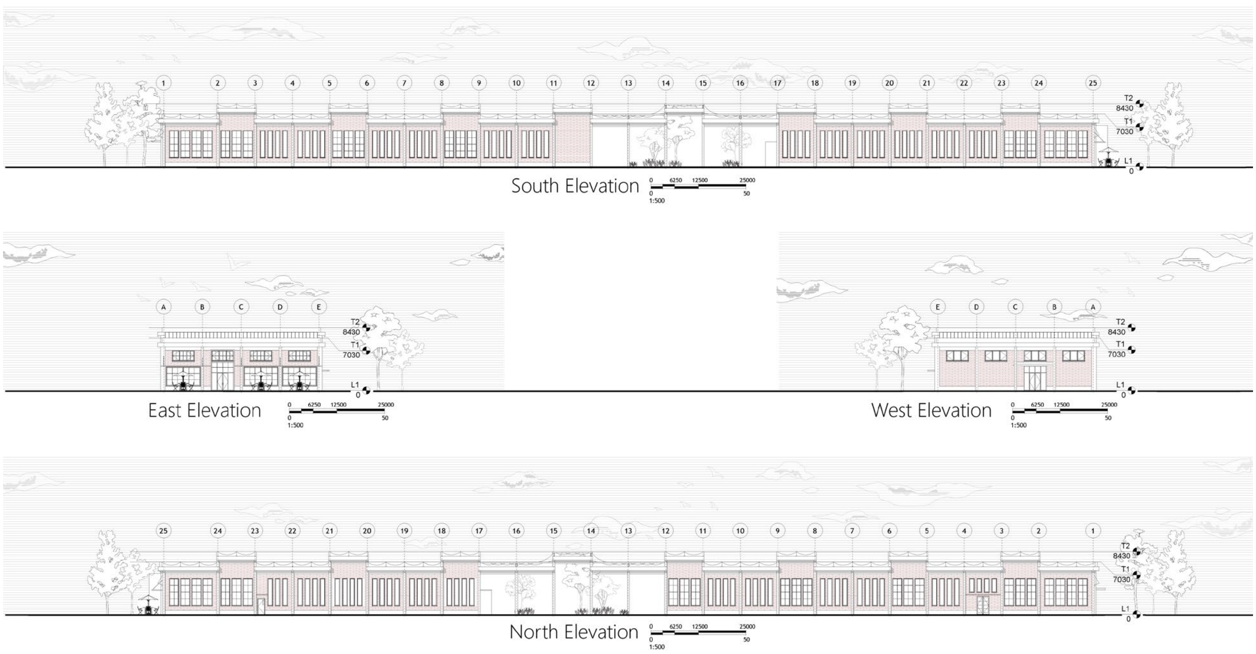


Figure 4.5 Building elevations.

4.3.4 Programmatic Axonometric Diagram

Entrance & exhibition space (Fig 4.6):

The entrance sequence is conceived as a welcoming threshold that mediates between the industrial exterior and the cultural interior. Upon arrival, visitors are introduced to a public café and seating area located adjacent to the entrance, which not only animates the threshold but also encourages informal gathering and social interaction before or after visiting the exhibitions.

From the entrance, circulation flows naturally into the main exhibition hall, where a flexible partition system organizes artworks into a sequence of enclosed and open viewing zones. This spatial arrangement generates diverse visual perspectives and supports adaptability for different curatorial requirements.

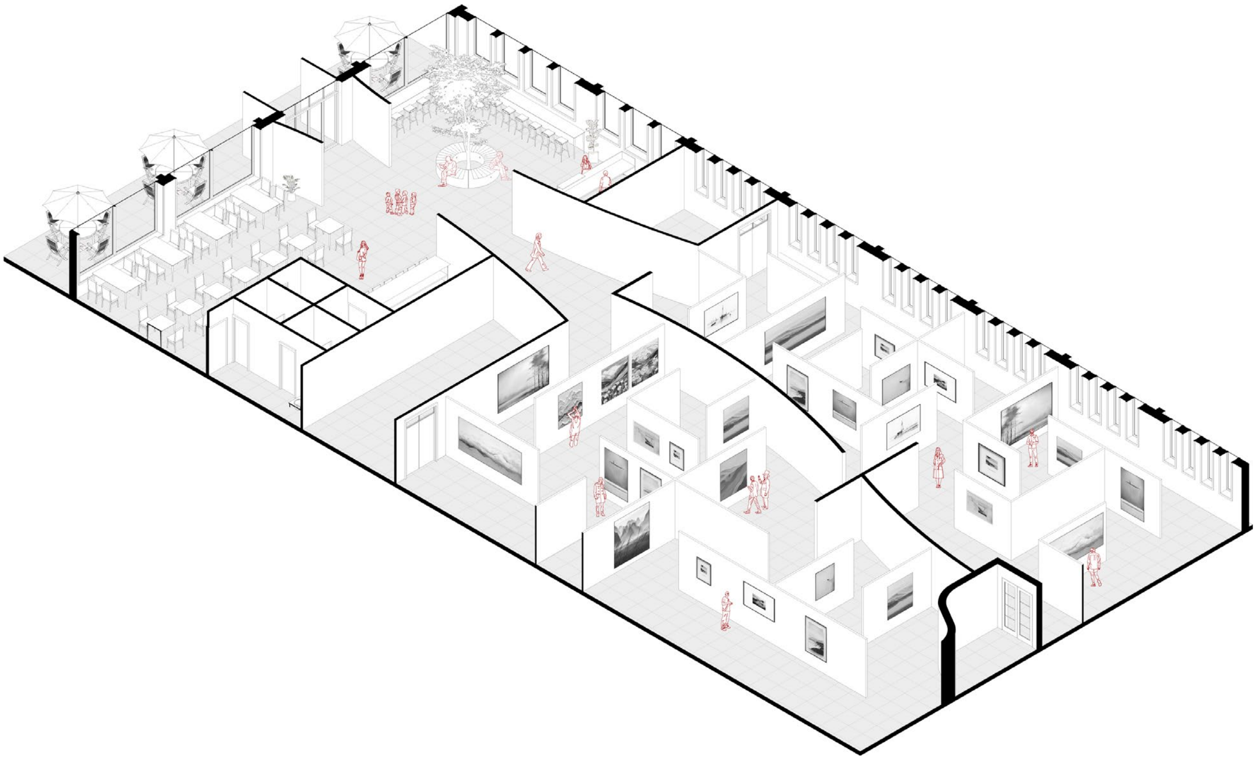


Figure 4.6 Axonometric diagram of entrance & exhibition space.

By combining a lively entrance café with contemplative exhibition galleries, the design establishes a balanced atmosphere—one that integrates cultural display with communal interaction, reinforcing the multifunctional identity of the building.

Green courtyard space (Fig 4.7):

The central courtyard is conceived as the breathing space of the building, providing natural light, ventilation, and a sense of openness within the dense warehouse fabric. By partially opening the roof and introducing greenery, the space transforms into a semi-outdoor garden that supports both ecological performance and social interaction.

The design carefully balances preservation and intervention. The original concrete structural frame is retained as a visible heritage element, while new wooden pillars and roof frames are inserted to support a lightweight fabric roof. This system provides shading and climatic comfort while maintaining permeability to air and daylight.

As a result, the courtyard functions as both a climatic regulator and a social hub, accommodating informal gatherings, exhibitions, and events, while reinforcing the adaptive reuse approach that integrates historical structure with contemporary environmental strategies.

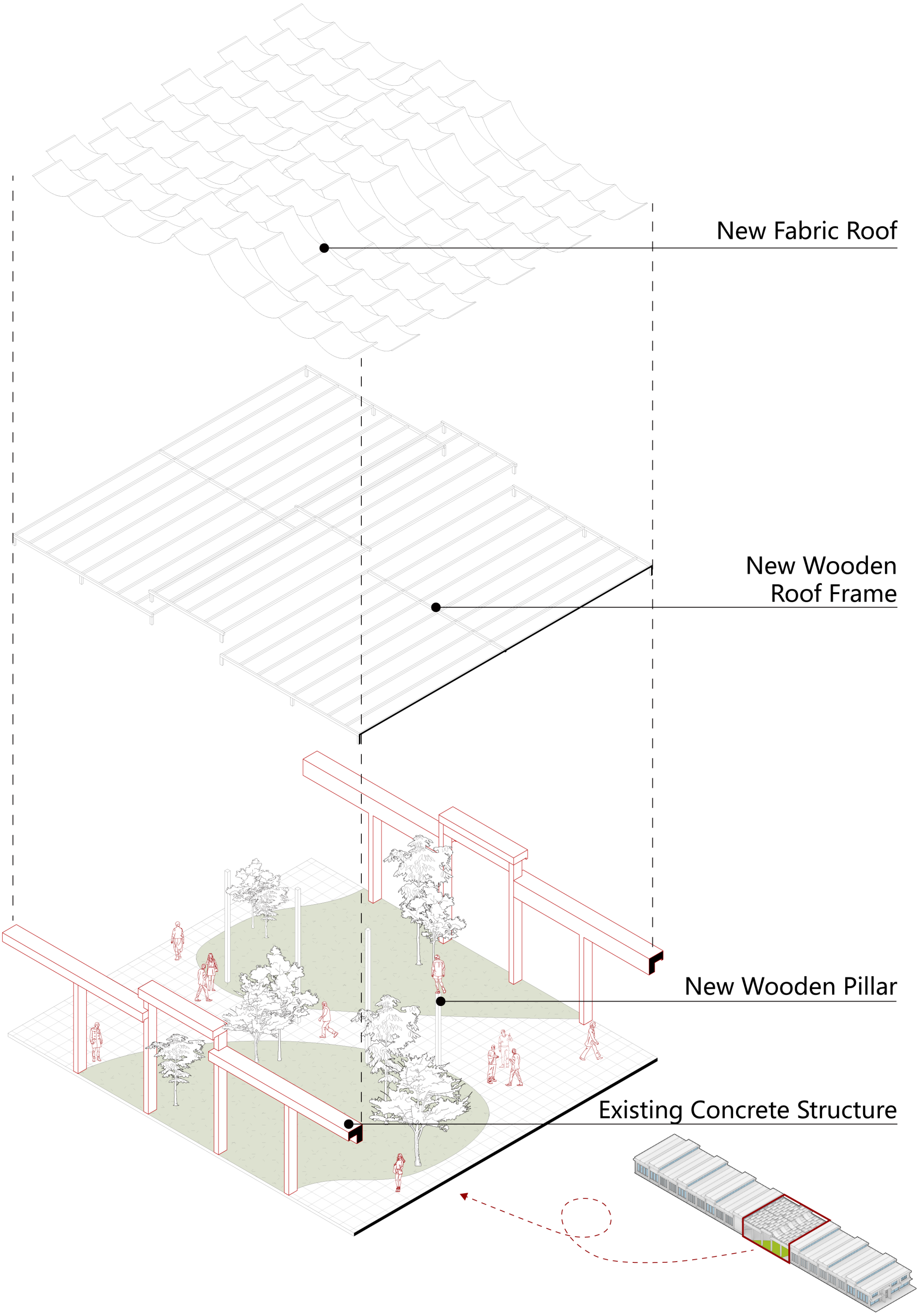


Figure 4.7 Axonometric explosion diagram of green courtyard.

Co-working & maker studio space (Fig 4.8):

The co-working and maker studio zone is designed as a flexible innovation environment that encourages collaboration, creativity, and knowledge exchange. The spatial layout integrates open-plan working areas, modular units, and informal meeting spots, allowing users to adapt the space to different project scales and activities.

A green linear strip traverses the interior, bringing natural elements into the workspace and reinforcing the continuity with the courtyard. This landscaped path functions not only as a circulation spine but also as a social connector, where spontaneous encounters and interdisciplinary interactions can occur.

The maker studio is equipped with workshops and fabrication spaces, directly accessible from the co-working areas, enabling a smooth workflow between conceptual development and hands-on production. By combining greenery, collaborative spaces, and production facilities, the design supports a dynamic and multifunctional innovation hub within the reused warehouse structure.

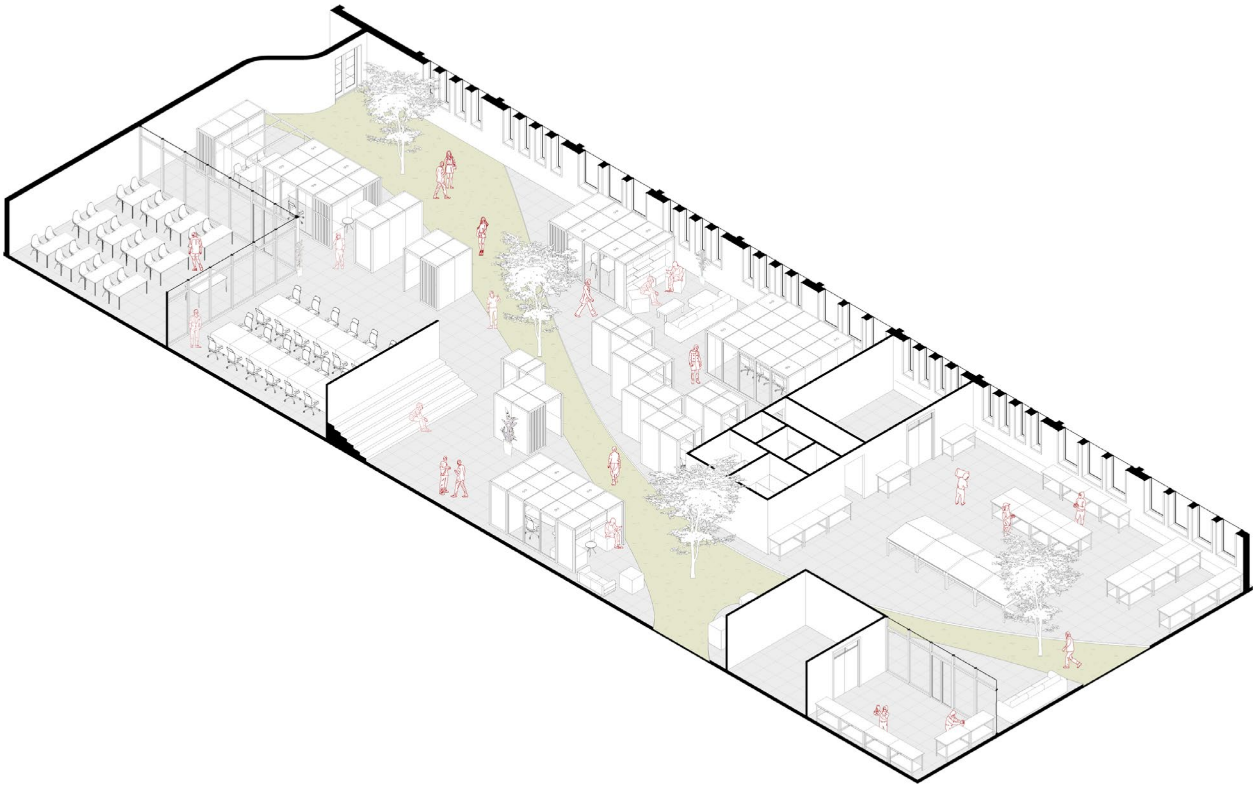


Figure 4.8 Axonometric diagram of co-working & maker studio space.

4.4 *Architectural renderings*

4.4.1 Entrance outside

This perspective (Fig 4.9) depicts the main entrance of Building No. 7, where the original concrete frame and brick infill—together with the existing graffiti murals—are preserved as part of the industrial heritage. A new public forecourt with outdoor seating enhances accessibility and fosters interaction between the reused warehouse and the surrounding urban context.

Figure 4.9 Perspective view of main entrance of Building No.7.

4.4.2 Entrance hall

This perspective (Fig 4.10) depicts the transformed entrance hall of Building No. 7. The original U-shaped precast concrete roof panels and industrial windows are preserved to retain architectural character, while the adaptive reuse introduces a bright foyer that combines skylight-driven daylight, indoor greenery, and flexible exhibition elements to enrich user experience and articulate the dialogue between heritage and contemporary intervention.

Figure 4.10 Perspective view of entrance hall.

4.4.3 Exhibition hall

This perspective (Fig 4.11) depicts Building No. 7 adapted as an exhibition hall. The preserved U-shaped precast concrete roof panels with continuous skylights provide abundant natural light, while new freestanding partitions enable flexible curatorial layouts; the original structural framework sustains the industrial identity and supports public engagement and cultural programming.

Figure 4.11 Perspective view of exhibition hall.

4.4.4 Green courtyard

This perspective (Fig 4.12) depicts the newly inserted green courtyard—conceived as a "breathing point" at the center of Building No. 7. The existing reinforced-concrete frame is retained as the spatial skeleton, and a lightweight timber framework with a fabric canopy modulates sunlight and microclimate, creating a shaded lawn and seating that support everyday use, small exhibitions, and informal gatherings within the reused envelope.

Figure 4.12 Perspective view of green courtyard.

4.4.5 Co-working space

This perspective (Fig 4.13) depicts Building No. 7 adapted as a co-working environment. The preserved U-shaped precast concrete roof panels and continuous clerestory windows secure generous daylighting, while modular prefabricated units organize the open hall into distinct working and meeting areas; these lightweight, reconfigurable components ensure future adaptability for entrepreneurial, academic, and collaborative activities.

Figure 4.13 Perspective view of co-working space.

4.4.6 Maker studio area

This perspective (Fig 4.14) depicts Building No. 7 adapted as a maker studio. The preserved U-shaped precast concrete roof panels and continuous clerestory glazing supply ample natural light, and the open-plan arrangement accommodates digital fabrication and manual prototyping; integrated greenery and informal seating enhance comfort and social interaction, establishing a multifunctional setting for collaborative production within the industrial framework.

Figure 4.14 Perspective view of maker studio area.

4.5 Envelope retrofit scenarios

4.5.1 Rationale for selection of external wall scenarios

The external walls of Building No. 7 are constructed of red brick infill combined with exposed reinforced-concrete frames, typical of 1920s industrial warehouses in Bologna. Although structurally stable, the walls exhibit poor thermal resistance and contribute significantly to heat losses in winter. Four scenarios are selected for comparison:

1. Baseline (Original wall): 380 mm brick with plaster finish, representing the existing condition.
2. Internal insulation: A cost-effective retrofit option, widely adopted in practice, but associated with condensation and thermal bridge risks.
3. External insulation (ETICS-type system with cladding): The most common retrofit method in Europe, ensuring continuity of the insulation layer and improved thermal stability. In this case, the external

insulation is combined with a ventilated cladding system using brick-like veneer panels or metal finishes, to preserve the industrial aesthetic of the original red-brick façade.

4. Double-wall system: An additional cavity wall with brick veneer, balancing thermal upgrading with heritage protection of the original industrial façade.

4.5.2 External wall structural composition & retrofit options

The four wall scenarios were modeled with detailed layered assemblies as follows:

1. Baseline: A single-leaf 380 mm solid red brick wall with interior plaster finish, representing the existing condition of Building No. 7. (Fig 4.16)

Internal insulation: The 380 mm red brick wall is supplemented on the interior side with a 20 mm gypsum board finish, a vapor retarder, a 90 mm flexible rock wool batt, and a 30 mm rigid mineral wool board, separated from the brick by a 20 mm service air gap. (Fig 4.17)

2. External insulation: The 380 mm red brick wall is upgraded externally with a ventilated cladding system consisting of a 30 mm brick veneer slip mounted on a 10 mm cementitious backer board, followed by a 40 mm ventilated air cavity, a 30 mm rigid mineral wool board, and a 90 mm rock wool batt. The interior retains the vapor retarder and 20 mm gypsum board finish. (Fig 4.18)

3. Double-wall system: A new cavity wall is added to the 380 mm red brick structure, comprising a 120 mm rock wool insulation layer, a 100 mm lightweight concrete block, and an air infiltration barrier, finished internally with a vapor retarder and 20 mm gypsum board. This configuration enhances thermal resistance while preserving the industrial aesthetic through the external brick façade. (Fig 4.19)

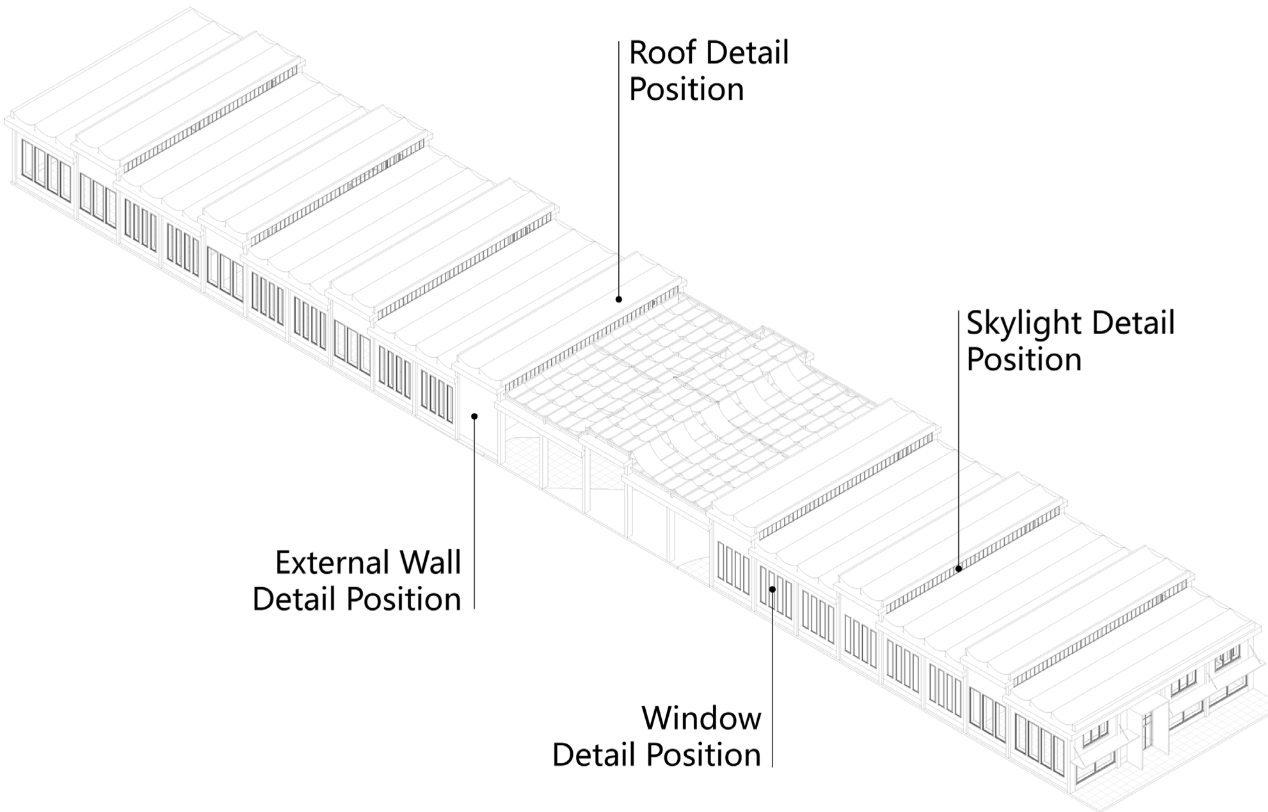


Figure 4.15 Envelope detail position.

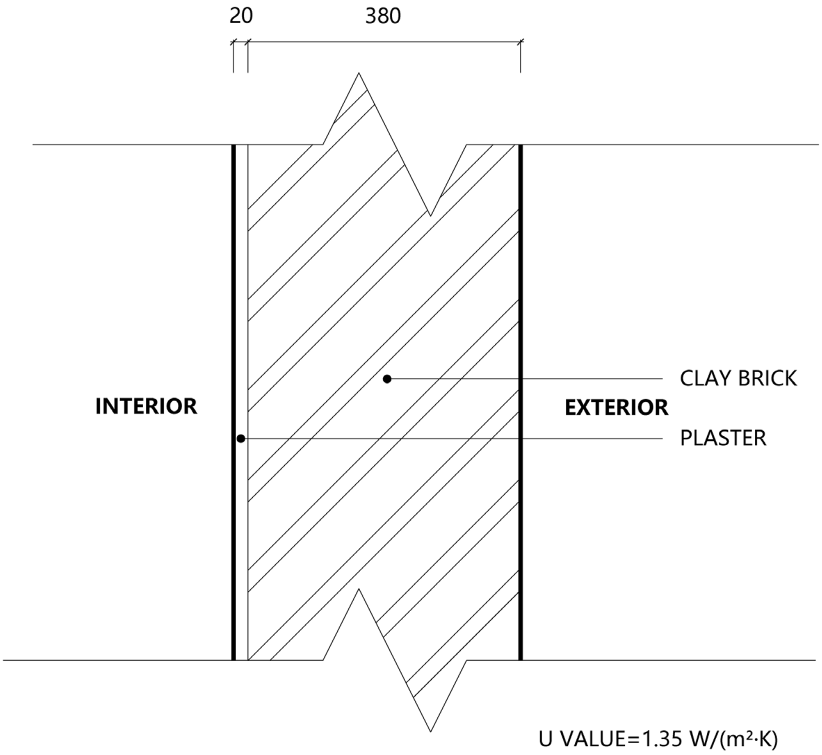


Figure 4.16 Baseline wall details.

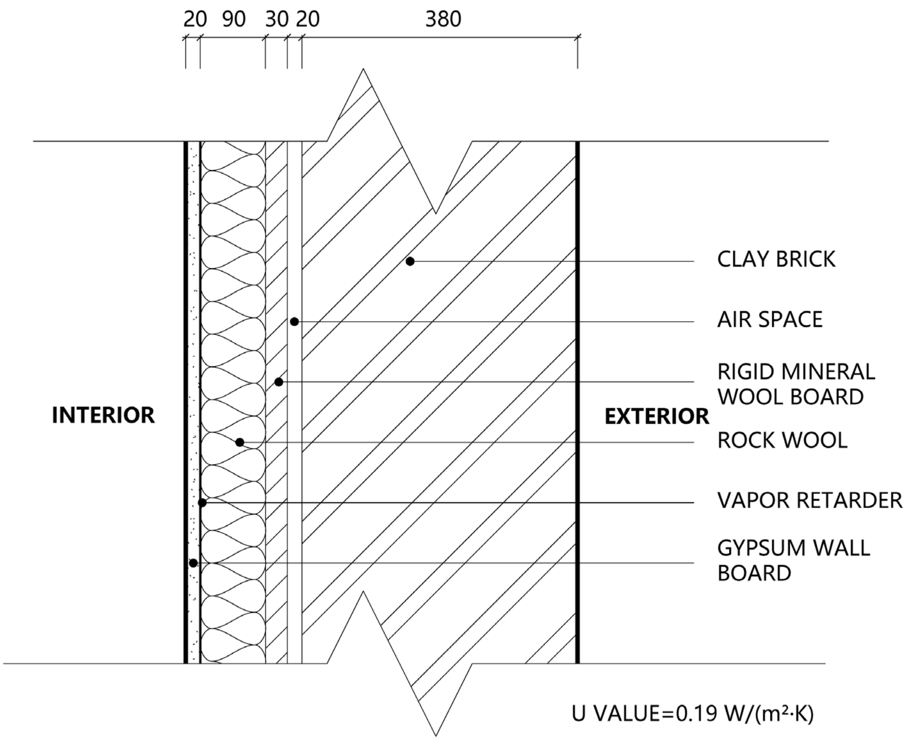


Figure 4.17 Internal insulation wall details.

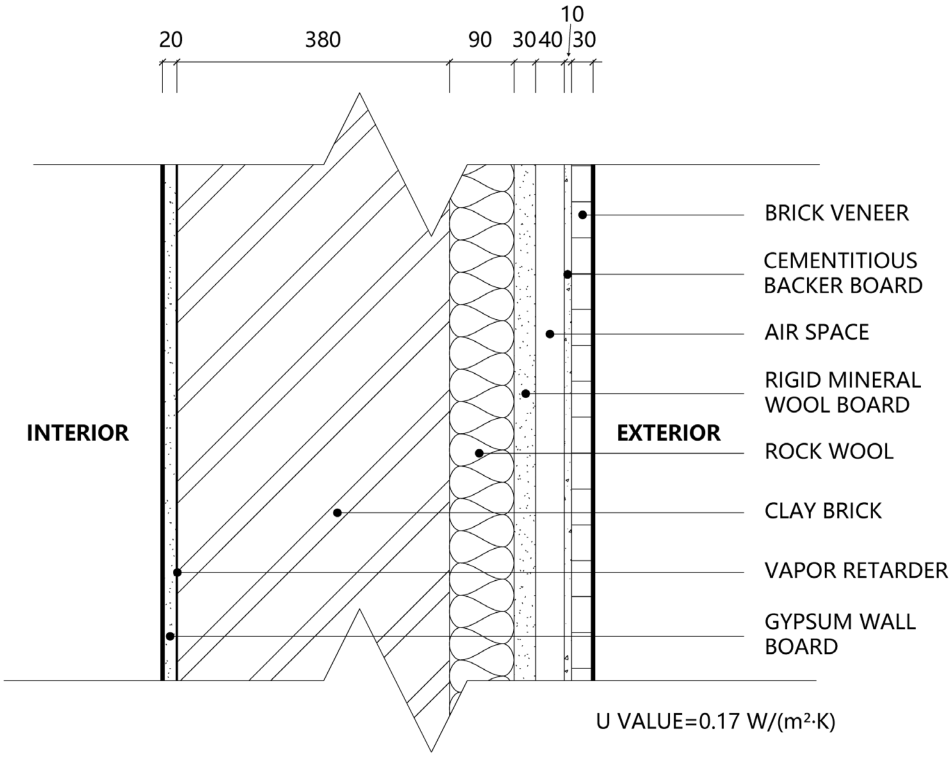


Figure 4.18 External insulation details.

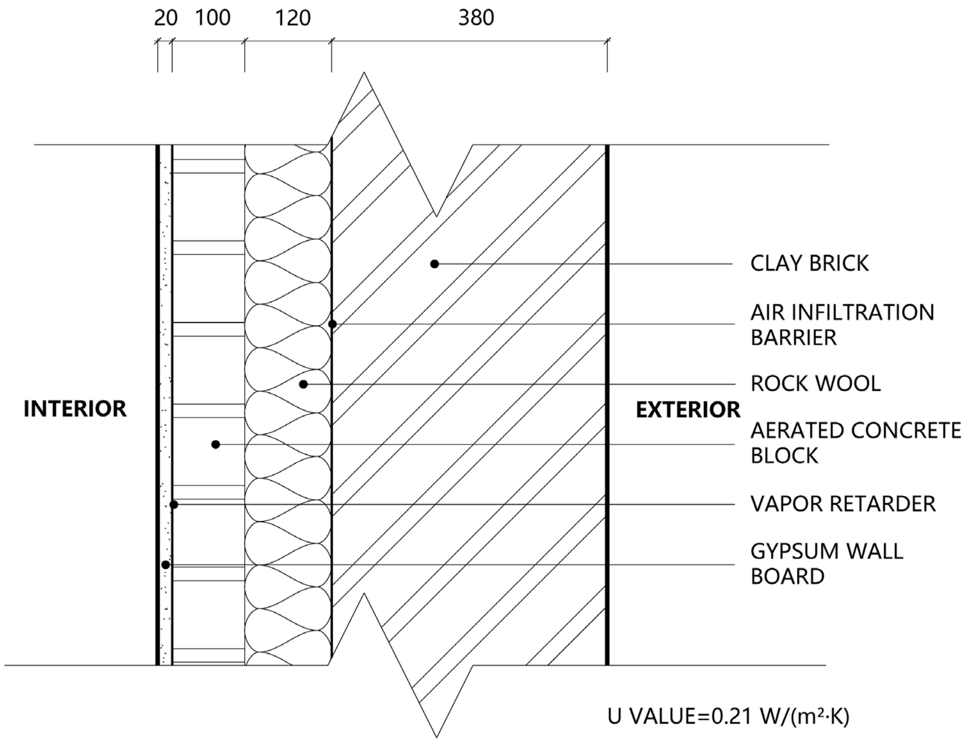


Figure 4.19 Double-wall system details.

4.5.3 Rationale for selection of window scenarios

To ensure representativeness and practical relevance, three options are assessed:

1. Baseline (single glazing): represents the existing low-performance window with higher heat loss/infiltration; used as the reference.
2. Double glazing: common, cost-effective retrofit reducing U-value and condensation risk; heritage-friendly.
3. Triple glazing: further lowers winter heat loss/cold-radiation and improves acoustics; tests the performance–embodied trade-off.

Dataset note: For the baseline scenario, a PVC-framed single-glazed window dataset was used in One Click LCA as a substitute for the original metal frame, since no dataset for metal single glazing was available.

4.5.4 Window structural composition & retrofit options

1. Baseline — single glazing (Metal frame): Single-pane glass in a PVC window frame with concrete windowsill integrated into the external wall. Uw $\approx$ 5.0 $W \cdot m^{-2} \cdot K^{-1}$. (Fig 4.20)
2. Double glazing — insulated glass unit (aluminum frame): Two panes separated by an air cavity (IGU), set in a thermally broken aluminum frame with concrete windowsill and wall connection. Uw $\approx$ 1.4 $W \cdot m^{-2} \cdot K^{-1}$. (Fig 4.21)
3. Triple glazing — three-pane IGU (aluminum frame): Three panes with two air cavities (3-pane IGU), installed in a thermally broken aluminum frame with concrete windowsill and wall connection. Uw $\approx$ 1.0 $W \cdot m^{-2} \cdot K^{-1}$. (Fig 4.22)

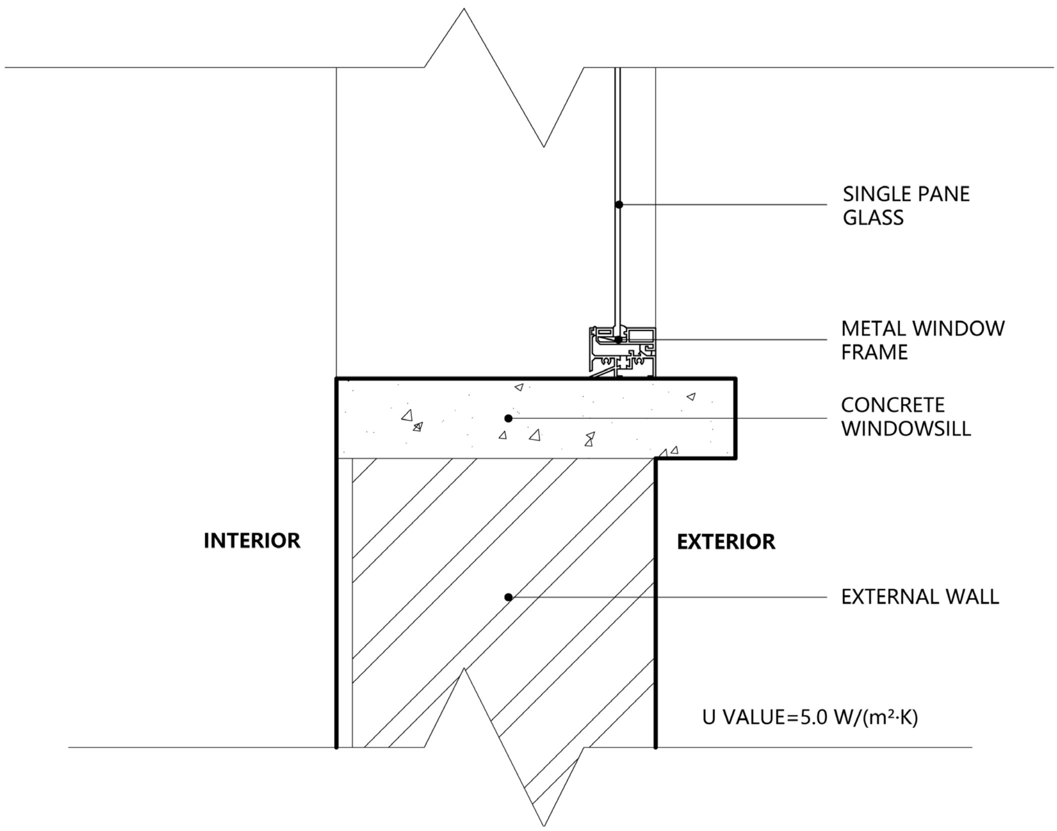


Figure 4.20 Baseline window details.

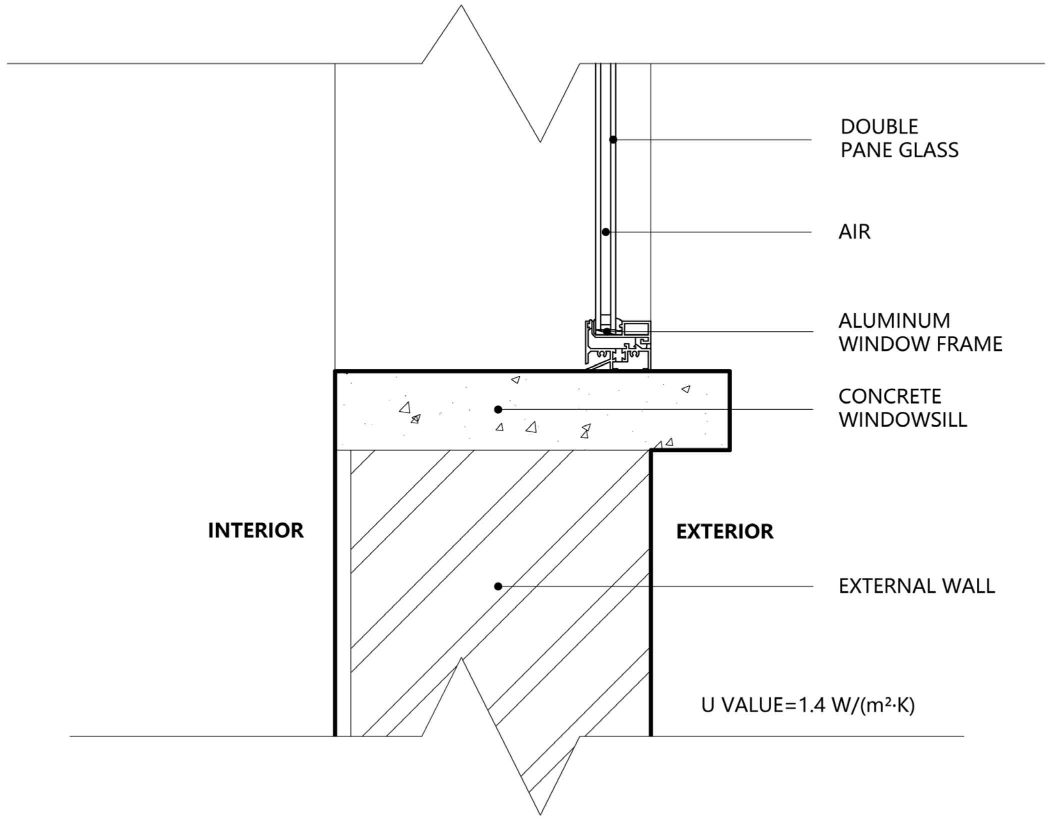


Figure 4.21 Double-glazed window details.

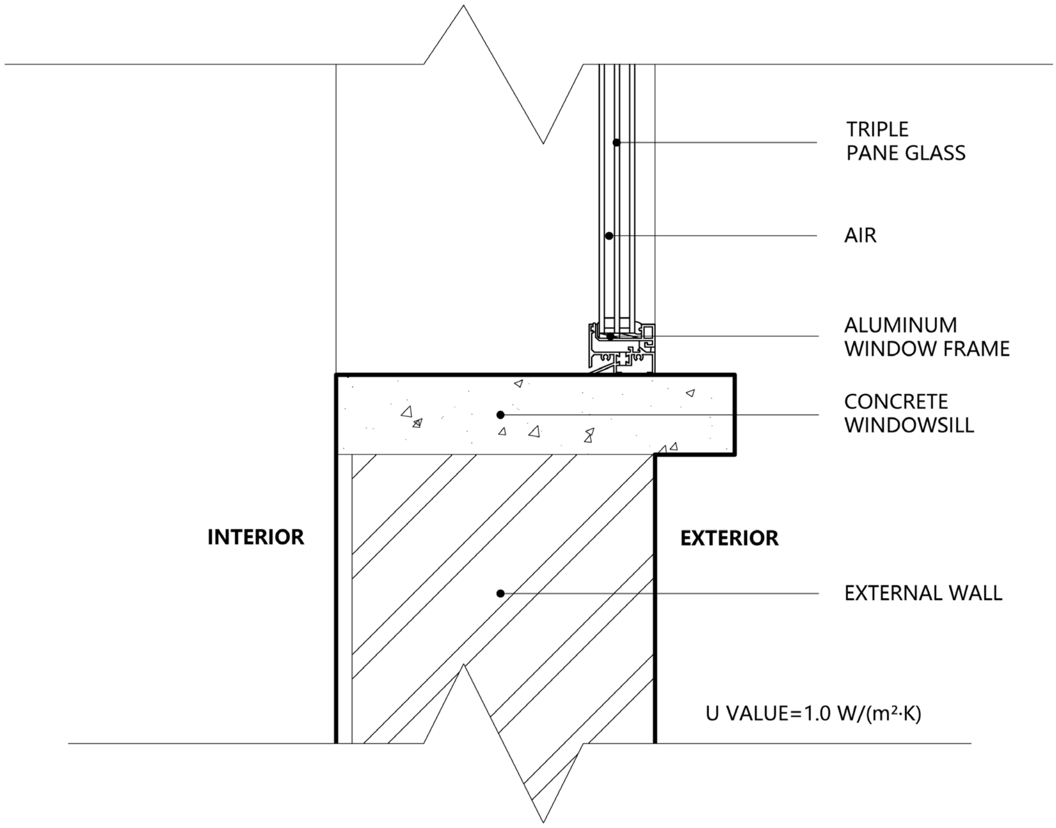


Figure 4.22 Triple-glazed window details.

4.5.5 Sunshade solution of window

To preserve the industrial façade while managing glare and summer gains, the project adopts internal adjustable blinds behind the preserved windows. The measure is reversible, minimally intrusive, and compatible with exhibition use; it can be scheduled to close under high irradiance during occupancy to curb cooling loads while allowing winter solar gains.

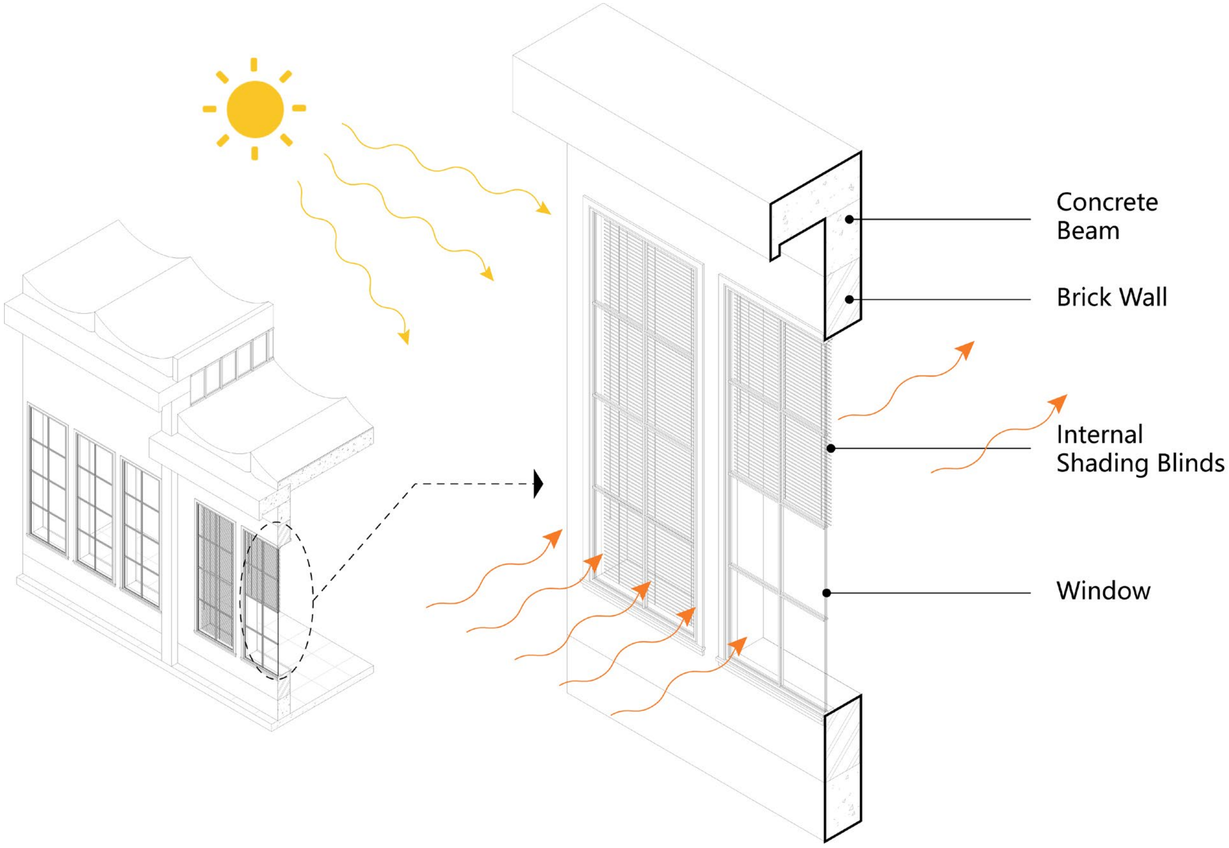


Figure 4.23 Sunshade details.

4.5.6 Rationale for selection of skylight scenarios

For skylight part, there are three scenarios selected as well.

1. Baseline (single-glazed skylight). The as-found roof light of Building No. 7: a curb-mounted metal frame with a single glass pane and limited airtightness. While it preserves the original roofscape, it exhibits poor thermal performance and a high risk of condensation and uncontrolled solar gains.
2. Double-glazed skylight. The most cost-effective retrofit: markedly lower U-value and improved condensation resistance, while keeping the original module size and appearance—suitable for heritage contexts.

Triple-glazed skylight. Further reduces heat loss and cold radiant asymmetry in winter and improves acoustic insulation; however, it adds weight and embodied carbon. Included to test the “higher operational benefit vs higher embodied carbon” trade-off.

4.5.7 Skylight structural composition & retrofit options

The existing skylight is a vertical strip set between the reinforced-concrete roof beam and the U-shaped roof shells. All options use an aluminum frame fixed to the concrete beam/roof curb; airtightness and geometry are kept constant.

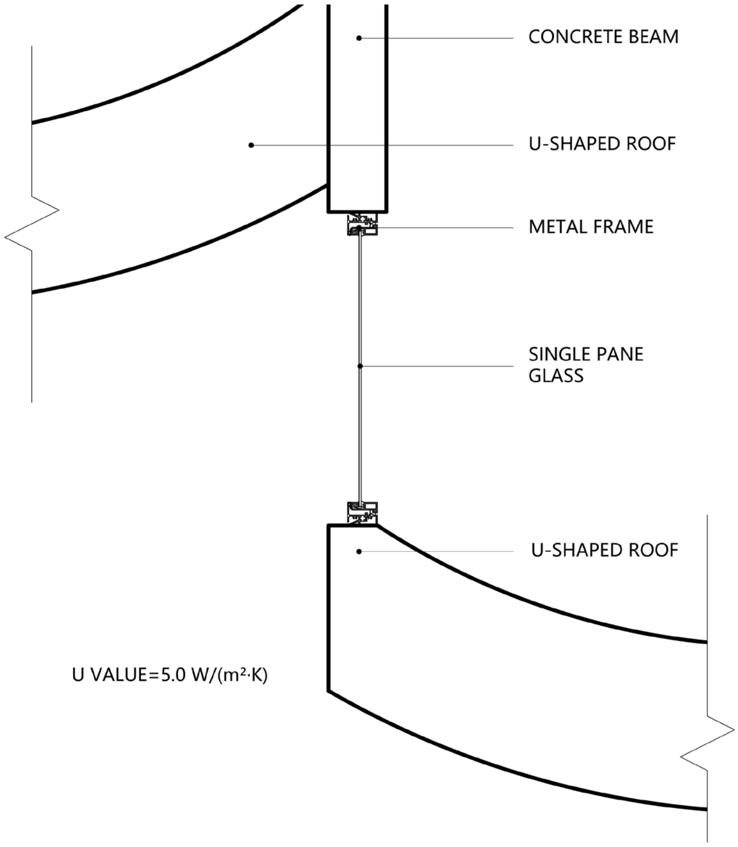


Figure 4.24 Baseline skylight details.

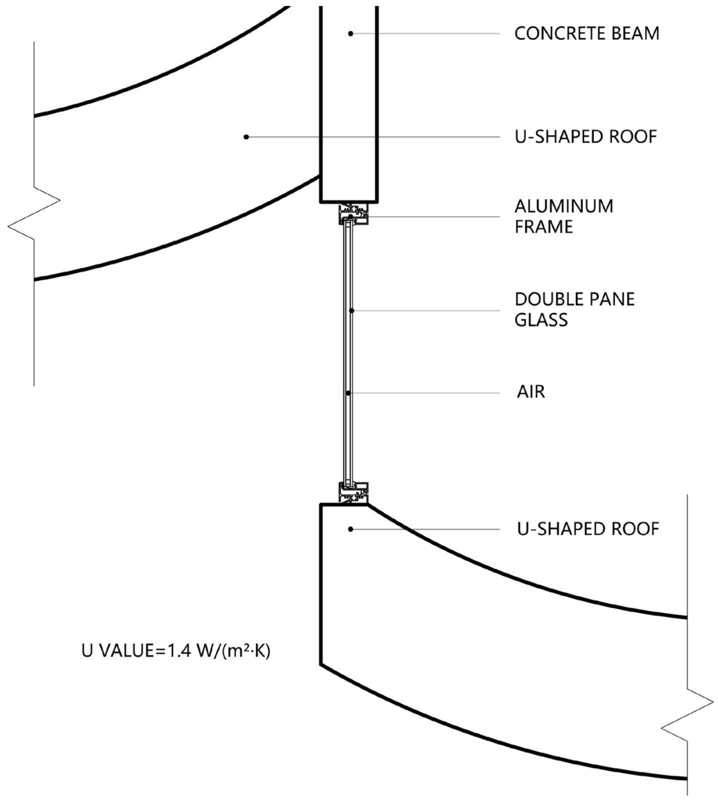


Figure 4.25 Double-glazed skylight details.

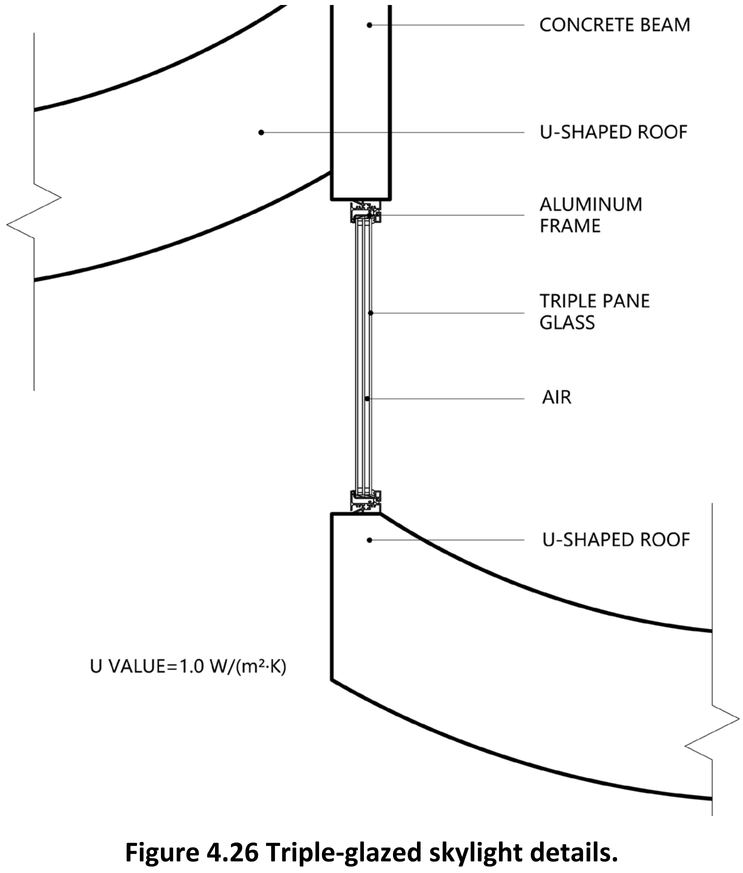


Figure 4.26 Triple-glazed skylight details.

1. Baseline – single-glazed skylight: Single pane set in a curb-mounted metal frame (Fig 4.24); installed between the concrete beam and U-shaped roof deck. Whole-window U-value (Uw): 5.0 W/m²·K.
2. Double-glazed skylight: Insulated glazing unit (double pane with one air cavity) in an aluminum frame (Fig 4.25); fixed between the concrete beam and roof curb. Uw: 1.4 W/m²·K.
3. Triple-glazed skylight: Insulated glazing unit (triple pane with two air cavities) in an aluminum frame (Fig 4.26); fixed between the concrete beam and roof curb. Uw: 1.0 W/m²·K

In One Click LCA, the baseline and double-glazed skylights are represented with generic/market-average skylight datasets (frame material not explicitly specified), whereas the triple-glazed option uses an aluminum-framed fixed glass skylight dataset. In the architectural details, however, the baseline is illustrated with a metal frame for consistency, while embodied-carbon results strictly follow the selected datasets.

4.5.8 Rationale for selection of roof scenarios

The roof was included in the retrofit analysis due to its large surface area and its dominant role in heat transfer and daylighting. The existing precast concrete roof panels afford minimal insulation, driving high heating demand. Accordingly, a PIR-insulated roof upgrade— adding continuous polyisocyanurate insulation above the existing concrete panels while preserving the original structure—was selected for comparison against the baseline.

4.5.9 Roof structural composition & retrofit options

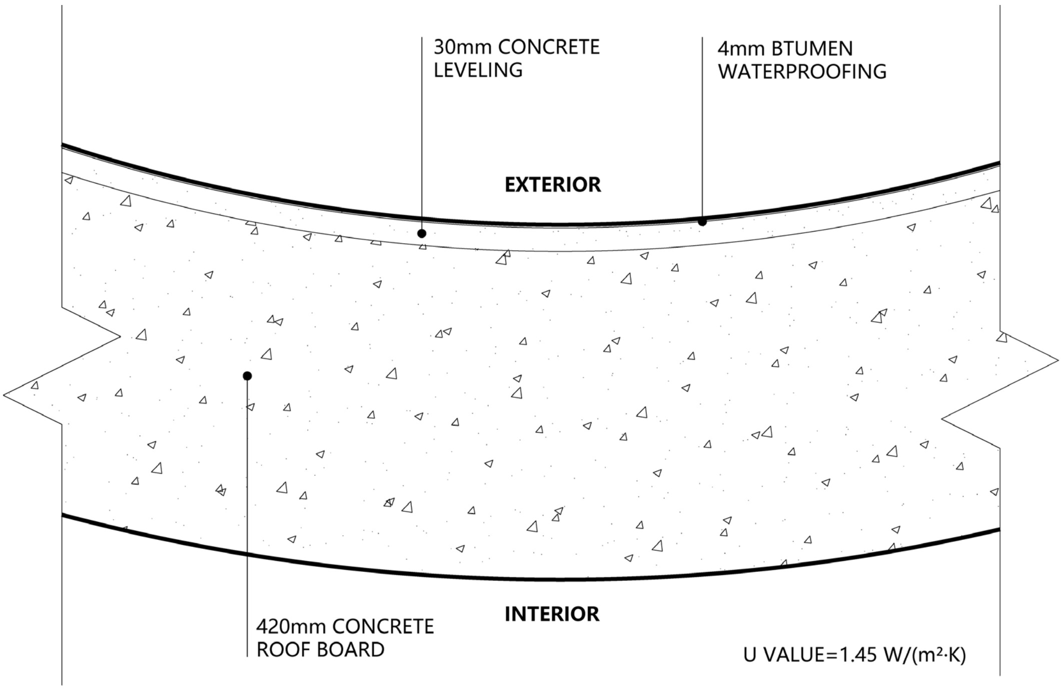


Figure 4.27 Baseline roof details.

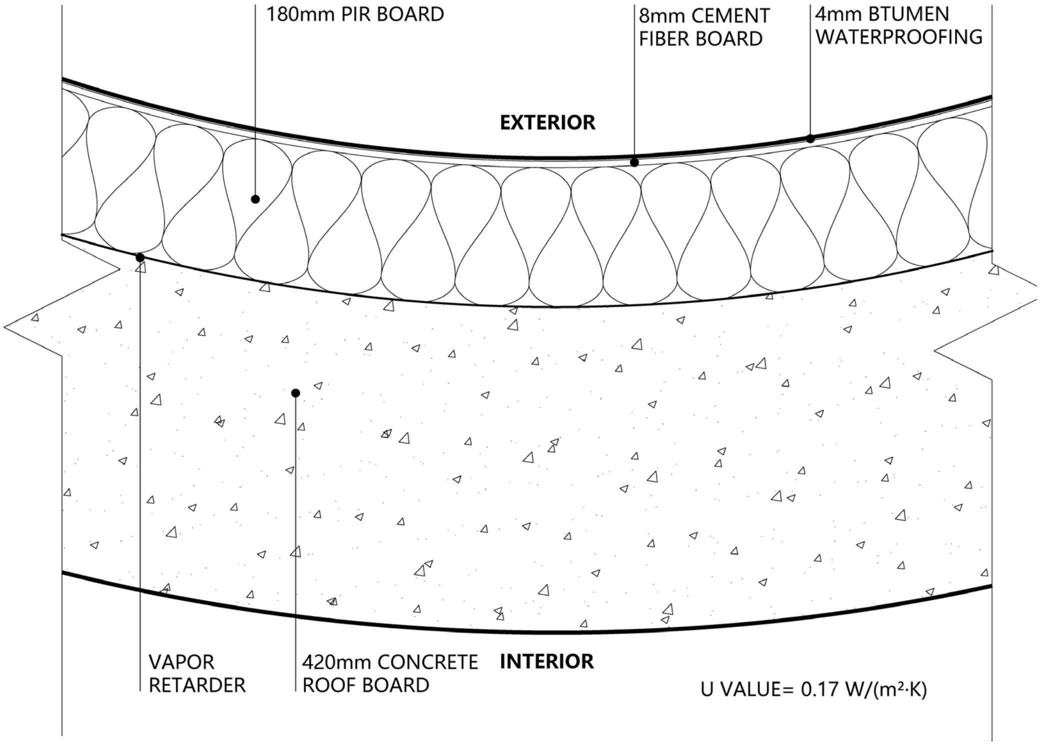


Figure 4.28 Roof improvement details.

1. Baseline roof: 4 mm bitumen waterproofing + 30 mm concrete leveling screed over 420 mm precast concrete roof panel (U $\approx$ 1.45 $W \cdot m^{-2} \cdot K^{-1}$; Fig. 4.27). The assembly has high thermal transmittance and relies almost entirely on the concrete's thermal mass, with little insulation.
2. Retrofit option — PIR-insulated overlay: 4 mm bitumen waterproofing + 8 mm cement fiber board (substrate) + 180 mm PIR board (polyisocyanurate, continuous) + vapor retarder + 420 mm precast concrete roof panel (U $\approx$ 0.17 $W \cdot m^{-2} \cdot K^{-1}$; Fig. 4.28). The PIR layer is placed above the existing structure as a continuous thermal envelope, with the vapor retarder on the warm side to control interstitial condensation.

The retrofit preserves the original U-shaped precast concrete roof while drastically lowering heat transfer ($\approx$ 88% reduction in U-value versus baseline) and improving hygrothermal robustness, with minimal intervention to the primary structure.

5. Comparative Analysis of Envelope Retrofit Scenarios

5.1 Introduction

This chapter reports simulation-only comparisons of envelope retrofit scenarios for Building No. 7. Detailed construction assemblies and design rationales are documented in Chapter 4 and are not repeated here; Chapter 5 focuses strictly on performance outcomes.

Scope and baseline.

The baseline corresponds to the as-found envelope of Building No. 7 (external walls, windows, skylights, roof). All results are normalized to the functional unit of 1 m² gross floor area over 50 years; whole-building totals are provided in the appendix.

Method overview.

A combined workflow is used: (i) dynamic energy simulation with Honeybee (Energy Plus); (ii) life-cycle carbon assessment with One Click LCA. To ensure clean attribution, a single-variable testing strategy is adopted: when one envelope component is modified, all other components remain at baseline in the energy model; in the LCA, only the embodied impacts of the tested component are counted for that comparison, while operational carbon (B6) is added from the corresponding Honeybee results for the whole building over 50 years.

System boundaries and assumptions.

LCA covers A1–A5 (product + construction) and B2–B5 / C1–C4 where applicable; Module D is reported separately and excluded from totals. Service lives and maintenance/replacement rates follow the datasets/EPDs used in One Click LCA. When an exact product is unavailable, a functionally equivalent proxy is used and identified in the relevant subsection (e.g., baseline single glazing with a PVC-frame proxy).

Fixed simulation inputs.

To isolate envelope effects, internal loads, schedules, HVAC/system type, set-points, infiltration/airtightness, and control logic remain constant across all runs; the same Bologna climate file is used for every case.

Indicators.

Energy: Energy Use Intensity (kWh/m²·year).

Carbon: GWP, $kgCO_2e/m^2 \cdot 50$ years, combining embodied carbon (as above) and operational carbon (B6) derived from the energy results using consistent emission factors.

Chapter structure.

Section 5.2–5.5 evaluate, respectively, external walls, windows, skylights, and roof, each presenting options, simulation outputs, and a short comparison. Section 5.6 synthesizes an integrated optimal envelope by combining the best-performing strategies.

To ensure clarity in the comparative analysis, Fig 5.1 summarizes the baseline conditions and the proposed retrofit scenarios for each envelope component (external wall, window, skylight, and roof). The table consolidates structural compositions with their thermal transmittance (U-value), energy demand (EUI), and life-cycle carbon performance, serving as the reference framework for the subsequent analysis.

As illustrated, all retrofit scenarios achieve notable reductions in U-values compared to the baseline, with corresponding improvements in energy efficiency and total carbon performance. These aspects are further discussed in Sections 5.2–5.5.

	PERFORMANCE INDICATORS							
ENVELOPE COMPONENT	**SCENARIOS**		**STRUCTURAL COMPOSITION**	**U-VALUE ($W/m^2{\cdot}K$)**	**EUI ($kWh/m^2{\cdot}yr$)**	**EMBODIED CARBON ($kgCO_2e/m^2$)**	**OPERATIONAL CARBON ($kgCO_2e/m^2{\cdot}$ 50yr)**	**TOTAL CARBON ($kgCO_2e/m^2{\cdot}$ 50yr)**
EXTERNAL WALL	**Baseline (Current)**		**380 mm red clay brick** → interior plaster	1.35	333.984	155280	33000000	33155280
	Retrofit	Interior Insulation	**380 mm red clay brick** → 20 mm service air gap → 30 mm rigid mineral wool board → 90 mm rock wool batt → vapour retarder → 20 mm gypsum board.	0.19	312.144	343990	30900000	31243990
		Exterior Insulation	30 mm brick-veneer slip → 10 mm cementitious backer board → 40 mm ventilated cavity → 30 mm rigid mineral wool board → 90 mm rock wool batt → **380 mm red clay brick** → vapour retarder → 20 mm gypsum board.	0.17	310.143	538750	30700000	31238750
		Double wall	**380 mm red clay brick** → air-infiltration barrier → 120 mm rock wool (cavity insulation) → 100 mm lightweight concrete block → vapour retarder → 20 mm gypsum board.	**0.21**	**310.612**	**185950**	**30700000**	**30885950**
WINDOW	**Baseline (Current)**		Metal frame with single pane glazing	5	333.984	567660	33000000	33567660
	Retrofit	Double Glazed	Aluminium frame, double glazing with air cavity	1.4	316.715	561831	31300000	31861831
		Triple Glazed	Aluminium frame, triple glazing with two air cavities	**1**	**313.873**	**641798**	**31000000**	**31641798**
SKYLIGHT	**Baseline (Current)**		Metal frame with single pane glazing	5	333.984	105431	33000000	33105431
	Retrofit	Double Glazed	Aluminium frame, double glazing with air cavity	1.4	324.814	347840	32100000	32447840
		Triple Glazed	Aluminium frame, triple glazing with two air cavities	**1**	**315.966**	**186404**	**31300000**	**31486404**
ROOF	**Baseline (Current)**		4 mm bitumen membrane + 30 mm leveling screed on **420 mm precast concrete roof panel**	1.45	333.984	316160	33000000	33316160
	Retrofit	**Improved Roof**	4 mm bitumen membrane + 8 mm fiber-cement board + 180 mm PIR continuous insulation + vapor retarder over **420 mm precast concrete roof panel**	**0.17**	**273.706**	**409100**	**27100000**	**27509100**

Figure 5.1 Envelope retrofit scenarios and corresponding performance indicators.

5.2 *External Walls*

5.2.1 Energy simulation results (External walls; Honeybee)

Dynamic energy simulations were conducted with Honeybee, using the baseline condition of windows, skylights, and roof to isolate the impact of wall retrofits. The baseline wall records the highest annual energy use intensity (EUI) of 333.98 kWh/m²·yr, largely due to its heating demand (206.78 kWh/m²·yr). All retrofit strategies demonstrate a reduction in heating loads, with only minor variations in cooling demand. Internal insulation lowers the EUI to 312.14 kWh/m²·yr, while external insulation and the double-wall system further reduce it to 310.14 kWh/m²·yr and 310.61 kWh/m²·yr, respectively. The relatively small differences among the three retrofit options can be attributed to their comparable U-values, as well as the fact that lighting and equipment loads remain constant across all scenarios.

Overall, the three retrofit strategies reduce the total EUI by approximately 6–7% compared to the baseline, with heating demand reductions of about 10–11%. While the quantitative improvement is modest, these results still confirm the effectiveness of wall insulation upgrades in lowering operational energy use

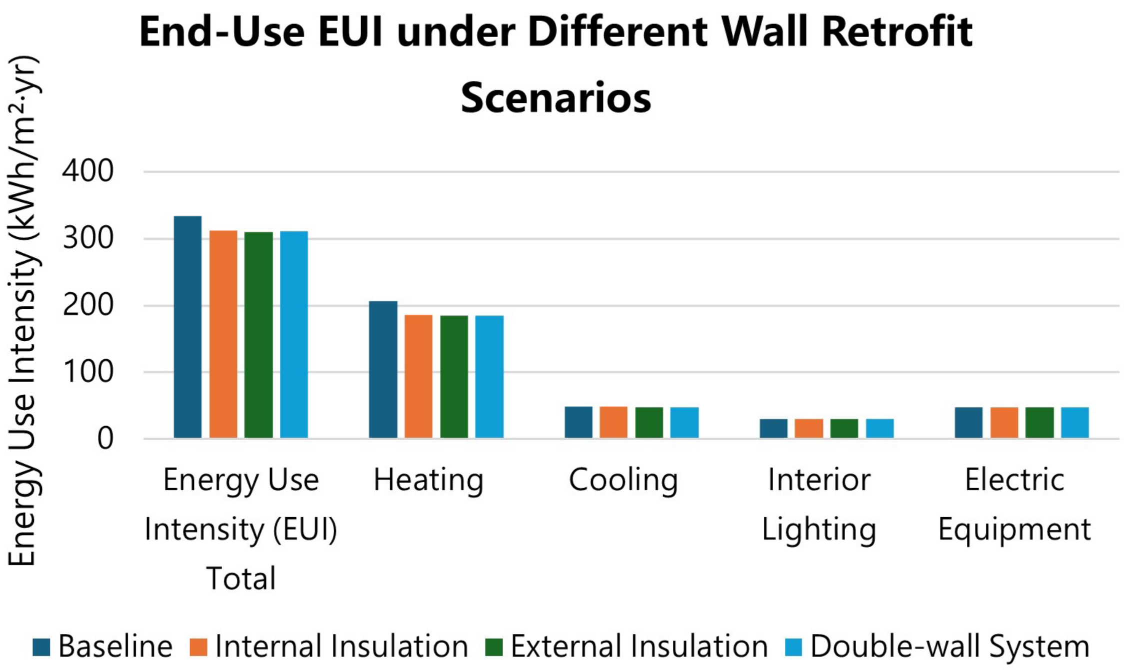


Figure 5.2 End-Use EUI under different wall retrofit scenarios.

5.2.2 Life Cycle Carbon Assessment (External wall; One Click LCA)

For each wall option, One Click LCA sums the embodied impacts of the tested wall (A1–A5; B4–B5/C1–C4 where applicable) with the operational carbon (B6) derived from the corresponding Honeybee run for the whole building. Results are 50-year totals; Module D excluded from totals.

Indicator selection. Results presented here are limited to Global Warming Potential (GWP, $kgCO_2e$) as the primary and comparable KPI for whole-life performance. Other impact categories were calculated but are not shown in the main text.

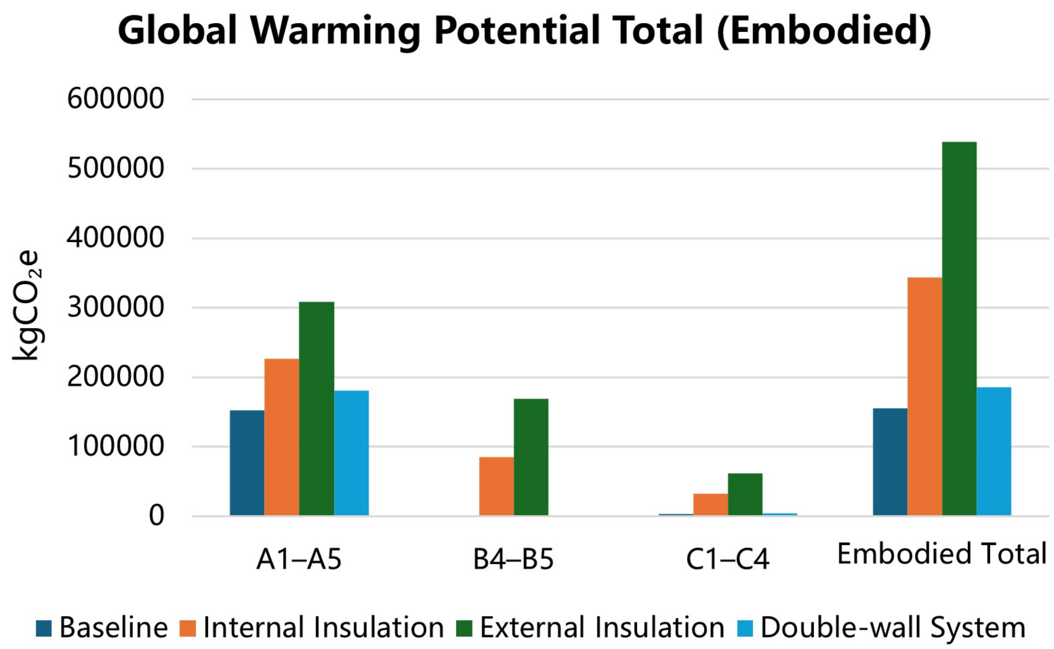


Figure 5.3 Embodied GWP of external walls.

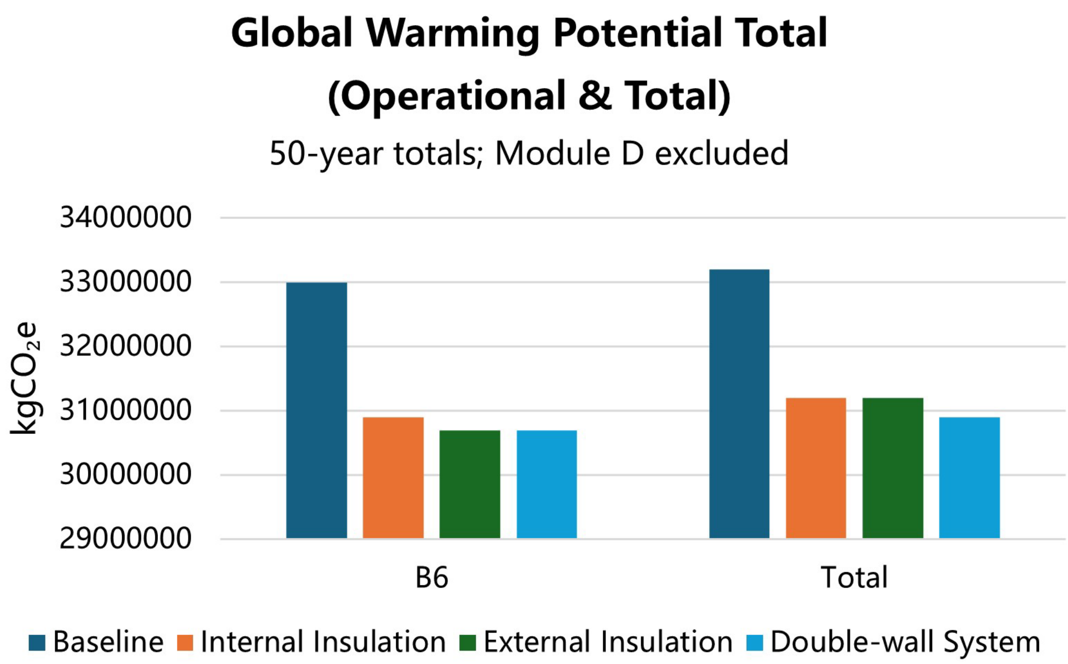


Figure 5.4 Operational & total GWP of external walls.

Findings (consistent with the two charts Fig.5.3, Fig.5.4)

1. Operational dominance: B6 contributes ≈98–99% of whole-life GWP for all options.
2. Baseline: Lowest embodied (no added layers) but highest B6, therefore the largest total over 50 years.
3. Internal insulation: Adds moderate embodied impacts and reduces B6 by 6–7% vs. baseline.
4. External insulation and double-wall: higher embodied due to extra materials but achieve similar B6 reductions (6–7%) through improved thermal performance.

5. Whole-life totals: Differences among retrofit options are small (<1%) because B6 dominates; all three retrofits outperform the baseline. Selection may therefore be guided by constructability, cost, and heritage appearance, alongside the operational-carbon reductions demonstrated.

5.2.3 Comparative discussion (External wall)

Scenario	Structural composition	Heating demand (kWh/m²·yr)	Cooling demand (kWh/m²·yr)	Total EUI (kWh/m²·yr)	Embodied carbon ($kgCO_2e/m^2$)	Operational carbon ($kgCO_2e/m^2$·50yr)	Total life-cycle carbon ($kgCO_2e/m^2$·50yr)
Baseline (Original wall)	**380 mm red clay brick** → interior plaster	206.776	49.205	333.984	155280	33000000	33155280
Internal insulation	**380 mm red clay brick** → 20 mm service air gap → 30 mm rigid mineral wool board → 90 mm rock wool batt → vapour retarder → 20 mm gypsum board.	185.351	48.79	312.144	343990	30900000	31243990
External insulation	30 mm brick-veneer slip → 10 mm cementitious backer board → 40 mm ventilated cavity → 30 mm rigid mineral wool board → 90 mm rock wool batt → **380 mm red clay brick** → vapour retarder → 20 mm gypsum board.	184.78	47.36	310.143	538750	30700000	31238750
Double-wall system	**380 mm red clay brick** → air-infiltration barrier → 120 mm rock wool (cavity insulation) → 100 mm lightweight concrete block → vapour retarder → 20 mm gypsum board.	184.868	47.741	310.612	185950	30700000	30885950

Figure 5.5 Comparison table of each external wall scenario.

The comparative assessment of the wall retrofit options demonstrates the balance between operational savings and embodied impacts. The baseline wall (380 mm red clay brick) records the lowest embodied carbon (≈155,000 $kgCO_2e$) but has the poorest thermal performance, resulting in the highest operational emissions (≈33.0 M $kgCO_2e$ over 50 years).

The internal insulation system improves energy efficiency, lowering the EUI by ~6.5% compared to baseline, but its embodied carbon (≈344,000 $kgCO_2e$) more than doubles, limiting its life-cycle advantage. The external insulation system performs similarly in energy demand reduction, yet its embodied impact is the highest (≈539,000 $kgCO_2e$), yielding no significant benefit in the total carbon balance.

By contrast, the double-wall system combines strong operational savings with relatively modest embodied emissions (≈186,000 $kgCO_2e$). It achieves one of the lowest heating and cooling demands and ultimately delivers the lowest total life-cycle carbon (≈30.9 M $kgCO_2e$), outperforming both internal and external insulation.

Therefore, the double-wall system emerges as the optimal retrofit strategy, as it balances durability, operational efficiency, and embodied carbon more effectively than the other options.

5.3 Windows

5.3.1 Energy simulation results (Windows; Honeybee)

Honeybee simulations were run by varying only the window construction (Uw: baseline 5.0; double 1.4; triple 1.0 $W \cdot m^{-2} \cdot K^{-1}$), while walls, skylights and roof remained at baseline.

Results (Fig 5.6) show a clear reduction in total EUI when upgrading from single glazing to IGUs:

1. Baseline (single-glazed): highest EUI, with demand dominated by heating.
2. Double-glazed window: EUI decreases by ≈6–7% relative to baseline, driven almost entirely by lower heating loads; cooling shows a small drop.
3. Triple-glazed window: a further ≈1–2% reduction versus double glazing; cooling remains similar; lighting and equipment are unchanged across scenarios.

Overall, window upgrades primarily reduce heating energy, while the marginal difference between double and triple glazing is small, consistent with their close thermal performance and identical internal gains.

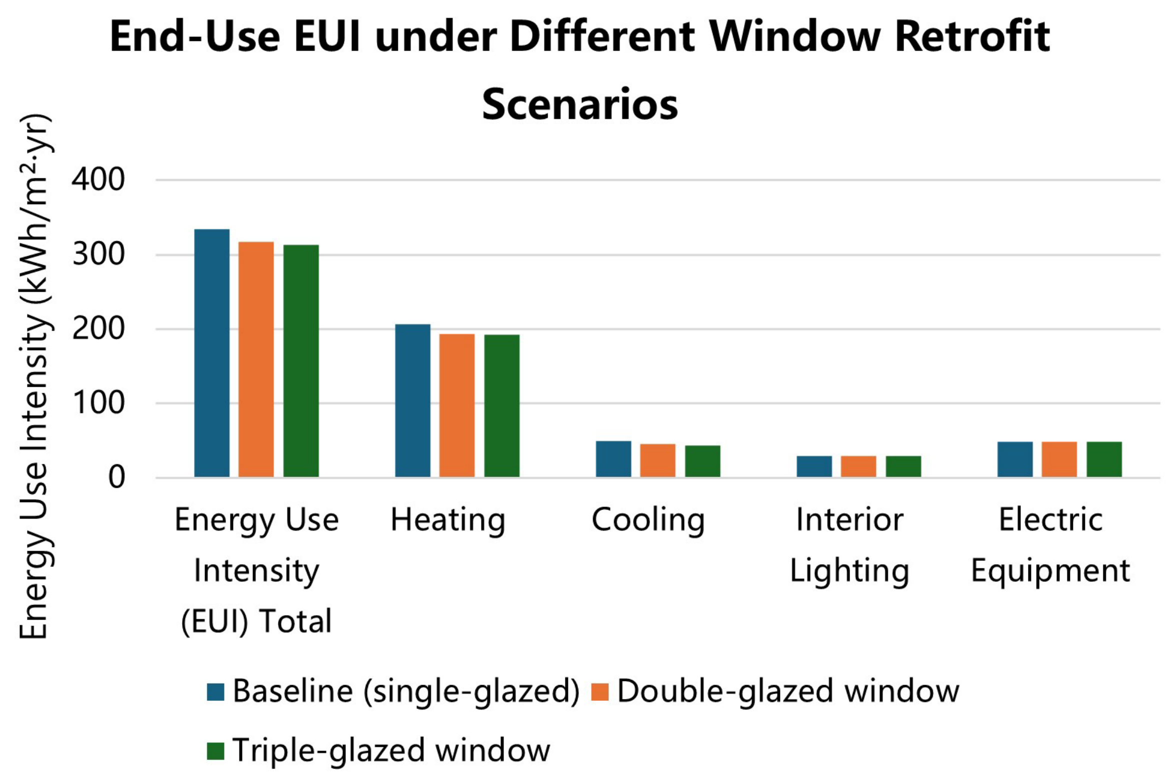


Figure 5.6 End-Use EUI under different window retrofit scenarios.

5.3.2 Life Cycle Carbon Assessment (Windows; One Click LCA)

The LCA results for the window retrofit scenarios are shown in Fig 5.7 and 5.8

Embodied carbon (A1–A5, B4–B5, C1–C4). The baseline single-glazed and the double-glazed windows show similar embodied impacts, while the triple-glazed option is noticeably higher due to additional material inputs and processing.

Operational carbon (B6, 50 years). Operational emissions dominate across all scenarios, exceeding 30 M $kgCO_2e$. The baseline performs worst, while double glazing reduces emissions by about 5% and triple glazing achieves a 6% reduction.

Total life-cycle impact. Despite its higher embodied carbon, the triple-glazed window achieves the lowest total GWP, followed by the double-glazed option, while the baseline remains the least favorable.

Conclusion. Triple glazing emerges as the most effective strategy in a 50-year perspective, as its operational savings clearly outweigh the embodied carbon penalty, whereas the double-glazed option offers only moderate net benefits.

Implication. Even with a uniform 40-year replacement cycle, the triple-glazed aluminum window delivers the lowest whole-life GWP in this study. Where budget/heritage constraints apply, double glazing captures most of the operational savings with a lower embodied uplift.

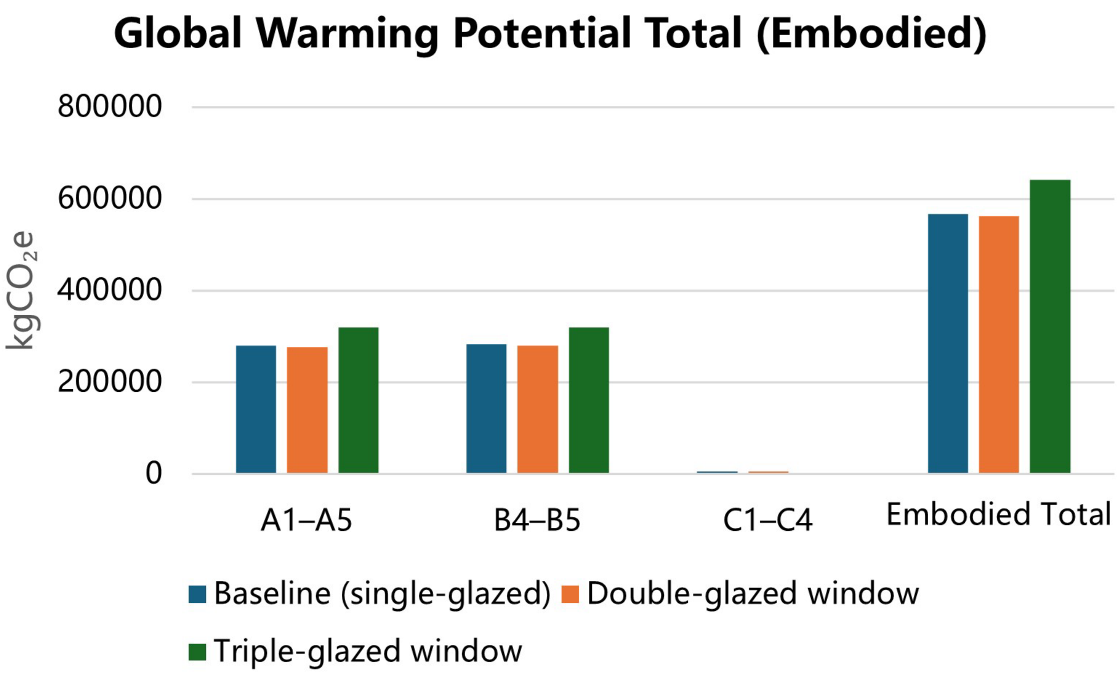


Figure 5.7 Embodied GWP of windows.

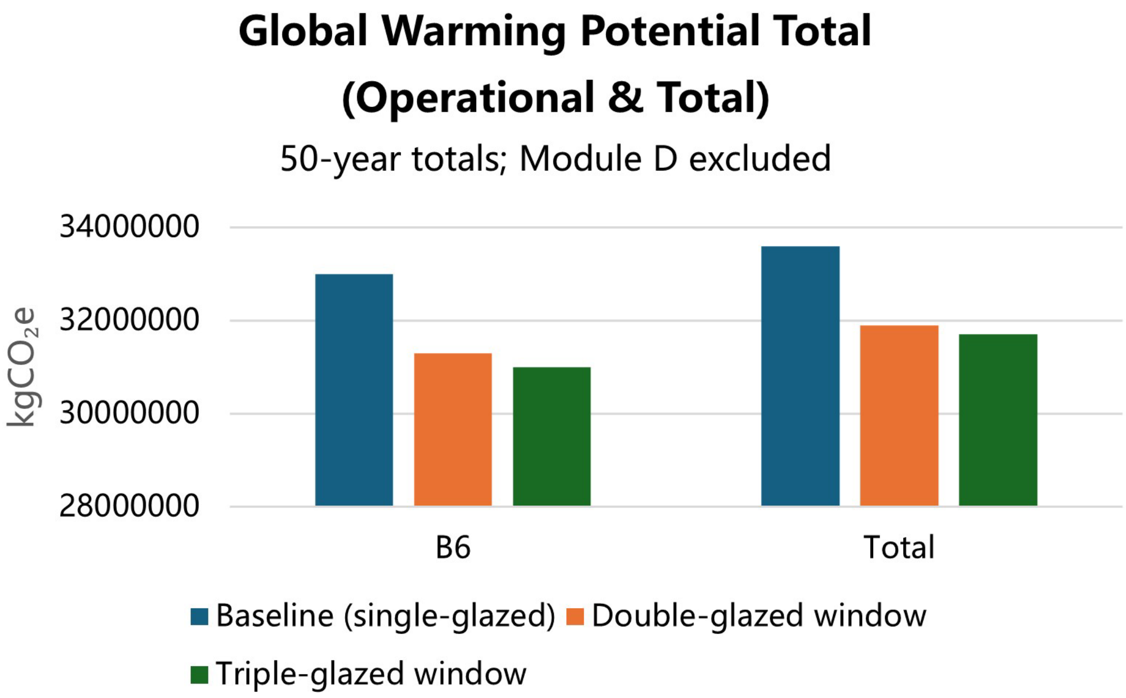


Figure 5.8 Operational & total GWP of windows.

5.3.3 Comparative discussion (Window)

The comparative results for the window scenarios reveal clear trade-offs between embodied and operational impacts. The baseline single-glazed window shows the lowest embodied carbon (≈568 tCO_2e) but the highest energy demand, leading to an operational carbon of 33.0 M $kgCO_2e$ over 50 years. The double-glazed window improves thermal performance, reducing heating and cooling loads by around 6–8%, and lowers operational emissions to 31.3 M $kgCO_2e$. However, its embodied impact remains like the baseline, which limits its life-cycle advantage. The triple-glazed window provides the best operational savings (31.0 M $kgCO_2e$, a 6% reduction compared to baseline), though it carries the highest embodied carbon (≈642 tCO_2e).

When both phases are combined, the triple-glazed window achieves the lowest total life-cycle carbon (≈ 31.6 M $kgCO_2e$), followed by the double-glazed option, while the baseline performs worst overall. Accordingly, triple glazing is selected as the preferred option from a life-cycle carbon perspective; economic feasibility (e.g., higher upfront cost relative to double glazing) is outside this study's scope and may affect practical decisions.

Scenario	**Structural composition**	**Heating demand ($kWh/m^2 \cdot yr$)**	**Cooling demand ($kWh/m^2 \cdot yr$)**	**Total EUI ($kWh/m^2 \cdot yr$)**	**Embodied carbon ($kgCO_2e/m^2$)**	**Operational carbon ($kgCO_2e/m^2 \cdot 50yr$)**	**Total life-cycle carbon ($kgCO_2e/m^2 \cdot 50yr$)**
Baseline (single-glazed)	Metal frame with single pane glazing	206.776	49.205	333.984	567660	33000000	33567660
Double-glazed window	Aluminium frame, double glazing with air cavity	193.664	45.048	316.715	561831	31300000	31861831
Triple-glazed window	Aluminium frame, triple glazing with two air cavities	192.534	43.036	313.873	641798	31000000	31641798

Figure 5.9 Comparison table of each window scenario.

5.4 Skylights

5.4.1 Energy simulation results (Skylights; Honeybee)

Using the single-variable setup (walls, windows and roof kept at baseline), upgrading the skylight from single glazing to double and triple glazing produces a modest but consistent reduction in annual EUI. The decrease is driven almost entirely by heating demand: moving to double glazing lowers heating by roughly one order of 10 kWh/m²·yr, and triple glazing delivers a further, smaller drop. Cooling changes only slightly (a few kWh/m²·yr), while interior lighting and equipment remain identical across scenarios by design. The difference between double and triple glazing is small because their whole-skylight U-values are relatively close and the skylight area is limited relative to the total envelope; consequently, overall EUI falls only by the order of 10–20 kWh/m²·yr from baseline to triple glazing. (Fig 5.10)

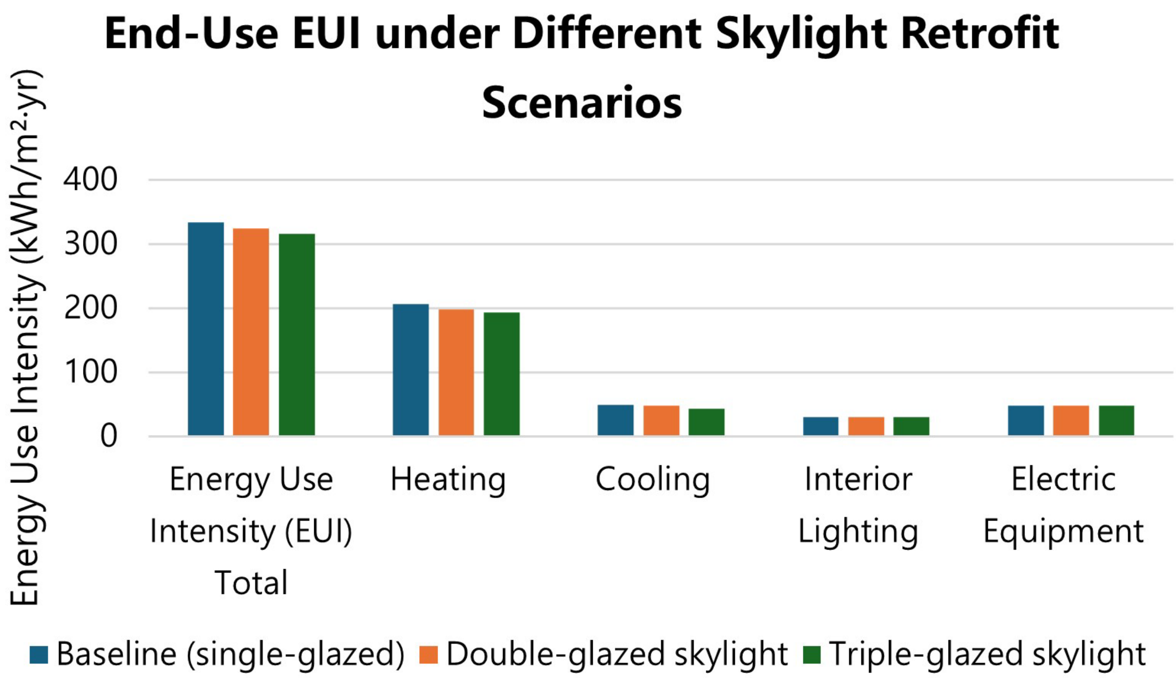


Figure 5.10 End-Use EUI under different skylight retrofit scenarios.

5.4.2 Life Cycle Carbon Assessment (Skylights; One Click LCA)

The LCA of skylight retrofit options (Fig 5.11–5.12) compared single-, double-, and triple-glazed scenarios.

Embodied carbon: Single glazing shows the lowest embodied GWP. Double glazing triples this impact, while triple glazing is lower but still above baseline.

Operational carbon (50 years): Operational emissions dominate. Single glazing performs worst, while double and triple glazing reduces emissions by 5% and 9%, respectively.

Total life cycle: Despite higher embodied carbon, both double- and triple-glazing lower total GWP vs. baseline. Triple glazing is optimal over 50 years—its operational savings outweigh the upfront impact—whereas double glazing offers only modest net gains due to its embodied penalty.

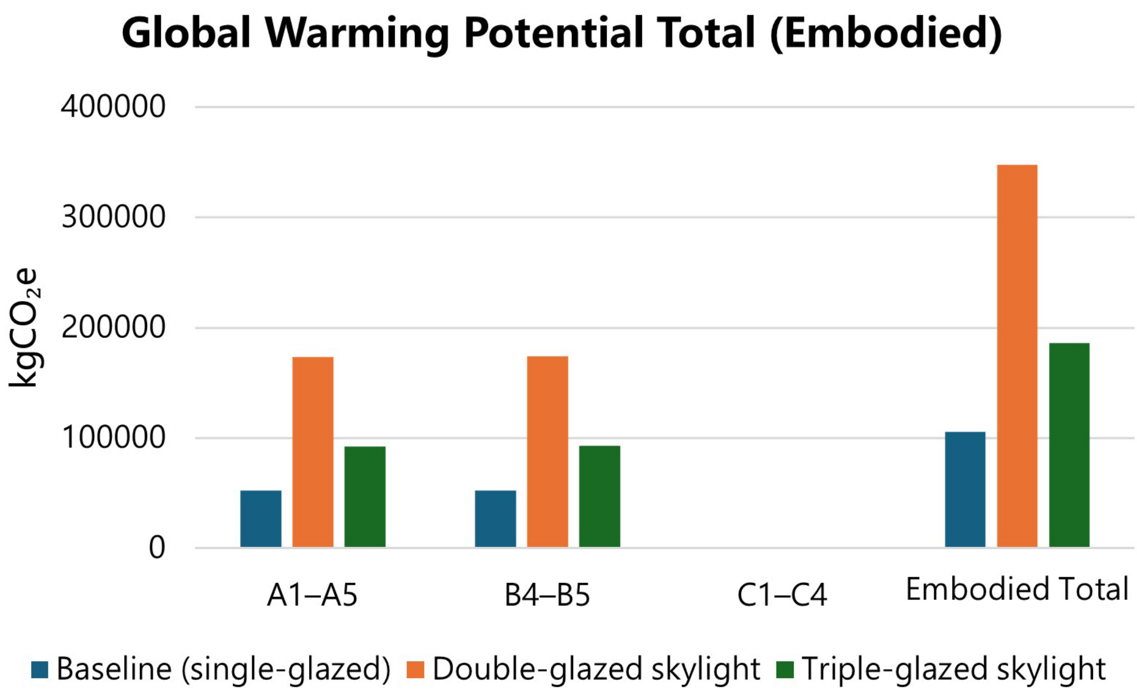


Figure 5.11 Embodied GWP of skylights.

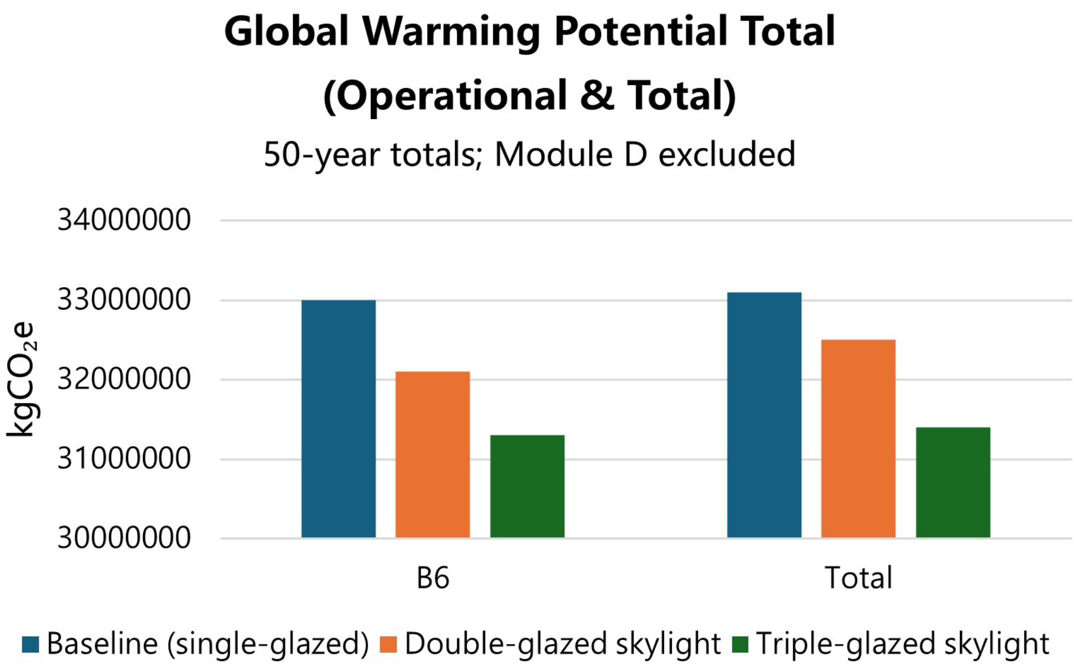


Figure 5.12 Operational & total GWP of skylights.

5.4.3 Comparative discussion (Skylight)

The comparative assessment highlights the trade-offs between embodied and operational carbon for different skylight systems. The baseline single-glazed skylight has the lowest embodied impact (≈105,000

$kgCO_2e$) but performs worst in terms of energy efficiency, leading to the highest operational carbon (≈33.0 M $kgCO_2e$ over 50 years). The double-glazed skylight improves thermal performance, reducing operational carbon by about 3% compared with baseline, but its embodied impact is more than three times higher, resulting in only moderate life-cycle improvement. By contrast, the triple-glazed skylight offers the best overall balance: although its embodied carbon is higher than the baseline, it is substantially lower than the double-glazed option, while at the same time achieving the greatest operational savings (−5% compared with baseline).

Scenario	Structural composition	Heating demand (kWh/m²·yr)	Cooling demand (kWh/m²·yr)	Total EUI (kWh/m²·yr)	Embodied carbon ($kgCO_2$ e/m²)	Operational carbon ($kgCO_2$ e/m²·50yr)	Total life-cycle carbon ($kgCO_2e$/m²·50yr)
Baseline (single-glazed)	Metal frame with single pane glazing	206.776	49.205	333.984	105431	33000000	33105431
Double-glazed skylight	Aluminium frame, double glazing with air cavity	198.739	48.073	324.814	347840	32100000	32447840
Triple-glazed skylight	Aluminium frame, triple glazing with two air cavities	193.917	44.047	315.966	186404	31300000	31486404

Figure 5.13 Comparison table of each skylight scenario.

Considering the combined life-cycle perspective, the triple-glazed skylight emerges as the optimal solution, achieving the lowest total GWP (≈31.5 M $kgCO_2e$). Accordingly, triple glazing is selected as the preferred option from a life-cycle carbon perspective; economic feasibility (e.g., higher upfront cost relative to double glazing) lies outside this study's scope and may influence practical retrofit decisions.

5.5 Roof

5.5.1 Energy simulation results (Roof; Honeybee)

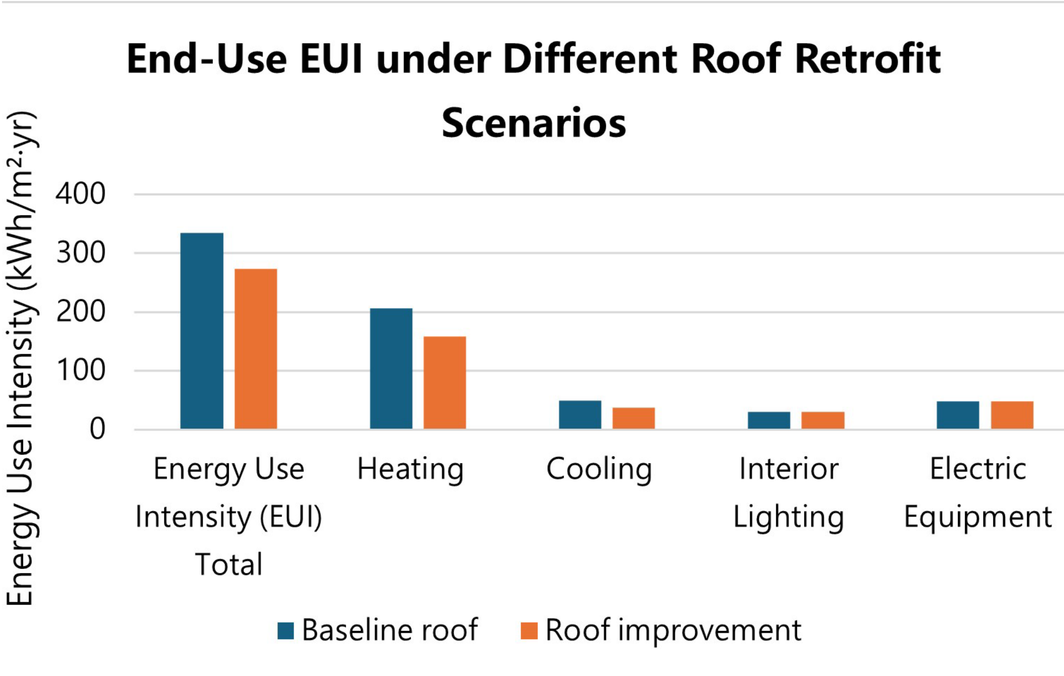


Figure 5.14 End-Use EUI under different roof retrofit scenarios.

Fig 5.14 compares end-use EUI for the baseline roof and the PIR-insulated roof. The retrofit lowers total EUI noticeably, driven primarily by a large reduction in space-heating demand. Cooling demand also declines modestly, consistent with lower conductive heat gains through the roof in summer. End uses are not directly affected by the roof assembly—interior lighting and plug/equipment load remain essentially unchanged.

Overall, the results confirm that improving the roof's thermal resistance is an effective lever for reducing operational energy in Building No. 7, with benefits concentrated in winter heating and secondary gains in summer cooling.

5.5.2 Life Cycle Carbon Assessment (Roof; One Click LCA)

Fig 5.15–5.16 compare the baseline roof with the PIR-insulated upgrade over a 50-year period (Module D excluded).

Embodied carbon (A1–A5, B4–B5, C1–C4).

The retrofit shows a clear increase in embodied GWP, driven mainly by A1–A3 (materials) for the PIR board and auxiliary layers. A4 (transport) is similar between cases, while A5 (installation) and C1–C4 (end-of-life) add smaller, secondary contributions.

Operational carbon (B6).

Consistent with the energy results, the upgraded roof substantially lowers B6, with the reduction dominated by decreased space-heating demand; cooling also declines slightly.

Total life-cycle impact:

When embodied and operational effects are combined, the PIR-insulated roof achieves a lower total GWP than the baseline. The operational savings over the assessment period outweigh the upfront embodied increase, confirming the retrofit as the preferable solution from a life-cycle carbon perspective.

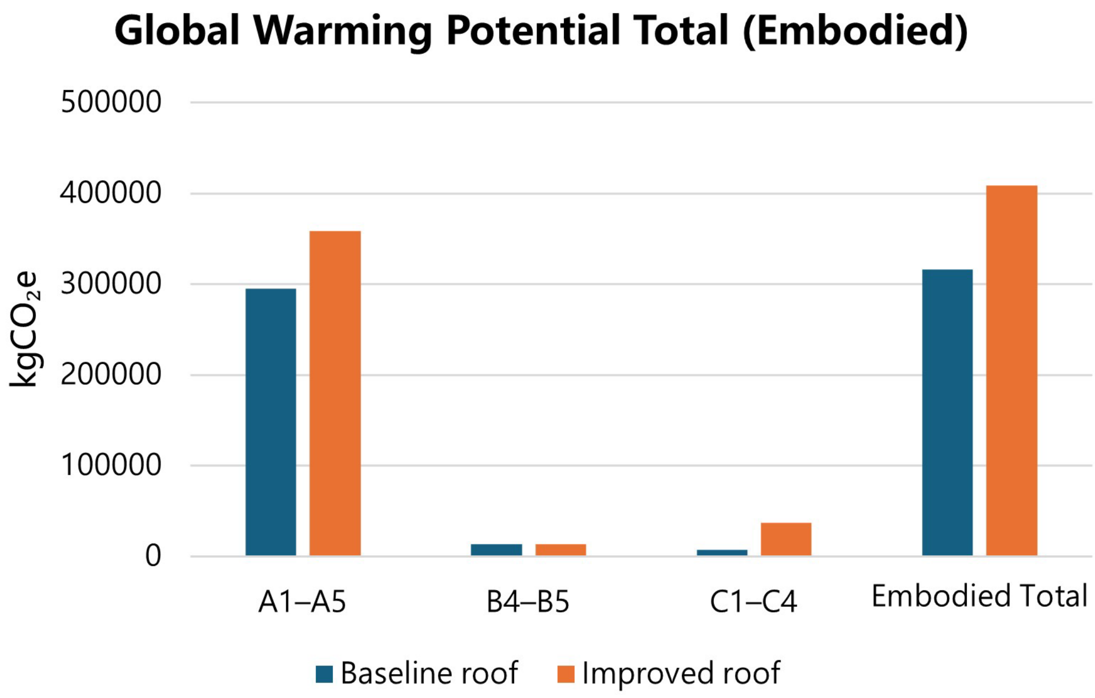


Figure 5.15 Embodied GWP of roofs.

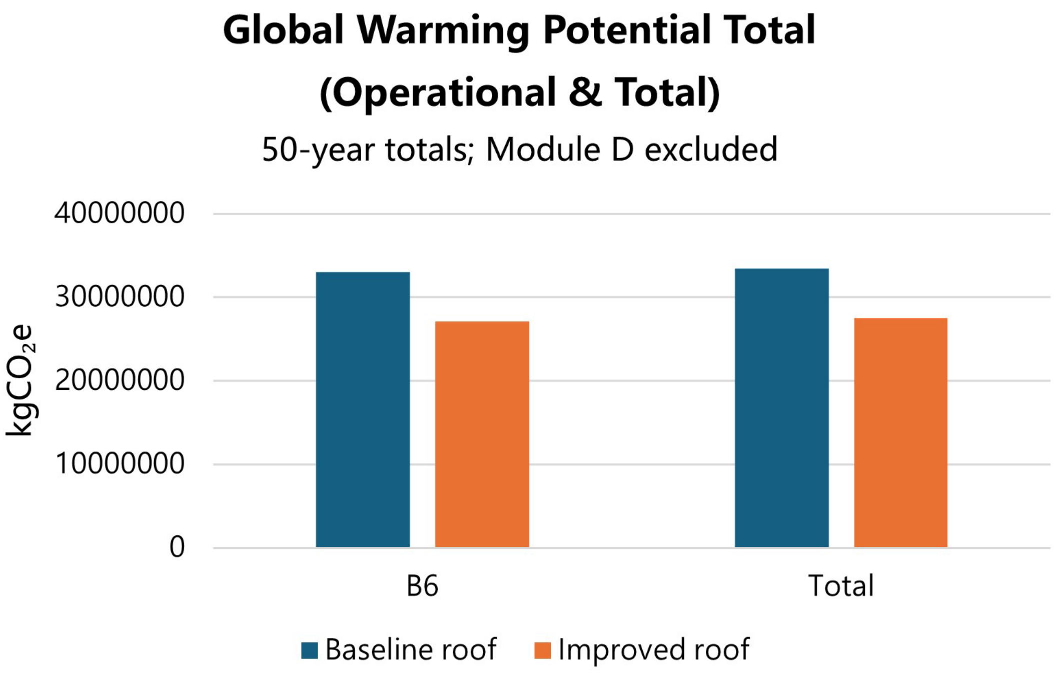


Figure 5.16 Operational & total GWP of roofs.

5.5.3 *Comparative discussion (Roof)*

The comparison between the baseline roof and the PIR-insulated upgrade shows a clear trade-off: the retrofit raises embodied carbon (≈ +29.4%) due to added materials, but delivers substantial operational gains. Heating demand drops by ≈ 23.5%, cooling by ≈ 23.8%, bringing total EUI down ≈ 18.0%. Over 50 years, operational carbon decreases by ≈ 17.9%, which outweighs the embodied penalty and yields a ≈ 17.4% reduction in total life-cycle GWP (≈ 5.81 $MtCO_2e$ absolute reduction).

Conclusion: From a life-cycle carbon perspective, the PIR-insulated roof is the preferable solution; its long-term operational savings dominate the overall balance, while cost considerations are outside the scope of this study.

Scenario	Structural composition	Heating demand (kWh/m²·yr)	Cooling demand (kWh/m²·yr)	Total EUI (kWh/m²·yr)	Embodied carbon ($kgCO_2e/m^2$)	Operational carbon ($kgCO_2e/m^2\cdot50yr$)	Total life-cycle carbon ($kgCO_2e/m^2\cdot50yr$)
Baseline roof	4 mm bitumen membrane + 30 mm leveling screed on **420 mm precast concrete roof panel**	206.776	49.205	333.984	316160	33000000	33316160
Improved roof	4 mm bitumen membrane + 8 mm fiber-cement board + 180 mm PIR continuous insulation + vapor retarder over **420 mm precast concrete roof panel**	158.192	37.512	273.706	409100	27100000	27509100

Figure 5.17 Comparison table of each roof scenario.

5.6 Whole-envelope synthesis (Baseline vs. Low-carbon package)

5.6.1 Package definition

This section compares whole-envelope packages over a 50-year reference study period. LCA boundaries follow Section 5.1: A1–A5 (product + construction) and, where applicable, B2–B5/C1–C4; Module D is reported separately and excluded from totals. B6 (operational carbon) is derived from the Honeybee energy results. Building geometry, internal loads, HVAC settings, schedules, shading, and controls are kept constant to isolate envelope effects. Unless otherwise noted, airtightness remains unchanged.

Package A — Baseline (as found)

As documented in Chapter 4 (see §§4.4), the existing envelope has the following thermal transmittances:

1. External wall: U = 1.35 $W \cdot m^{-2} \cdot K^{-1}$.
2. Windows: U = 5.0 $W \cdot m^{-2} \cdot K^{-1}$.
3. Skylights: U = 5.0 $W \cdot m^{-2} \cdot K^{-1}$.
4. Roof: U = 1.45 $W \cdot m^{-2} \cdot K^{-1}$.

Package B — Selected low-carbon envelope (assemblies and detailing in Chapter 4, here only performance targets)

External wall (double-wall retrofit): U = 0.21 $W \cdot m^{-2} \cdot K^{-1}$.

Windows (thermally broken frames, triple IGU): U = 1.0 $W \cdot m^{-2} \cdot K^{-1}$.

Skylights (triple, fixed): U = 1.0 $W \cdot m^{-2} \cdot K^{-1}$.

Roof (PIR insulated overlay on precast panels): U = 0.17 $W \cdot m^{-2} \cdot K^{-1}$.

Datasets and service lives.

OCL datasets and replacement cycles follow Sections 5.2–5.5. Where exact EPDs were unavailable, functionally equivalent proxies were used and flagged in the component sections.

5.6.2 Whole-envelope energy performance of two packages (Honeybee)

Fig 5.18 compares the baseline envelope with the selected low-carbon package under identical geometry, internal loads, schedules and HVAC settings.

Total EUI drops markedly—by roughly 40%—when the whole envelope is upgraded.

Heating demand shows the largest improvement ($\approx$ 50% reduction), reflecting lower transmission losses through the insulated roof and wall and the high-performance glazing.

Cooling demand also declines ($\approx$ 60% reduction), consistent with reduced solar/convective gains from triple glazing and better roof insulation.

Lighting and plug/equipment end uses remain essentially unchanged, as expected for measures focused on the envelope.

Overall, upgrading the entire envelope substantially shifts the building's energy profile from shell-dominated losses to internal-load driven uses, providing the basis for the operational carbon (B6) reductions reported in the LCA.

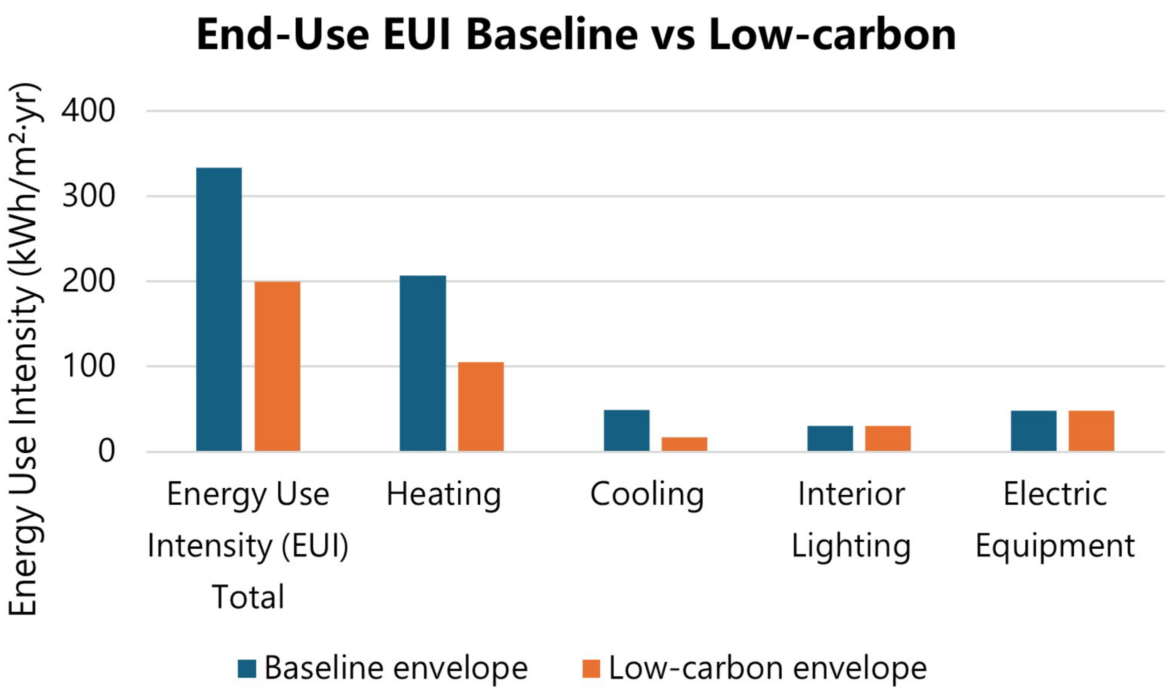


Figure 5.18 End-Use EUI baseline vs low-carbon of envelope packages.

5.6.3 Life-Cycle Carbon performance of two packages (One Click LCA)

Fig 5.19–5.20 compare the baseline envelope with the low-carbon package over a 50-year RSP (Modules A1–A5, B4–B5, C1–C4; Module D excluded).

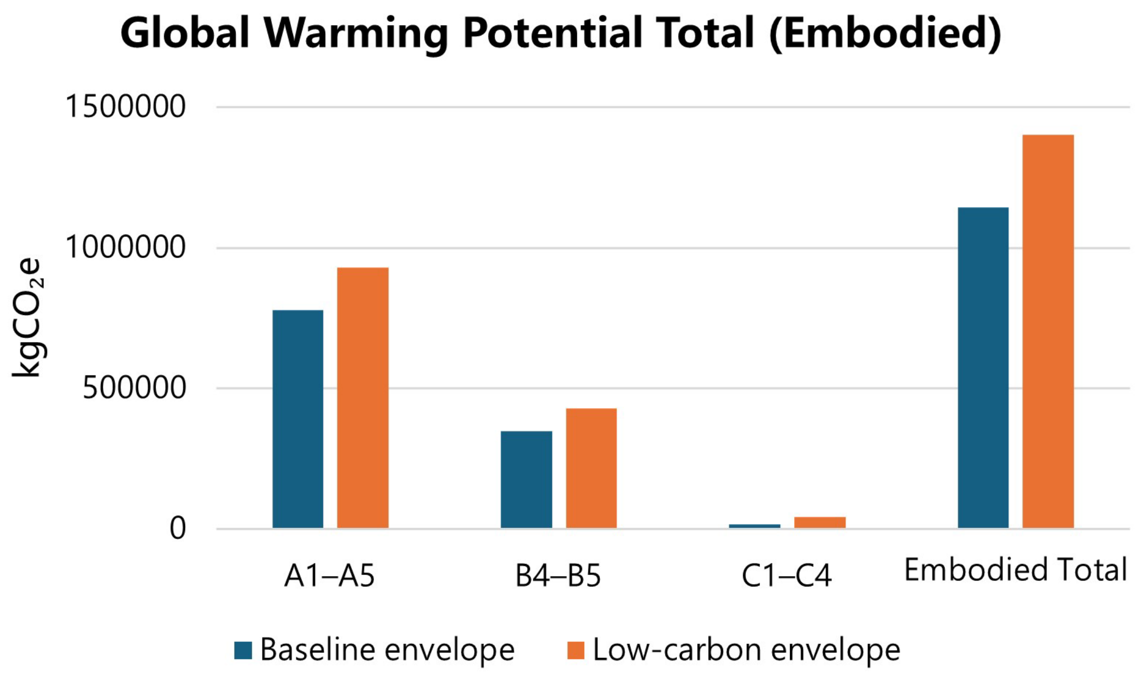


Figure 5.19 Embodied GWP of baseline envelope package.

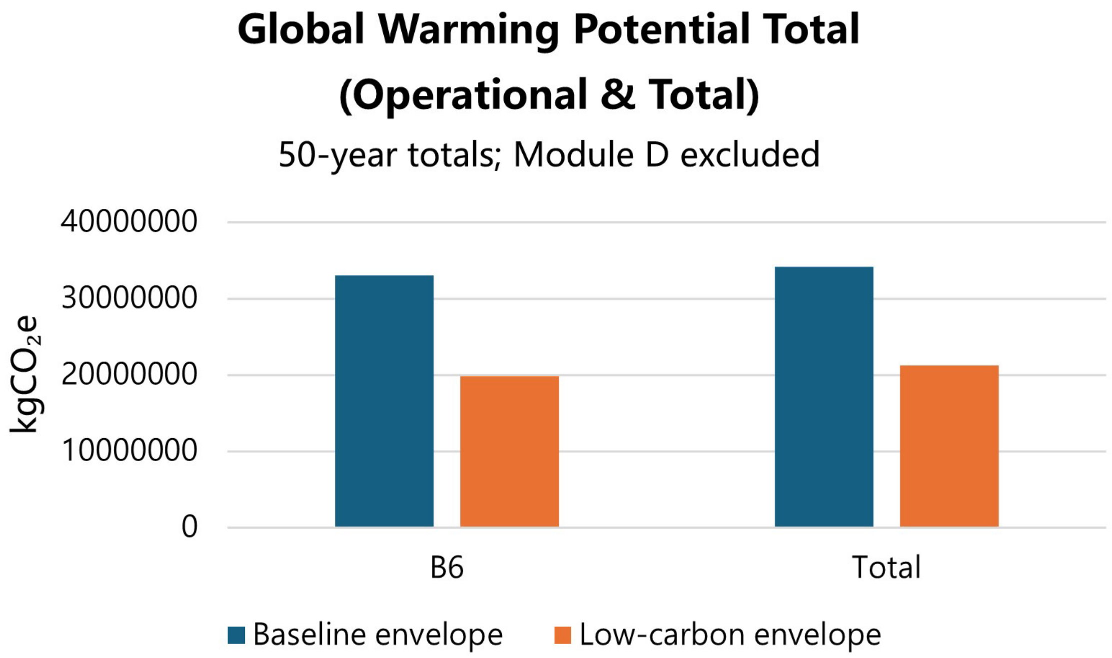


Figure 5.20 Operational & total GWP of low-carbon envelope package.

Embodied carbon:

The low-carbon package shows a clear increase in embodied GWP, driven mainly by A1–A3 (materials) for the added insulation layers and triple-glazed units; B4–B5 contribute modestly and C1–C4 add a small end-of-life increase. Overall, embodied totals are higher than baseline.

Operational carbon:

Operational emissions dominate the life cycle and are substantially lower with the low-carbon package, reflecting the reductions in space-heating (and secondary cooling) seen in the energy model.

Total life cycle GWP:

When embodied and operational phases are combined, the low-carbon envelope achieves a markedly lower total GWP than the baseline. In other words, the operational savings decisively outweigh the embodied-carbon penalty introduced by the added materials.

From a life-cycle carbon perspective, adopting the low-carbon envelope package is preferable for Building No. 7; economic feasibility is outside the scope of this study and may influence implementation choices in practice.

5.6.4 Conclusion & Discussion

The whole-envelope comparison (Fig 5.21) shows that the low-carbon package delivers a decisive life-cycle benefit.

Energy performance. Total EUI falls by ≈40% (−134 kWh/m²·yr), driven mainly by heating (−≈49%) and supported by a strong decline in cooling (−≈66%). Lighting and plug loads are unchanged, confirming that gains come from the envelope.

Operational carbon (B6). With identical internal loads/HVAC settings, B6 drops by ≈40% (−13.2 MtCO_2e over 50 years).

Embodied carbon. Package-level embodied GWP rises by ≈23% (+0.258 $MtCO_2e$), primarily from added insulation and triple-glazed units.

Total life cycle GWP. Despite the embodied penalty, the operational savings dominate, yielding a ≈38% reduction in total GWP (−13.0 $MtCO_2e$) over 50 years.

	Baseline envelope	**Low-carbon envelope**
External wall	**380 mm red clay brick** → interior plaster	**380 mm red clay brick** → air-infiltration barrier → 120 mm rock wool (cavity insulation) → 100 mm
Windows	Metal frame with single pane glazing	Aluminium frame, triple glazing with two air cavities
Skylight	Metal frame with single pane glazing	Aluminium frame, triple glazing with two air cavities
Roof	4 mm bitumen membrane + 30 mm leveling screed on **420 mm precast concrete roof panel**	4 mm bitumen membrane + 8 mm fiber-cement board + 180 mm PIR continuous insulation + vapor retarder over **420 mm precast concrete roof panel**
Total EUI ($kWh/m^2 \cdot yr$)	333.984	199.671
Heating ($kWh/m^2 \cdot yr$)	206.766	105.125
Cooling ($kWh/m^2 \cdot yr$)	49.205	16.543
Operational carbon B6 ($kgCO_2e$, 50 yr)	33000000	19800000
Embodied total (A1–A5+B4–B5+C1–C4, $kgCO_2e$)	1144800	1402600
Total life-cycle GWP ($kgCO_2e$, 50 yr)	34200000	21200000

Figure 5.21 Comparison table of two envelope packages.

The combination of double-wall external walls, triple-glazed windows/skylights, and a PIR-insulated roof shifts the building from shell-dominated losses to internal-load-driven uses. From an LCA perspective, this package is clearly preferable for Building No. 7.

6. Conclusion

6.1 Key findings

This thesis evaluated envelop retrofit strategies for Building No. 7 through component-level analysis (external walls, windows, skylights, roof) and a whole envelope synthesis grounded in a reuse design. Energy performance was modelled with Honeybee and life cycle impacts quantified with One Click LCA over a 50-year period (A1–A5, B4–B5, C1–C4, B6; Module D excluded).

Operational carbon dominance. Across all scenarios, operational emissions (B6) dominate total life cycle GWP, confirming the primacy of envelope performance in a heating-driven, warehouse-type building.

Component insights. Triple-glazed windows and skylights deliver the largest operational reductions among glazing options; the PIR-insulated roof substantially lowers transmission losses; the double-wall external wall provides the best balance between improved thermal performance and embodied impacts.

Whole-envelope outcome. The selected package—double-wall wall + triple-glazed windows and skylights + PIR-insulated roof—reduces total EUI by ~40% and total life cycle GWP by ~35–40%, despite a moderate rise in embodied carbon.

Methodological contribution. The study links reuse design constraints with component-to-package LCA, offering a replicable decision path for industrial-heritage retrofits.

6.2 Limitations

Datasets and assumptions. Embodied results rely on generic/market-average datasets (e.g., baseline glazing not always explicitly aluminum), aligned service lives, and consistent emission factors; results are sensitive to these inputs.

Airtightness and controls. Airtightness, schedules, and HVAC/control strategies were held constant; additional gains may be obtainable through air-sealing and control optimization.

Scope exclusions. Module D (benefits and loads beyond the system boundary) was excluded. Economic analysis and carbon payback were not performed. Moisture/comfort and construction logistics were addressed qualitatively only.

Model granularity. Simplifications in thermal bridging, installation waste, and end-of-life scenarios may under- or over-estimate embodied impacts.

6.3 Implications and recommendations

For industrial-heritage warehouses with similar typologies and climates, deep envelope upgrades can deliver substantial life-cycle carbon benefits even when embodied impacts rise moderately.

Triple glazing and high-performance roof insulation should be prioritized where feasible; double-wall assemblies are a robust option when heritage expression and durability are critical.

Early integration of reuse design helps define feasible retrofit space, reconcile heritage constraints, and avoid abortive work.

6.4 Future work

Cost and payback: couple LCA with life-cycle cost analysis; evaluate capital cost, maintenance, and carbon/payback under varying energy prices.

Airtightness & controls: quantify savings from air-sealing, demand-controlled ventilation, and smart controls; include infiltration sensitivity.

Comfort & moisture: assess hygrothermal risk (e.g., Glaser/HT simulations), summer comfort, daylight/ glare for the selected package.

Data & Module D: incorporate project-specific EPDs, construction waste factors, and explore Module D (reuse/recycling benefits).

Heritage detailing: develop conservation-grade details for interfaces (sills, parapets, skylight curbs) to minimize thermal bridges while preserving character.

6.5 Closing remark

The research demonstrates that an envelope-led pathway—structured from component evidence to a whole-building package—can materially decarbonize an industrial-heritage warehouse while respecting reuse ambitions, offering a pragmatic template for climate-aligned regeneration in similar European contexts.

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