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Decarbonization of a warehouse building: A life cycle assessment of embodied and operational carbon

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Author: **Tarik Jelačić**

Student ID: 10942417

Advisor: Enrico De Angelis

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Abstract

The construction sector is responsible for a significant share of global greenhouse gas (GHG) emissions, yet warehouse buildings which are one of the fastest growing types of facilities of the built environment remain under-represented in the life cycle assessment (LCA) existing body of literature. This thesis aims to address that gap by performing a whole-life carbon assessment on a case study of a modern prefabricated warehouse building located in Bologna, Italy, as a contribution to the decarbonization of the industrial building sector.

The baseline scenario results of material inventory obtained using One Click LCA and an energy model developed in IES-VE produced a whole-life global warming potential (GWP) of 786.6 kgCO₂e/m², split almost equally between embodied carbon (392.1 kgCO₂e/m²) and operational carbon (394.5 kgCO₂e/m²). Three decarbonization axes were developed: structural embodied carbon reduction through alternative concrete mixes and low-carbon steel reinforcement, building envelope embodied carbon reduction through a timber frame panel system and reduction of operational carbon through a roof-integrated photovoltaic (PV) system with battery storage.

The comparative analysis of 46 concrete mix designs from peer-reviewed literature identified CEM V/B composite cement as the best-performing solution with a 74% lower GWP per cubic meter than the baseline OPC concrete. The timber frame envelope reduced the envelope's GWP by 34.7% and the 1,800 kWp photovoltaic system with 750 kWh of battery storage integrated, cut operational carbon by 86%. These three strategies combined reduced the whole-life building GWP by 46.8%, reaching 418.3 kgCO₂e/m² or 42.0 kgCO₂e/m³. The results confirm the importance of the combined effect between embodied and operational carbon optimization for decarbonization, and contribute as a benchmark to a field that still lacks comparable whole-life warehouse case studies.

Key-words: Life Cycle Assessment (LCA), Embodied carbon, Operational carbon, Global Warming Potential (GWP), Decarbonization strategies, Warehouse building.

Abstract in Italiano

Il settore delle costruzioni è responsabile di una quota significativa delle emissioni globali di gas serra (GHG); tuttavia, gli edifici adibiti a magazzino, pur rappresentando una delle tipologie di strutture in più rapida crescita all'interno dell'ambiente costruito, risultano ancora sottorappresentati nella letteratura esistente sulla valutazione del ciclo di vita (LCA). Questa tesi mira a contribuire a colmare tale lacuna attraverso una valutazione del carbonio lungo l'intero ciclo di vita applicata a un caso studio di un moderno edificio prefabbricato adibito a magazzino, situato a Bologna, in Italia, contribuendo così al percorso di decarbonizzazione del settore degli edifici industriali.

I risultati dello scenario di riferimento, ottenuti a partire dall'inventario dei materiali elaborato con One Click LCA e da un modello energetico sviluppato in IES-VE, hanno evidenziato un potenziale di riscaldamento globale (GWP) lungo l'intero ciclo di vita pari a 786,6 kgCO₂e/m², ripartito quasi equamente tra carbonio incorporato (392,1 kgCO₂e/m²) e carbonio operativo (394,5 kgCO₂e/m²). Sono stati sviluppati tre assi di decarbonizzazione: la riduzione del carbonio incorporato nella struttura attraverso miscele alternative di calcestruzzo e armature in acciaio a basse emissioni, la riduzione del carbonio incorporato nell'involucro edilizio attraverso un sistema di pannelli con telaio in legno, e la riduzione del carbonio operativo tramite un sistema fotovoltaico integrato in copertura con accumulo a batteria.

L'analisi comparativa di 46 miscele di calcestruzzo tratte dalla letteratura scientifica peer-reviewed ha individuato il cemento composito CEM V/B come la soluzione con le migliori prestazioni, con un GWP per metro cubo inferiore del 74% rispetto al calcestruzzo di riferimento a base di cemento Portland ordinario (OPC). L'involucro con telaio in legno ha ridotto il GWP dell'involucro del 34,7%, mentre il sistema fotovoltaico da 1.800 kWp, integrato con 750 kWh di accumulo a batteria, ha ridotto il carbonio operativo dell'86%. Complessivamente, le tre strategie combinate hanno ridotto il GWP dell'edificio lungo l'intero ciclo di vita del 46,8%, raggiungendo 418,3 kgCO₂e/m², equivalenti a 42,0 kgCO₂e/m³. I risultati confermano l'importanza dell'effetto combinato tra ottimizzazione del carbonio incorporato e del carbonio operativo ai fini della decarbonizzazione, e contribuiscono a fornire un benchmark per un ambito di ricerca che presenta ancora una carenza di casi studio comparabili su magazzini valutati lungo l'intero ciclo di vita.

Parole chiave: Valutazione del ciclo di vita (LCA), Carbonio incorporato, Carbonio operativo, Potenziale di Riscaldamento Globale (GWP), Strategie di decarbonizzazione, Edificio adibito a magazzino.

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1. Introduction

1.1. Global context

1.1.1. Climate urgency and the built environment

Mitigation of climate change has become the major challenge of the 21st century, with the built environment being recognized as a pivotal area for prompt action. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1] the objective to limit global warming to 1.5C means the greenhouse gas (GHG) emissions must peak before 2025 and also be reduced by 43% by 2030. The construction sector is recognized as a critical sector for interventions towards decarbonization, considering that in 2019, on the global level buildings contributed to 21% of GHG emissions. In the European Union (EU), however, the construction sector contributes to 36% of GHG emissions among all sectors and for approximately 40% of energy consumption [2]. In the EU, the urgent topic of climate change has been translated into action through regulatory frameworks, such as the Energy Performance of Buildings Directive (EPBD) 2010/31/EU that entered into force in June 2010. The EPBD mandated that new construction must be certified as nearly zero-energy buildings (NZEB) starting from the 31st December 2020 [3].

The general strategies reported in both IPCC report and EPBD framework regarding the building sector is to ensure high energy efficiency levels of new construction and focus on renovation of the existing structures. For new constructions, effective mitigation strategies must be implemented at each stage, including design, construction, retrofit, use and disposal stage. In terms of design and construction, the materials must be low emission and the performance of the building envelope highly efficient. During both construction and use phase, the integration of renewable energy solutions is greatly emphasized, accompanied using high efficiency equipment. In the disposal stage, recycling and re-use of construction materials is of utmost importance with the purpose of minimizing the amount of virgin content used.

Therefore, besides buildings' energy efficiency, the focus on materials efficiency is becoming more prominent in the recent years as well. It is justified by the fact that construction sector is the largest consumer of materials in Europe, contributing to 50% of all extracted raw materials and 32% of waste flow [4]. This fact expands the narrative to the embodied energy of construction materials being substantial contributors to climate change [5], along with the energy consumption of buildings related to their operational stage [6]. Decarbonization of the building sector therefore encompasses efforts in reducing both embodied and operational impacts of a building [7]. Consequently, the necessity of performing a Life Cycle Assessment (LCA) as a methodological tool to measure the environmental impact of a building is of high relevance. This necessity is officially recognized in the EPBD framework 2024/1275 [8] in force from May 2024. Namely, starting from January 1st of 2028, for all the newly constructed buildings with a useful floor area larger than 1000 m² a life cycle assessment must be performed, reporting at least the global warming potential (GWP) as the environmental impact category. By 2030 this rule will apply to all new buildings.

1.1.2. Position of a warehouse building within the global context

As the thesis presented deals with a life cycle assessment of a warehouse building, considering the surface area of such building typology, the requirement of the 2024 Directive is directly applicable. However, the question emerges how does such a building fit into the greater image of climate change and environmental impact on a global level. According to the World Economic Forum, as of November 2025, the logistics sector accounts for approximately 11% of the total greenhouse emissions globally [9]. This percentage includes the facilities for storage of the goods itself such as warehouses, but also ports and freight transportation, therefore including the totality of logistics infrastructure. The report of the World Economic Forum states that the logistics sector is experiencing a rapid growth, in response to the expanding market demand.

As supply chain management is a fundamental engine driving the global market, recently studies have been emerging related to the topic of decarbonization of the global logistics. Angel et al. in their systematic literature review of green warehousing show that the expansion of the e-commerce sector has lead to the increasing demand for building warehouses [10]. Rostamzadeh et al. and Kumar et al. researched the reduction of warehouses' environmental footprint through sustainable practices within a supply chain, in which the term „green warehousing“ has been introduced [11]. Therefore the research presented a rather wider approach to sustainable warehousing not only focusing solely on building construction of such a building. This lead to further research, such as De Oliveira's et al. systematic literature review on green supply chain management, that provides a definition of green supply chain management (GSCM) which is the integration of „environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as the end-of-life management of the product after its useful life“ [12].

Therefore, there is a growing body of work in the recent 15 years in relation to decarbonization of supply chains, including sustainable solutions of operating warehouses. Moving into the impact of a warehouse itself, among the total of emissions of the logistics sector, warehouse buildings contribute to 11% of emissions [13]. However, the picture is more complex than that since warehouse buildings are at an interesting intersection between the logistics asset and the construction sector. From the logistics asset point of view, warehousing is a key link in the supply chain [14] while from the construction sector point of view, the average size of warehouses that are newly built is increasing, therefore their importance in the impact that they have on the emission of greenhouse gases is also increasing. As there is a trend of the number of warehouses growing, so do the greenhouse emissions, contributing to climate change. With new European regulations for climate protection emerging, life cycle optimization is increasingly becoming a priority for industrial investors [15]. The industrial sector undoubtedly has a strategic importance in the process of decarbonization due to its resource-intensive activities [16]. This leads to considerations of not solely the management of production processes but investors are also seeking the development of „green“ industrial facilities from a building's energy efficiency point of view, as one component of the entire value chain. As explained earlier in this introduction chapter, high level of energy efficient performance and the target of a zero-energy building is becoming a

requirement, that drives the developers and investors into implementing the low-carbon emission concepts as well into the logistics/warehouse buildings.

When it comes to the existing body of work on environmental impact of a warehouse, a literature review paper by Bartolini et al. [17] presents what macro-themes are explored besides the warehouse management. The paper outlines the following two macro-themes: 1. The environmental impact of warehouse buildings, and 2. The energy saving in a warehouse. A significant step in warehouse sustainability research was the establishment of a framework for sustainability standard for a warehouse building by Bank and Murphy (2013) [18]. The authors introduced a framework named Sustainable Logistics Initiatives (SLI). The primary metrics of the SLI included electricity, water, liquid fuel consumption, and recycling. This paper was the first one to introduce such a framework to consider both material handling and operational energy consumption. Following this research, Colicchia et al. (2013) [19] highlights eco-design and energy efficiency as key initiatives. These initiatives include the following strategies: installing skylights and clerestory windows in distribution centers to utilize natural light for interior lighting, implementing alternative energy sources like solar panels, landscaping materials that reduce water waste, and grey water systems.

The literature review paper by Bartolini et al. [10] also introduces the sustainability protocols as an incentive for reducing carbon emissions of a warehouse building. According to the research of Malinowska (2022) [20], certifications such as BREEAM, LEED, HQE and DGNB¹, although not a direct framework towards sustainability of warehouses specifically, are at least structured support systems in measuring the environmental sustainability performance (Malinowska, 2022). Referencing the listed sustainability protocols, this paper proposes a framework particular for sustainability assessment of a warehouse building, named the COMET method. It consists of 22 criteria, among which the following twelve refer to eco-design and energy efficiency, while the other 10 relate to operations and logistics: 1. the use of energy-saving and ecological lighting, 2. the use of light lighting control devices, 3. the roof surface covered by skylights, 4. light transmittance in skylights, 5. the use of renewable energy, 6. the use of alternative water sources, 7. the use of mechanisms reducing the water flow, 8. the level of building insulation, 9. the use of automatic temperature control devices, 10. the use of air purification methods and tools, 11. the use of environmental friendly materials in building structure, 12. environmental friendly plot area, while the rest relate to intra-logistic optimizations.

Based on the existing research that frames the importance of environmental sustainability assessment of a warehouse within a larger picture of reduction of greenhouse gas emissions on the global scale, it is possible to state that carbon footprint of such buildings cannot be overlooked

¹ The abbreviations listed stand for the following sustainability protocols:

BREEAM – Building Research Establishment Environmental Assessment Methodology – British Assessment system developed by the Building Research Establishment;

LEED – Leadership in Energy and Environmental Design – the American assessment system developed by the U.S. Green Building Council;

HQE – Haute Qualité Environnementale - French assessment system developed by Cerway;

DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen - the German assessment system developed by Deutsche Gesellschaft für Nachhaltiges Bauen, i.e. the German sustainable construction association, in cooperation with the Federal Ministry of Transport, Construction and City Development.

and reduction of resources such as fuel, electricity, water, land and materials must be considered. The following literature review will present into more detail the existing research on strategies used for reduction of carbon emissions, based on materials (building structure and envelope) optimizations, as well as energy efficiency in terms of lighting and HVAC design.

Although the research papers presented in this literature review are mostly based on case studies, still the green warehousing literature lacks more case studies and empirical data which is going to be addressed in this thesis by analyzing a case study of a warehouse building in terms of both materials optimization and operational energy. The following literature review is a continuation of the discussion of the environmental impact of a warehouse building, with regards to its life cycle assessment.

1.2. Literature review

1.2.1. Life cycle assessment of a prefabricated industrial building

Although Life Cycle Assessment has become one of the most methods to evaluate environmental impact of buildings, research attention has been mostly focused on residential and office buildings, while warehouses/logistics centers remain less developed as LCA case studies, despite their large floor areas and consequently the demand of materials and energy consumption.

This gap in case studies is highlighted by Ascione et al. [16] who published in 2026 the state of the LCA research for industrial buildings and discovered that the field is underrepresented compared to other building categories. Their systematic review reveals that most of the existing studies rely, however, on Cradle-to-Gate boundaries, while Cradle-to-Grave and especially Cradle-to-Cradle approaches are less frequently performed and published. This finding is important because warehouse buildings have long-term operational carbon impacts but might have as well the relevant recovery potential at the end-of-life. Hence, if the system boundary of the analysis is limited only to material production, the full environmental impact of the building might be overlooked or misinterpreted. A similar finding appears in the review paper of Bartolini et al. (2019) mentioned in the introduction, that describes green warehousing as an emerging research field, with energy saving being the most frequently investigated topic. Their review shows that research interest has increased especially after 2014, but they reaffirm that the field still lacks empirical case studies and measured data.

The need for a more structured approach in assessing the environmental impacts of warehouses is emphasized by Dobers et al. (2023) [21] who argue that logistics platform buildings should be evaluated through sustainability key performance indicators (KPIs) that include embodied carbon, operational carbon, share of renewable energy, but also carbon emissions per tonne or pallet handled, emphasizing the importance of categorizing the industrial buildings by the level of automation, because that directly affects the impacts of lighting, refrigeration, material handling equipment and throughput.

Overall, existing literature suggests that warehouses are increasingly recognized as important facilities for decarbonization in the building sector, but they remain methodologically less

developed than other building categories. This means that there is a clear need for more research that is based on case studies, better benchmarks, transparent data sources, clear categorization according to the building's level of automation and gross floor area, expanding the system boundaries to achieve a stronger integration between embodied and operational carbon. This provides the background for this thesis which focuses on this integration by performing an LCA of a case study building, examining how different design choices and increasing the share of renewable energy can influence total carbon impacts.

1.2.1.1. Reported carbon impacts in warehouse case studies

Collecting the results of published scientific papers reporting case studies, the literature shows a wide range of reported carbon impacts, depending on the building type, size, functional unit, geographical context, system boundary assessed. Some studies report impacts per square meter, while others use cubic meters, justified by large internal volumes of warehouse buildings. This variety therefore makes a direct comparison difficult, but still useful to identify the order of magnitude and methodological differences behind the results.

Table 1: Summary of reported carbon impacts in warehouse case studies.

Study	Building type and area	System boundary / scope	Carbon indicator	Reported result
Bonamente et al. (2014)	Italian prefabricated industrial buildings; parametric range from 1,000 to 25,000 m ²	Cradle-to-grave; includes production, assembly, transport, use and end-of-life over 20 years	Embodied + operational carbon	103.5 kg CO ₂ e/m ³ for a 1,000 m ² building, decreasing to 85.3 kg CO ₂ e/m ³ for a 20,000 m ² building
Bonamente and Cotana (2015)	Four Italian prefabricated industrial buildings; 1,048 to 21,910 m ²	Cradle-to-grave over 50 years	Embodied + operational carbon	144.6 kg CO ₂ e/m ³ for the smallest building, decreasing to 123.5 kg CO ₂ e/m ³ for the largest building
Bonamente and Cotana (2015)	Same four buildings	Cradle-to-grave, excluding use phase	Embodied carbon only	Average of 33.95 kg CO ₂ e/m ³ when the use phase is excluded
Rodrigues et al. (2018)	Industrial building in Portugal; 6,733 m ² effective construction area and 68,107 m ³ volume	Construction-focused embodied assessment; architectural and stability phases	Embodied carbon only	508.57 kg CO ₂ e/m ² , of which 495.79 kg CO ₂ e/m ² came from materials
Marrero et al. (2021)	Small industrial buildings in Seville; representative projects based on surveyed typologies	Construction and recovery potential assessment	Embodied carbon / construction carbon	Approximately 300–350 kg CO ₂ e/m ² , depending on construction solution

Ferreira et al. (2022)	Retail/warehouse-type building shell in Portugal; 16,473 m ²	Cradle-to-gate material assessment with comparison to operational data over 50 years	Embodied carbon and operational comparison	1,689 kg CO ₂ e/m ² embodied carbon; embodied carbon represented 94% of life cycle carbon
Arab et al. (2025)	Industrial building in Cairo; area not specified in the summary	OneClick LCA assessment focused on construction materials	Embodied carbon	29,122 t CO ₂ e total, equal to 132.98 kg CO ₂ e/m ² /year as reported
Dobers et al. (2023)	European logistics hubs; based on 416 projects	Life-cycle benchmark for hubs	Embodied carbon benchmark	Average of 8.3 kg CO ₂ e/m ² /year; DGNB benchmark of 9.4 kg CO ₂ e/m ² /year over 20 years

Table 1 shows that it is not possible to compare the reported results without considering the functional unit and boundary conditions. For instance, Bonamente et al. (2014) [22] and Bonamente and Cotana (2015) [23] assessing four case studies of precast industrial buildings in Italy report impacts per cubic meter as a functional unit. Their results shows that larger buildings have a lower carbon impact per unit volume because certain materials and envelope impacts are distributed over a larger internal volume. In Bonamente and Cotana [23], the carbon footprint decreased from 144.6 kgCO₂e/m³ for the smallest building to 123.5 kgCO₂e/m³ for the largest one. Similarly, Bonamente et al. [22] reported a decrease from 103.5 to 85.3 kgCO₂e/m³ as the building floor area increased. However, their results also show that the carbon impact does not decrease linearly with the increase of the building's size.

On the other hand, Rodrigues et al. (2018) [24], Marrero et al. (2021) [25] and Arab et al. (2025) [26] report results in terms of the building's floor area. Rodrigues et al. [24] found an embodied carbon impact of 508.57 kgCO₂e/m² for an industrial building in Portugal, while Marrero et al. [25] reported values around 300 to 350 kgCO₂e/m² for smaller industrial buildings in the city of Seville. In contrast, Ferreira et al. (2022) [27] reported a much higher embodied carbon impact of 1,689 kgCO₂e/m² for a storage building for retail in Portugal, which is actually related to the particular building typology, considering inclusion of an underground concrete structure and steel structure above the ground. This shows that industrial buildings can have very different embodied impacts depending on their structural systems and layouts.

A key takeaway from these case studies is that LCA results of industrial buildings are highly impacted by the selected functional unit. Impacts expressed per functional unit of square meter area are useful when comparing results in terms of floor area efficiency, while impact expressed per cubic meter might be more suitable for industrial buildings because two buildings with the same floor area can offer very different storage volumes, that affects the warehouse's operational capacity.

1.2.1.2. Contributors to embodied vs. operational carbon

In terms of embodied carbon, across the reviewed literature, the most consistent finding is that structural materials i.e. concrete, cement and steel are the dominating contributors to embodied carbon emissions. Case study of Rodrigues et al. [24] performing an LCA analysis of upfront carbon (concluding with the A5 stage) shows that out of the total embodied carbon of 508.57 kgCO₂e/m², only 4% is emitted from direct on-site construction inputs such as electricity, water and diesel, while 96% is due to materials production stage A1-A3. Arab et al. [26] arrived to a similar finding in their One Click LCA study where concrete and steel represented 84% of embodied carbon in the product stage for an industrial building in Cairo, with ready-mix concrete used in slabs and beams having dominantly the highest impact, followed by reinforcing steel bars. This aligns with results of Marrero et al. [25] who also identify concrete, cement and additionally metals as the main drivers of carbon footprint for a case study in Seville. Concrete and cement account for 75% of contributions to embodied carbon. The paper also touches upon the topic of recovery potential with metallic roofs offering high recycling potential, important when considering future reuse.

Another important perspective that a few research papers deal with is also the warehouse building shell/envelope. Ferreira et al. [27] show that even though reinforced concrete represented the most of the building's mass, it is not necessarily a factor that determines the highest environmental impact. Cement mortar and reinforced concrete were the highest contributors to embodied carbon, but also extruded polystyrene (XPS) showed relevant impacts. This finding is important because it shows that even lightweight envelope materials can still show significant contributions because of their energy-intensive manufacturing processes, but also replacement cycles, as they are less durable than the more massive and resistant reinforced concrete structures. Therefore, more attention shall be also given to the analysis of environmental impacts of the insulations materials used.

Kovacic et al. [28] focus particularly on the building envelope, comparing steel liner trays system, steel sandwich panels and cross-laminated timber (CLT) panels, showing that envelope choices can produce very different carbon results. Steel-based systems had a GWP of approximately 39-40 kgCO₂e/m², while CLT panels reached only 7.83 kgCO₂e/m² of the envelope. This represents a reduction of almost 80% in embodied carbon related to the envelope compared to steel alternatives, which is particularly relevant for warehouses with large envelope surfaces, and novel envelopes solutions such as timber-based ones represent a great potential in reducing the building's embodied impacts. However, this research also present a nuance in terms of service life, estimating two different scenarios. Baseline scenario of 35-years service life and prolonged scenario of 40-year service life are compared, where life cycle cost analysis revealed that the variant with CLT panels envelope becomes the most expensive one due to costs of replacement of the wood-fiber insulation in the 40th year. This gives a valuable insight for novel non-traditional solutions as durability issues might cause non-negligible additional impacts compared to traditional envelope solutions.

For what concerns operational carbon, the ratio between operational and embodied impacts is not consistent across the studies; however, the use phase often dominates. Bonamente et al. [22]

reported that the use phase accounted for 62% of the total carbon footprint for a 20-year buildings' service life, while Bonamente and Cotana [23] who used a 50-year service life found that the use phase had even higher contributions, reaching up to 75% of the total carbon footprint although a high-efficiency systems were implemented, without natural gas as the energy carrier. It is noteworthy mentioning that the case studies published do not include impacts of exterior works nor any materials outside the boundary of the physical building itself.

In the retrofit case study of Ciacci and Bazzocchi [29], the importance of operational energy in existing Italian precast warehouse buildings is confirmed. The operational B6 stage of LCA accounted for approximately 85-85% of total GWP of a typical traditional Italian precast warehouse constructed before modern energy standards, characterized by poor insulation of vertical walls and roofs delimiting conditioned spaces, asbestos-containing roof components, inefficient heating systems where generation of energy for space conditioning relies on natural gas boilers and fluorescent lighting systems. However, other studies show that embodied impacts become more visible as the operational energy is reduced through more efficient building systems or renewable energy. Dobers et al. [21] report that for modern warehouses user more efficient systems the difference between operational and embodied carbon impacts can be reduced, with literature estimates around 47% of embodied and 53% of operational carbon impacts on an annual basis. This means that as the buildings are becoming decarbonized from operational energy use point of view, the embodied carbon becomes proportionally more important.

The reviewed literature therefore suggests that the balance of embodied vs. operational impacts depends on three main factors: the life span assumed for the study, the energy performance of the building envelope and the type of energy supply and its carbon intensity. For a traditional building with natural gas heating and electricity completely taken from the grid, operational energy is reported to dominate. On the other hand, for a high-performance building that includes PV generation, embodied carbon impacts are emerging to the surface as the hotspot. This is very important for an LCA study of a modern warehouse, where both the construction materials and the operational energy profile must be assessed together.

1.2.1.3. Strategies for reducing the life-cycle impacts of warehouse buildings

The reviewed papers report several strategies for reducing the environmental impact of warehouse buildings. Overall, the proposed strategies can be grouped into four main categories: improving operational energy performance, integration of renewable energy, reduction of embodied carbon through finding alternative solutions for most impacting building materials, and increasing circularity through recycling and reuse.

The first strategy is suggested by Bonamente et al. [22] who in their case study show that higher level of insulation on walls delimiting conditioned spaces increase the embodied carbon of the product stage; however, this increase is compensated by lower energy demand during the use phase of the building. Balancing the impacts on embodied vs. operational carbon, the authors report the overall life cycle carbon reduction of 11%. Bonamente and Cotana [23] affirm these results by performing another case study, in which embodied carbon due to higher level of

insulation increased for 19.5% but the by reducing the operational carbon, the total net life cycle carbon reduction of 15.6% was achieved. This gives a valuable insight to how increasing the quantity of material used can actually reduce the building's whole-life carbon. However, the degree of reduction depends from case study to case study, depending on climate, considered service life, energy source, building composition, but also the year in which a warehouse was built. In modern warehouses with higher-efficiency building systems that also integrate PV plants, the additional impacts of insulation might be hardly justifiable, while in poorly insulated traditional warehouse buildings using natural gas for heating, increasing insulation thickness can be beneficial and a reasonable strategy.

Retrofit studies such as the one performed by Ciacci and Bazzochi [29] on an Italian precast warehouse show that combining envelope improvements with upgrades to buiding systems can actually produce stronger results than single isolated measures. The authors examined various retrofit scenarios, from the material substituion point of view such as wall insulation and roof development, to building systems improvements such as implementation of heat pumps, PV panels and LED lighting with smart controls.

Envelope component	Name	Type of intervention	Constructive solution
External Wall + windows	W1	Retrofit of the external walls without demolishing the existing ones	Installation of an internally insulated (rock wool insulation) false wall
External Wall + windows	W2	Retrofit the external walls without demolishing the existing ones	Installation of external sandwich panels (polyurethane insulation)
Roof + skylights	R	Demolition of the external fibre cement panels with asbestos and substitution of the existing roof	Installation of sandwich panels (polyurethane insulation)
System component	Name	Type of intervention	Constructive solution
System + Renewables	HP + PV _{min}	Substitution of the existing heating system and integration with renewables on-site	Installation of a heat pump and PV panels (minimum area)
System + Renewables	HP + PV _{max}	Substitution of the existing heating system and integration with renewables on-site	Installation of a heat pump and PV panels (maximum area)
LED + Light Control	LED + LC	Substitution of the existing lighting system	Installation of LED lighting and related lighting control
Combination	Name	Type of intervention	
External Envelope	COMB1	W2+R	
External Envelope + System	COMB2	R + LED + LC	
External Envelope + System	COMB3	R + HP + PV _{min}	
External Envelope + System	COMB4	R + HP + PV _{max}	
External Envelope + System	COMB5	R + HP + PV _{min} + LED + LC	
External Envelope + System	COMB6	W2+R + HP + PV _{max} + LED + LC	

Figure 1: Redevelopment measures proposed for a case study of an existing industrial building in Italy, Ciacci and Bazzochi (2024).

The most effective scenarios were the ones combining roof improvements with replacement of the heating system fueled by natural gas to air-to-air heat pump and PV installation. COMB 4 including roof, heating and PV and COMB 6 including walls, roof, heat pump, PV and LED lighting, both allowed the case study warehouse to become carbon-zero, with COMB 6 achieving up to 60% of electrical energy savings compared to the baseline.

Integration of the photovoltaic systems appears indeed as a one of the strongest strategies in warehouse buildings because of their large roof surfaces. In the aforementioned case study, installing the PV plant meant completely compensating for the environmental cost due to retrofit measures on the building materials and creating additional benefits through the export of generated electrical energy. In the case studies reported in the literature review of Ascione et al. [16] PV integration combined with recycling of building materials can even turn industrial buildings into net energy exporters, meaning that extending the system boundary to net benefits beyond the boundary itself (including the module D) is a novel way to approach life cycle assessment of modern warehouses.

Freis et al. [30] provide very valuable insights into carbon emissions of warehouse buildings depending on the level of automation and their intra-logistics systems. Their study also confirms that a low-carbon warehouse requires an integrated approach, including envelope, building systems and logistics of handling goods and materials. The optimized scenario of this case study includes measures such as VRF (VRV) space conditioning, LED lighting with dimming control and integration of PV systems. However, the authors also emphasize that reaching to a carbon-zero warehouse depends on the level of automation. Manual warehouses reach it more easily, while semi- and fully-automated warehouses may not be able to reach it following these strategies alone due to intra-logistics energy demands.

Finally, circularity and recovery potential are increasingly important, as highlighted by Ascione et al. (reference), who underline the need to move beyond the cradle-to-gate assessment and include end-of-life modules as well as even module D benefits more consistently, as the future of research on this topic. This is particularly relevant for warehouse buildings, as due to their large surface area and usually shorter service life than other building types, they can be re-adapted, expanded or dismantled. Overall, the literature suggests that the strongest reductions come from several measures combined rather than a single strategy, and that no single measure is sufficient in all cases. Therefore, the future of research in this field should focus on expanding the number of case studies, with various typologies of structure, envelope, level of automation and surface areas, to obtain a larger picture of the life cycle assessment of this building typology and move towards benchmarking the impacts according to main key performance indexes identified.

1.2.2. Reduction of a structure's GWP: Environmentally sustainable concrete alternatives

This part of literature review will focus more closely on the decarbonization challenge of cement and concrete, compared to the first part of literature review that provided an overall image of the state-of-the-art. The cement and concrete industry is recognized as one of the most carbon-intensive sectors globally, accounting for approximately 7–8% of human-induced CO₂ emissions. The extent and structure of these emissions are comprehensively detailed in "A Sustainable Future for the European Cement and Concrete Industry – Technology Assessment for Full Decarbonization of the Industry by 2050" from ETH Zurich [31]. This document presents the specific challenges that decarbonizing cement means today.

An important aspect of the ETH Zurich report is its clear depiction of cement decarbonization as a complex challenge that requires actions across the entire value chain, rather than relying solely on isolated technological solutions. The report identifies four levels of intervention that collectively define the pathway to achieving net-zero concrete by mid-century, therefore providing the context for the work analyzed in this thesis. Those stages are:

- The initial stage of intervention,
- The second level of intervention,
- The third level of intervention,
- The fourth level of intervention.

The initial stage of intervention is centered on improving the cement production process through initiatives such as enhancing energy efficiency, substituting fuels, electrifying processes, and implementing carbon capture techniques. According to the ETH Zurich roadmap, these measures primarily aim to reduce emissions intensity during production. However, they face limitations due to the process emissions inherent in clinker calcination. The report highlights that a substantial portion of emissions will continue to exist even with fully decarbonized energy sources unless the chemical composition of clinker itself is addressed.

As a result, the second level of intervention focuses on altering materials and cement composition by reducing the clinker content through the addition of supplementary cementitious materials (SCMs). The ETH Zurich report identifies clinker reduction as a very effective and easily implementable strategy for emissions reduction, especially in regions with established production capabilities. This aspect of intervention is a focal point in various studies, such as the study by Purnell and Black (2012) [32], which underlines the significant impact of cement quantity on embodied emissions.

The third level of intervention emphasizes the efficient use of concrete in construction and building projects, that focuses on material efficiency, structural optimization, and performance-based design. This approach shifts the emphasis from solely addressing the carbon intensity of materials to reducing overall material demand. The ETH Zurich roadmap highlights that excessive design and inflexible standards often lead to unnecessary material consumption. This perspective aligns with subsequent research, such as Almasailam et al. (2025) [33] and Berndt (2009) [34], which

identify structural design choices and concrete mix-design as leading drivers influencing life-cycle emissions.

The fourth level of intervention extends beyond individual structures. This includes strategies such as prolonging the lifespan of materials, promoting adaptive reuse, improving construction techniques, and reducing the overall demand for new concrete. This report therefore presents a systematic overview that highlights the importance of integrating material, structural, and design approaches rather than treating them as isolated components.

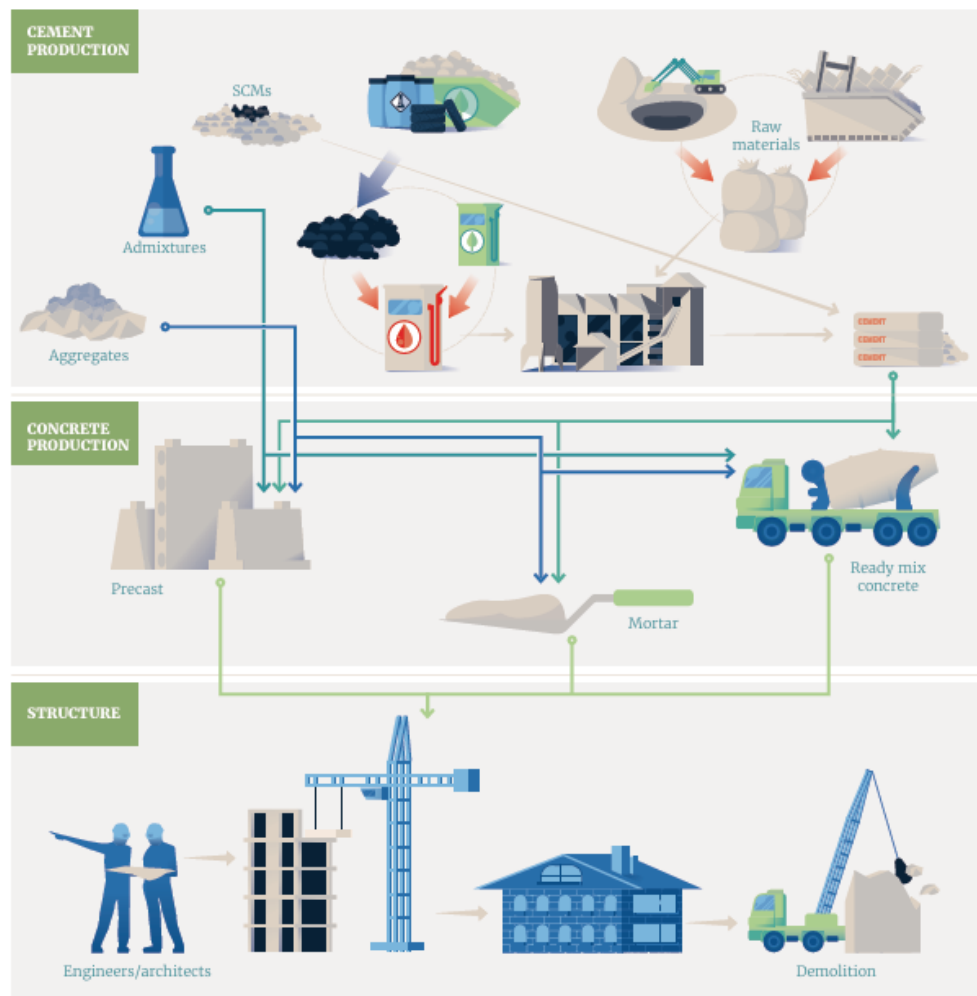


Figure 2: Representation of the levers for CO2 reduction along the concrete industry value chain.

In the literature reviewed, there is a general alignment with this four-level framework, even if the authors do not explicitly use the same terminology. This is relevant to the current thesis, which primarily focuses on the second and third levels: the reduction of clinker content and the influence of structural choices, but also the first level by analyzing the current market in the context of common production pathways of reinforced concrete. The following chapters focus deeper into how decisions regarding mix design, the use of secondary cementitious materials, and structural efficiency collectively contribute to reducing the embodied carbon in concrete construction.

In addition to material and structural strategies, the ETH Zurich report particularly underlines also carbon capture and storage (CCS) and carbon capture and utilization (CCU) as supply-side solutions to address the residual emissions that cannot be completely eliminated by merely reducing clinker usage. CCS involves capturing CO₂ emissions from the flue gases of cement plants and storing them geologically for prolonged periods, while CCU aims to convert captured CO₂ into products such as synthetic fuels, aggregates, or carbonated materials. The report asserts that these technologies are technically feasible and theoretically capable of addressing most emissions from clinker calcination. However, their extensive adoption is limited by significant capital costs, high energy requirements, infrastructure needs for transportation and storage and scalability. As a result, CCS and CCU are considered novel and necessary but insufficient strategies, where CCS and CCU are viewed as long-term enablers rather than primary decarbonization tools.

1.2.2.1. Mix design parameters affecting concrete carbon emissions

A general consensus through the reviewed literature is that the environmental performance of concrete is most of all influenced by the mix-design, rather than the choice of aggregates or transport distances which represent only a small fraction of environmental burden, which is particularly outlined in the research of Purnell and Black [32], emphasizing the role of cement content for the amount of embodied carbon in concrete.

To address the issue of environmental burden of cement content, it is important to understand the interdependence between the amount of cement, water and workability as a consequence. Mix-design is a recurring topic across the analyzed literature, among which Proske et al. (2013) [35] specifically address it by performing laboratory tests in which the authors show that the carefully targeted use of superplasticizers and particle packing make it possible to reduce both water and cement content but without compromising the mechanical strength.

This statement is supported by Müller and Haist (2024) [36], where the authors argue that reduction of water-to-cement ratio by optimally adding admixtures not only allows for reduced clinker content but also mechanical performance and durability. The author stress the importance of a performance-driven approach where a whole set of parameters must be tested together and the improvements are not achieved in isolation, i.e. slightly changing water-to-cement ratio will influence the superplasticizer dosage and vice versa. Research papers also address the question of environmental impact of adding admixtures, such as Almasailam et al. [33] which states that embodied carbon of admixtures is negligible to the one of the binder and that the benefits of using them in SCM cements greatly outweigh their negative environmental impact. Figure 3 presented in the paper by Proske et al. [35] illustratively summarizes the general path to achieving a more environmentally friendly concrete: targeted usage of superplasticizers increases packing density, important for achieving water reduction without compromising workability. Binder composition consequently changes by reducing the volume of cement and increasing SCM within the binder.

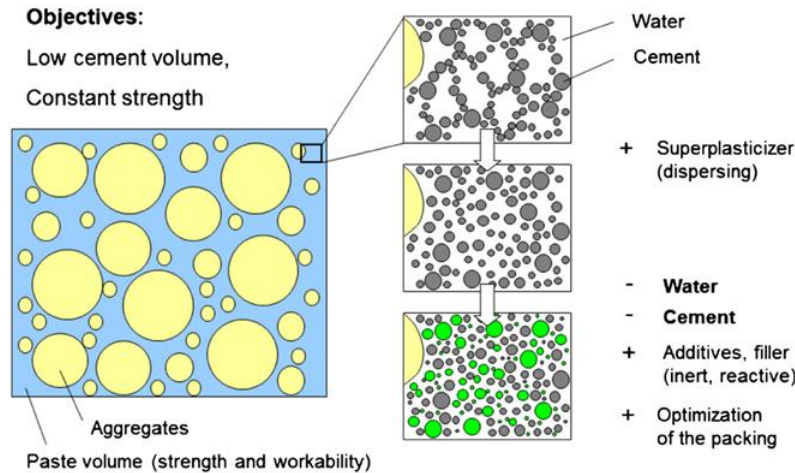


Figure 3: Illustrative summary of the pathway to achieve a more environmentally friendly concrete.

The addition of SCMs fundamentally transforms mix design approaches. A comparative sustainability assessment of binary blended concretes by Rahla et al. (2019) [37] reports a structured analysis of mixtures that include ground granulated blast furnace slag (GGBS), fly ash, and additional SCMs. The study shows that rates of clinker substitution result in corresponding decreases in embodied CO₂ at the material level. However what the study emphasizes is that the reduction of embodied carbon using SCMs directly depends on the replacement percentage of clinker by the SCM.

Relation between water content and SCM use is tested in multiple papers. Besides outlining the strategies to reduce cement volume, Proske et al. [35] also state among limestone, GGBS and fly ash, limestone is recommended as it contributes significantly to strength development, also achievable with the other two SCMs but their availability is a disadvantage compared to limestone which is widely available. Berndt's research paper on properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate [34] examines how the partial replacement of these materials with clinker affects the water dosage. For example, using fly ash enables both reductions of water content and plasticizer usage, while obtaining great workability. In contrast to this, replacement with GGBS while showing impactful result in reduction of embodied carbon as it allows higher percentage of clinker replacement compared to other SCMs, the dosages must be carefully controlled to obtain the desired early-strength, as discussed in the research paper of Crossin (2015) [38].

Figure 4 shows that concretes with lower clinker concrete mixed with SCMs are absolutely comparable and even better performing in terms of compressive strength compared to ordinary Portland cement. At the same amount of reduced clinker content and water volume, fly ash shows the best results although with a higher fly ash content and limestone mixes show the lowest earliest as well as later stage compressive strength development. On the other hand the highest

Furthermore, in terms of the embodied carbon impacts of sustainable concrete solutions, a comparative cradle-to-gate life cycle assessment of various concrete mix designs by Tait and Cheung (2016) [39] explicitly shows how concrete mix-design approaches influence the embodied

carbon of concrete within the Cradle-to-Gate life cycle boundaries. Conventional ordinary Portland cement mixture composed 100% of clinker is compared with mixes composed of fly ash of 35% and GGBS of 70%. With 28-day compressive strengths varying up to 5% between the tested mixes, it is demonstrated that per cubic meter of concrete sample, embodied carbon values equal to 334, 227 and 127 kgCO₂e per cubic meter sample for Mix 1, Mix 2 and Mix 3, respectively. This means that the mix containing 70% of GGBS reached 62% of decrease in embodied carbon compared to the mix fully containing clinker.

The magnitude of embodied carbon reduction aligns with the research of Purnell and Black [32], which provides more detail about the relation between mechanical strength and embodied carbon. This research is interesting as it provides values of embodied carbon of concrete per unit of structural performance. The results show that the strength at which ratio of embodied carbon per unit of structural performance is optimized is approximately 60 MPa. The implication that this conclusion leaves is that it is important to improve the mechanical performance of the concrete, in order to reduce its impact.

1.2.2.2. SCMs: Types, performance, environmental impacts and limitations

Table 2 offers a comparative overview of the main supplementary cementitious materials addressed in this review, summarizing concrete mixtures not only based on the global warming potential but also regarding the structural performance and real-world applicability. The table therefore reports environmental performance, mix design considerations, mechanical and durability factors, and important constraints.

Table 2: Summary of the main supplementary cementitious materials and real-world performance and applicability.

Study	SCM	Typical clinker replacement range	Reported GWP reduction (material level)	Mix design and water demand effects	Mechanical & durability implications	Main limitations & uncertainties
Crossin (2015), Rahla et al. (2019), Berndt (2009)	Ground granulated blast furnace slag (GGBS)	30–70% (higher in specific applications)	~40–60% reduction per tonne of binder	Neutral to slightly increased water demand; requires careful control of water-to-binder ratio and curing	Slower early-age strength; good long-term strength and durability	Allocation assumptions in LCA; dependence on steel industry; early-age performance
Rahla et al. (2019), Berndt et al. (2009), Purnell et al. (2012)	Fly ash	15–50% (typically lower in structural applications)	~20–40% reduction depending on replacement level	Reduced water demand due to spherical shape; improved workability; can reduce superplasticizer use	Slower early strength; improved long-term durability and workability	Declining availability due to coal phase-out; variability in quality
Müller et al. (2024), Tait et al. (2016)	Silica fume	5–10% (performance-driven, not bulk replacement)	Limited direct GWP reduction; indirect via strength optimisation	Increases water demand; typically requires superplasticizers	Enables high strength and durability; reduced permeability	Limited availability; high processing energy; not suitable for large-scale substitution
Rahla et al. (2019), Müller et al. (2024)	Natural pozzolans	10–40% (region-dependent)	Moderate GWP reduction; context-specific	Variable water demand; requires mix-specific optimization	Moderate strength development; good durability when well designed	Material variability; regional availability; limited standardisation
Proske et al. (2013), Berndt (2009)	Combined SCM systems (e.g. slag + fly ash)	30–60% (combined)	Potentially higher than single SCM systems	Can balance workability and strength development	Synergistic effects on durability and later-age strength	Increased mix complexity; need for performance-based design
Ghazy et al. (2025), Barbhuiya et al. (2023), Hosen et al. (2025)	Limestone Calcined Clay Cement (LC3)	~40–50% clinker reduction (~50% clinker, 30% calcined clay, 15% limestone, 5% gypsum)	~35–45% reduction vs OPC, driven by deep clinker reduction and low-carbon SCMs	Slightly higher use of superplasticizers to optimize workability; further research needed into the long-term durability	Comparable or superior later-age strength to OPC; good durability	Requires calcined clay availability and controlled calcination; limited industrial deployment to date

The introduction given for the use of alternative binders from environmental point of view will now be deepened with the analysis of the four types of SCMs analyzed for this thesis, also giving a consideration to important constraints in their use.

Fly Ash

Fly ash is examined in both Berndt's [34] and Rahla et al. [37] research papers. These studies indicate reductions in embodied carbon usually between 20% and 40%, directly depending on replacement amounts. Fly ash has been demonstrated to enhance workability, mechanical strength comparable to the one of OPC and long-term durability, especially against chloride penetration. As a by-product from electricity generation by the process of burning of the pulverised coal [40], the environmental burdens assigned to fly ash are negligible. At the same time, authors highlight uncertainties on the supply side. The reduction of coal-fired electricity production in decarbonizing economies is recognized as a significant constraint on the long-term scalability of approaches integrating fly ash into the binder. This represents a conflict between short-term mitigation possibilities with fly ash and long-term accessibility.

Silica fume and Natural pozzolans

Silica fume is mainly addressed as a performance-boosting SCM instead of a mass clinker substitute. Research such as the one by Müller and Haist [36] highlights that although silica fume allows for the creation of high-strength and high-durability concretes, its restricted availability but also economic considerations limit its effectiveness for reduction of emissions on a larger scale. Natural pozzolans are regionally significant alternatives especially for Italy since the origin of natural pozzolana is from volcanic deposits [40]. They provide moderate CO₂ reductions with less supply limitations; however there is a great potential in using natural pozzolans exactly due to natural formation hence their availability, that could be a decisive factor to opt for this type of SCM rather than other types that are by-products of industrial processes.

Ground Granulated Blast Furnace Slag (GGBS)

GGBS along with fly ash is the most reported and tested SCM, due to its ability of high replacement percentage with clinker. The study by Crossin [38] indicates that substituting clinker with GGBS can lower embodied CO₂ by over 40–60% per tonne of cementitious product, varying based on allocation assumptions and substitution levels. This is aligned with results of Tait and Cheung [39]. It is very crucial, however, for GGBS to consider allocation assumptions, addressed in the research of Proske et al. [35] that emphasizes methodological sensitivities in life cycle assessment, especially concerning co-product allocation in steel manufacturing.

Figure 4 presented in the aforementioned research paper shows that GWP of concretes that use GGBS is higher when economic allocation is considered. GGBS is essentially a by-product of iron manufacturing using a blast furnace production path. As recently the iron production process has been electrified by the use of electric arc furnaces, blast furnace slag is becoming less available and is a source directly dependent on the existence of blast furnace production plants. Due to higher need of exporting of the furnace slag, assigning the slag in the life cycle methodology as a valuable product rather than a waste (or by-product) means assigning a certain percentage of environmental burdens coming from iron/steel production.

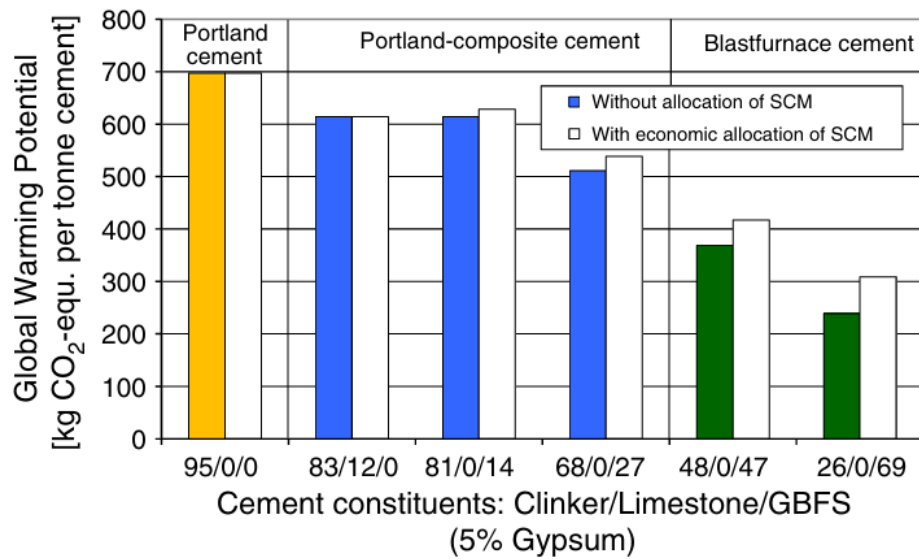


Figure 4: GWP of GGBS (or GBFS) with and without economic allocation.

Therefore, the availability limitation presents a challenge: although GGBS provides significant environmental benefits, a widespread use of GGBS may not be practical or ideal for every application. As a result, various studies analyzed suggest that GGBS should actually be implemented for exposure classes where its durability advantages are the most significant factor, which leaves space to consider also other low-clinker binders such as LC3, that depend on more available raw materials.

Besides this limitation, authors such as Berndt [34] outline positive long-term strength growth and durability traits. Nonetheless, reduced early-age strength development is a practical limitation addressed, that affects curing practices and construction timelines.

1.2.2.3. Limestone Calcined Clay Cement (LC3): Properties, mix-design and decarbonisation potential

Limestone Calcined Clay Cement (LC3) has gained increasing attention as a novel low-clinker binder capable of addressing both the environmental limitations of Portland cement and the resource constraints associated with conventional SCMs. LC3 systems are based on a combination of clinker, calcined clay and limestone, that enables substantial clinker reduction while maintaining performance.

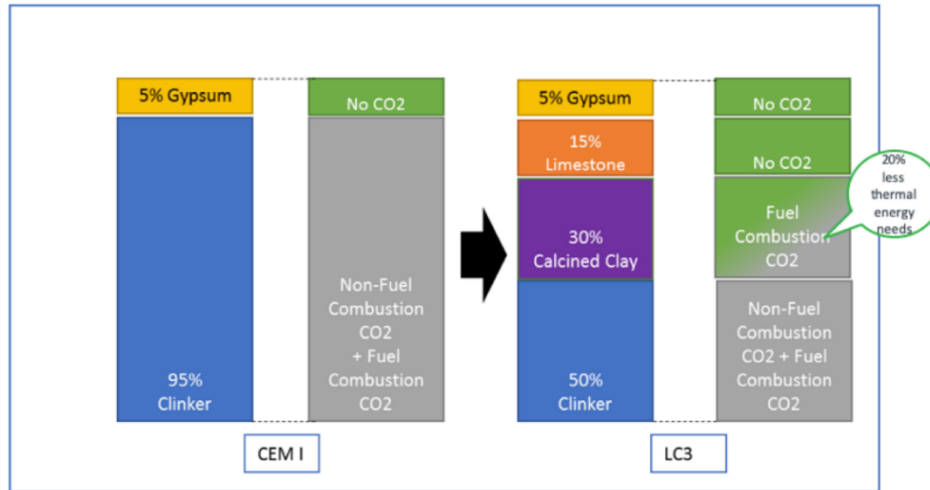


Figure 5: Composition of the LC3 cement.

As discussed in a review paper by Hosen and Chen (2025) [41], LC3 typically incorporates 30–40% calcined clay and 10–15% limestone, with clinker contents reduced to approximately 50% or even less. The calcination of clay occurs at significantly lower temperatures than clinker production, resulting in significantly reduced energy demand and CO₂ emissions. Importantly, the clays suitable for LC3 production are widely available globally, often requiring clays with lower level of purity, compared to kaolinite-rich clays used in metakaolin production.

The performance of LC3 is achieved by hydration mechanisms between calcined clay and limestone. A review on the properties, compatibility, environmental benefits and future directions of limestone calcined clay cement (LC3) concrete by Barbhuiya et al. (2023) [42] describes how alumina released from calcined clay reacts with calcium carbonate from limestone to form carboaluminate phases, refining pore structure and improving early-age strength development. While LC3 systems may exhibit slightly higher water demand due to the fine particle size of calcined clays, optimized mix designs using modern superplasticizers have been shown to achieve workability and strength levels comparable to OPC-based concretes.

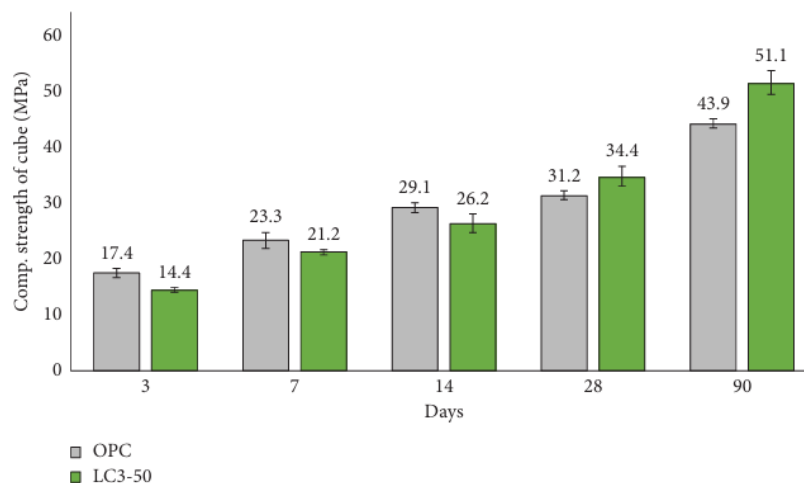


Figure 6: Comparison of the strength development of LC3-based concrete vs. concrete with Ordinary Portland cement.

From an environmental perspective, LC3 consistently demonstrates reductions in global warming potential. A comprehensive review of limestone calcined clay cement (LC3) by Ghazy et al. (2025) [43] reports CO₂ emission reductions in the range of 30–50% relative to conventional CEM I systems, depending on clinker substitution levels and regional energy mixes. These reductions are primarily due to lower clinker content and reduced calcination temperatures, rather than reliance on scarce industrial by-products. Published review papers on LC3 concrete position it as a strategic bridge between traditional SCM use and future alternative binders. By utilizing abundant raw materials and an already established cement production infrastructure, LC3 offers an industrially realistic pathway toward deep decarbonisation of cement and concrete.

Overall, the reviewed literature positions LC3 as one of the most promising solutions for a widespread low-carbon concrete production, particularly in regions where GGBS and fly ash availability is limited. The combination of environmental performance, material availability but also compatibility with existing construction practices makes LC3 a compelling focus for the present thesis.

1.2.2.4. Structural optimisation and material efficiency strategies

Beyond material substitution at the mix level, several of the reviewed studies demonstrate that structural optimisation and material efficiency actually play a decisive role in reducing the embodied carbon of concrete construction. Rather than focusing solely on the carbon intensity of concrete per cubic metre, these studies shift the analytical focus toward the functional unit of the structural element or building which actually reveals important interactions between concrete strength, material volume, and cement content.

A very insightful contribution is provided by Almasailam et al. [33]. This study systematically evaluates how changes in concrete strength influence the total carbon footprint of reinforced concrete structures. The authors demonstrate a clear structural trend: increasing concrete compressive strength allows for reduced cross-sectional dimensions, leading to a decrease in total concrete volume. From a purely structural efficiency perspective, higher-strength concrete therefore appears advantageous. However, the study also reveals a critical paradox. When ordinary Portland cement (CEM I) is retained as the binder, higher-strength concretes consistently exhibit higher total embodied carbon, despite the reduction in material volume. This outcome is explained by the disproportionately higher cement content required to achieve increased compressive strength, which outweighs the emissions savings associated with volume reduction. As a result, the authors show that strength-based optimisation alone does not guarantee lower carbon footprints when conventional cement systems are used.

Research papers such as Hafez et al. (2024) [44] who present a parametric study on the decarbonization potential of structural system and concrete mix design choices, affirm this trend. Through a parametric building-scale analysis, the authors demonstrate that while higher-strength concrete can reduce structural material quantities, the net carbon outcome remains highly sensitive to binder composition. In scenarios relying on high-strength CEM I-based concretes,

total embodied emissions frequently increase, confirming that structural efficiency gains can be actually negated by cement-intensive mix designs. This discovery motivates the exploration of alternative binder compositions. In Almasailam's research paper [33], the authors extend their analysis by replacing CEM I with a GGBS-based cement (CEM III/A). Under this configuration, they report carbon footprint reductions of up to approximately 45% in non-aggressive exposure environments.

Crucially, these reductions are achieved while retaining the structural benefits of higher-strength concrete, indicating that SCM-based binders can fundamentally change and enhance the strength–carbon relationship. A similar conclusion is reached by Hafez et al. [44] where the combination of SCM-rich binders and optimised structural systems leads to substantially lower embodied emissions compared to conventional designs. The authors highlight in their findings that structural optimisation becomes environmentally effective only when paired with low-clinker or SCM-rich concrete mixes. However, despite the demonstrated environmental benefits of GGBS-rich cement systems, several authors explicitly underline that GGBS is a scarce and regionally constrained resource, whose availability is linked to steel production. As a result, the authors argue that GGBS should be prioritised for applications where its durability benefits are essential, such as aggressive exposure environments.

In conclusion, the reviewed literature establishes that structural optimisation is not an independent decarbonisation strategy, but one that is tightly coupled to concrete mix design. Higher-strength concretes can reduce material demand, but without low-clinker binders, these gains may be offset by increased cement-related emissions. Conversely, when combined with SCM-rich cements, structural efficiency becomes a promising lever for reducing embodied carbon. The available literature therefore provides a nuanced understanding of sustainability that extends beyond carbon metrics alone, but also shows how important it is to account for resource availability and long-term material supply constraints. Rather than maximising clinker replacement in all cases, the authors advocate a context-sensitive approach.

1.2.3. Main research question

The purpose of this thesis is to respond to research gaps that remain in the reviewed literature. The first major gap is the limited number of real case studies and the fact that industrial buildings remain underrepresented in LCA literature, as highlighted in the literature review. Although some research papers mention certain KPIs such as embodied carbon, operational carbon and share of renewable energy, there is still a need for more case studies of various warehouses among structural and envelope systems, building technologies and levels of automation, in order to enable for the categorization and benchmarking. Therefore, this case study can present a contribution to the current state-of-the-art by expanding it with a life cycle assessment of a real modern warehouse building aligned with sustainability protocols such as LEED and BREEAM.

The second gap concerns comparability. The reviewed studies use different functional units, but also reference service lifetimes, system boundaries and data sources. Some papers report GWP impacts in terms of $\text{kgCO}_2\text{e}/\text{m}^2$, i.e. as the functional unit of gross floor area of the building, others

in terms of $\text{kgCO}_2\text{e}/\text{m}^3$ or $\text{kgCO}_2\text{e}/\text{m}^2/\text{year}$. Another limitation to a just comparison is that some include operational carbon, while some papers focus exclusively on embodied carbon. Furthermore, many studies include only the system boundary of the product stage A1-A3, following the Cradle-to-Gate approach. This makes it difficult to define a single benchmark for carbon performance of a warehouse. Since both floor area and volume are important, the research field might benefit from future studies reporting both.

The third gap, and the one that this thesis case study particularly focuses on is the integration between embodied carbon and operational energy. Namely, besides the state-of-the-art having a lack of real case studies, the ones that exist rarely include both with strategies of optimization represented on a building level regarding the whole-life carbon. Although the optimization of building materials might seem detached from reduction of building's operational carbon emissions, the connection between the two is what this thesis seeks to explore as well, through proposed decarbonization pathways for reduction of embodied carbon due to production processes of most carbon-intensive materials, and decarbonization of the grid through integration of renewable energy systems. Going beyond a single optimization strategy as a strong approach is confirmed through the literature review. A following step is then understanding the energy-intensive production processes behind materials that as output of LCA report the highest emissions. Possibility of these reductions in both structural and non-structural materials before the building is even built, combined with on-site energy generation during the building's use, is a point of view that has been explored in literature and that this thesis will attempt to deepen even further.

The fourth and final major gap is the treatment of replacement, refurbishment and end-of-life scenarios. As highlighted, many studies still do not fully account replacement cycles and possible benefits due to the end-of-life treatment and through module D beyond system boundaries. This is a limitation in assessing buildings such as warehouses, where envelope panels (depending on the type of system), building systems and lighting may have to be replaced during the building's life. In conclusion, there remains a need for more whole-life case-study-based and warehouse-specific life cycle assessment studies that report both embodied and operational carbon in a transparent, comparable way, that also propose optimization strategies on a whole-building level. This thesis will therefore seek to explore these gaps.

2. Life Cycle Assessment and Methodology of the study

2.1. Basic principles of LCA and technical standards

Life Cycle Assessment (LCA) is a systematic and transparent methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle. It allows a thorough analysis of the methods of materials extraction, production, transportation, use, and end-of-life, with the objective to suggest actions to reduce the environmental footprint utilizing specific indicators [45]. LCA focuses on environmental impacts in areas such as ecosystem health, human health, and resource depletion, without considering economic or social aspects. LCA is recognized as a standardized framework that includes four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation. They are defined as follows:

- Goal and scope definition: This initial phase establishes the purpose of the study and the reasons for conducting it. The scope is defined, including system boundaries and the functional unit, which serves as the reference point for all calculations.
- Life Cycle Inventory (LCI): In this phase, detailed data are collected on all inputs (i.e. raw materials, energy, water) and outputs (emissions, waste, by-products) associated with the system. Accurate and comprehensive data collection is essential for reliable results. The data are organized into energy and material flows, forming a detailed inventory of the system.
- Life Cycle Impact Assessment (LCIA): The inventory data are then evaluated to assess potential environmental impacts. These are categorized into impact categories such as climate change, eutrophication, acidification, resource use, human toxicity, etc. Each category is quantified to determine its environmental significance.
- Interpretation: The final phase involves analyzing the results from the previous steps to draw meaningful conclusions and make recommendations. It includes identifying key areas for improvement, evaluating data quality and reliability, and proposing strategies to reduce environmental impacts. The interpretation must align with the goals established at the beginning of the assessment.

By considering all stages of a product's life cycle, LCA supports optimizing use of resources and guiding informed decision-making. Furthermore, it facilitates compliance with environmental regulations and standards such as ISO 14040 and ISO 14044, contributes to corporate responsibility and transparency, and promotes communication with stakeholders. It can also lead to cost savings through more efficient resource management and encourage innovation in environmentally friendly solutions.

It is noteworthy mentioning that defining material is not a simple process. To explain this, studies such as Ascione et al. (2026) [16] give an example of concrete. Although cement and concrete are both materials, cement is one component of concrete. Their composition, raw material extraction location and production plant may completely differ. After all the components of a concrete mix are defined and their impacts quantified, the product can be defined. It is defined as the composition of multiple components that constitute the final product. Quantification is

performed by summing up the emissions of each material that the final product is composed of. Therefore, evaluating the final product (such as a building, or the concrete that creates it) means evaluating the individual components that compose it, with all their individual material emissions.

Life Cycle Assessment is governed by internationally recognized standards that establish the fundamental principles and methodological framework to ensure consistency, transparency and credibility in the results. The complete regulatory framework includes the following European and ISO standards.

The core standards that regulate LCA are ISO 14040 and ISO 14044:

1. ISO 14040 – *Environmental Management – Life Cycle Assessment – Principles and Framework*. This standard provides a general overview of the key principles, structure and requirements for conducting an LCA [46].
2. ISO 14044 – *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. This standard specifies the technical and methodological requirements, including goal and scope definition, inventory analysis, impact assessment, and interpretation [47].

These standards ensure that the LCA process is systematic and based on robust and reliable data, covering all life cycle stages from raw material extraction to final disposal.

The European standards, focused on the built environment, are the following:

1. EN 15804:2012+A2:2019 – *Sustainability of construction works – Environmental Product Declarations – Core rules for the product category of construction products (Product level)*
2. EN 15978:2011 – *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (Building level)*
3. EN 15643:2021 – *Sustainability of construction works – Framework for assessment of buildings and civil engineering works (Sustainability assessment framework)*

Standards related to Environmental Labeling and Declarations are the following:

1. ISO 14021:2016 – *Environmental Labels and Declarations – Self-declared Environmental Claims (Type III)*
2. ISO 14024:2018 – *Environmental Labels and Declarations – Type I Environmental Labelling – Principles and Procedures*
3. ISO 14025:2010 – *Environmental Labels and Declarations – Type III Environmental Declarations – Principles and Procedures*

Finally, the standards addressing particularly sustainability in construction are:

1. ISO 21930:2017 – *Sustainability in buildings and civil engineering works – Core rules for Environmental Product Declarations of construction products and services*
2. ISO 15392:2019 – *Sustainability in buildings and civil engineering works – General Principles*

2.2. Stages of Life Cycle Assessment

Performing a Life Cycle Assessment means including the following stages, structured according to the modular approach defined in the standard EN 15804:

- **A1 – Raw Material Supply:** Extraction and processing of raw materials used in construction products.
- **A2 – Transport:** Transportation of raw materials to manufacturing facilities.
- **A3 – Manufacturing:** Production of construction materials and components.
- **A4 – Transport to the site:** Delivery of construction products to the building site.
- **A5 – Construction and installation:** On-site construction activities, including energy use, waste generation, and resource consumption.
- **B1 to B7 – Use Phase:**
 - B1: Use of the building.
 - B2: Maintenance.
 - B3: Repair.
 - B4: Replacement of components.
 - B5: Refurbishment.
 - B6: Operational energy use.
 - B7: Operational water use.
- **C1 to C4 – End-of-life:**
 - C1: Deconstruction and demolition.
 - C2: Transport of waste materials.
 - C3: Waste processing.
 - C4: Final disposal.
- **D – Benefits and Loads Beyond the System Boundary:** Potential environmental benefits from reuse, recycling, and energy recovery of materials at the end of the building's life.

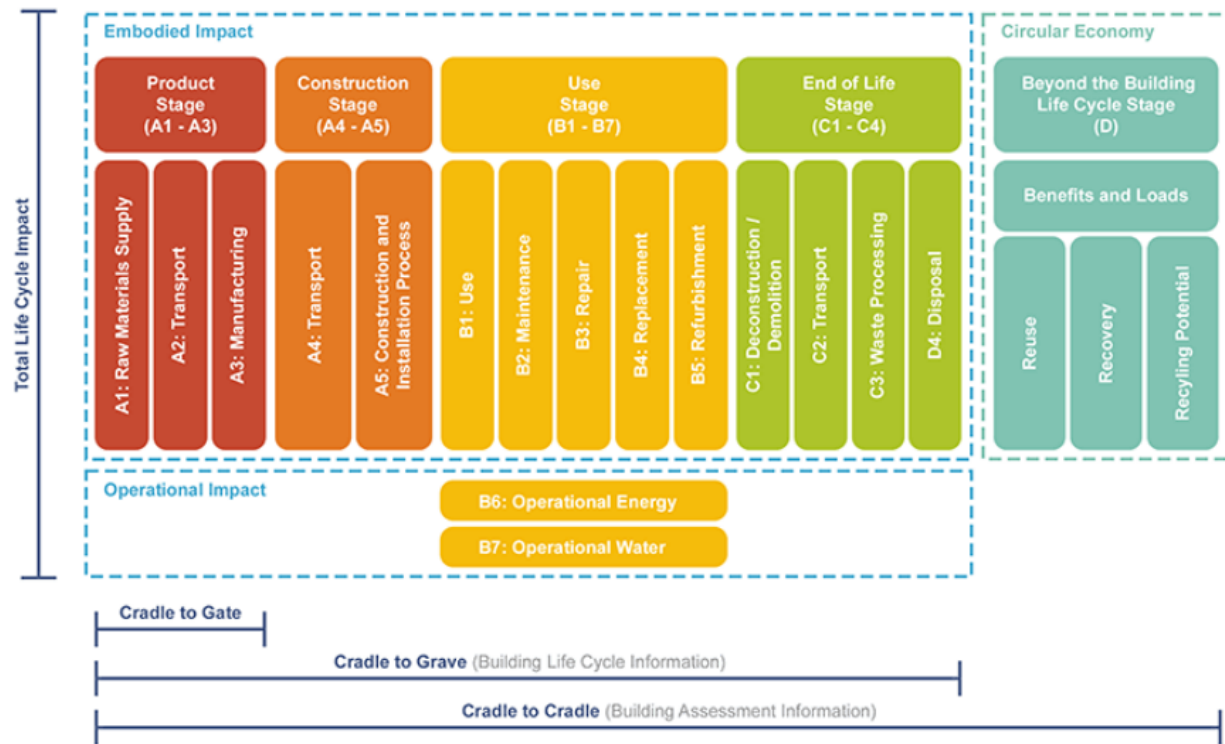


Figure 7: Schematic representation of all the stages of the Life Cycle Assessment.

In Life Cycle Assessment it is crucial to distinguish between embodied impact and operational impact (which in this thesis will be referred to as embodied carbon and operational carbon).

Embodied carbon (EC) refers to the total GHG emissions associated with materials and construction processes across the entire life cycle of a building [48]. EC also depends on the chosen system boundary within the life-cycle assessment, therefore there are three commonly accepted definitions: cradle-to-gate, cradle-to-site and cradle-to-grave EC. Depending on the life stage during which carbon is emitted, EC is classified into three categories: initial, recurring and demolition EC [49]. Initial EC is emitted due to production and construction stages, while recurring EC is emitted due to building maintenance and renovation/rehabilitation, two terms used interchangeably in the literature. Finally, demolition EC is emitted from the end-of-life (EoL) stage.

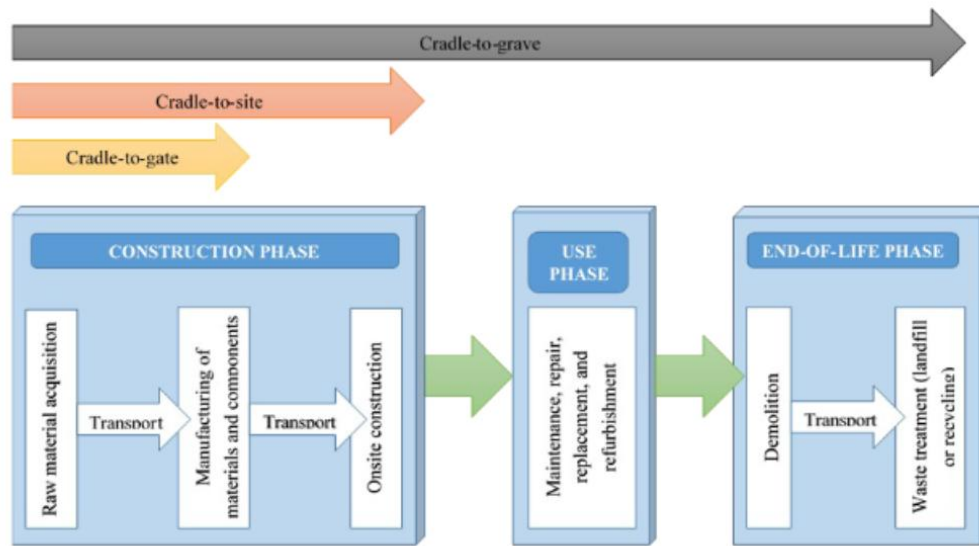


Figure 8: Schematic representation of the three main stages of Life Cycle Assessment.

On the other hand, Operational carbon (OC) emissions are released from direct combustion of fossil fuels and indirect purchase of electricity and heat for the building's operational stage [48]. OC emissions are directly related to maintaining comfort inside of the building, consumption of domestic hot water, lighting and appliances. Therefore, the share of operational carbon emissions in the life-cycle carbon emissions (LCCE) is highly related to the final destination of use of the building, i.e. the level of operational energy consumption [50].

Table 3: Origins of embodied and operational carbon.

Embodied carbon	Operational carbon
Carbon resulting from: – Embodied energy used to extract, process, assemble, transport, construct, repair, deconstruct and dispose of materials – Chemical reactions – Sequestration (carbon absorbed)	Carbon resulting from: – Operational energy use; whole building uses a mix of fuel types

2.3. Goal and Scope of the study

The goal of this LCA study is to evaluate the environmental performance of the building with a gross floor area (GFA) of 55,167.82 m², located in the Castel San Pietro Terme Municipality, in the city of Bologna (BO), in Italy. The building's destination of use is a logistics platform building

or a warehouse. Further on, this thesis will refer to the building as the warehouse. In terms of the impact categories assessed, this analysis is limited in scope of assessment to Global Warming Potential (GWP) impact category exclusively. Global warming potential is currently identified as an impact with the highest profile [51]. This means that it is the most policy-relevant impact category, with decarbonisation strategies in the construction sector being primarily driven by the materials' effect on the greenhouse gases emissions. Other impact categories most frequently reported in published studies are Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP).

The scope of this LCA has been defined according to the following categories:

- Functional unit. The analysis quantifies environmental impacts based on individual product data provided in Environmental Product Declarations (EPD) or from an existing data-base in case there is no available EPD for a material. Environmental impacts are referenced against a declared unit (e.g. 1m, 1m², 1m³, 1kg, 1t). The impacts are then normalized to the project's functional unit, which in this case study can be defined both as the gross floor area measured in square meters (m²) or gross volume measured in cubic meters (m³), as the discussed scientific papers in the literature review show report both as the functional unit.
- System boundaries. In terms of the boundary to which life cycle stages are assessed, this study adopts a Cradle-to-Grave boundary (Modules A1–C4) and intentionally excludes Module D (Benefits and loads beyond the system boundary). While Module D will provide valuable insight into potential future circularity, academic literature cautions that it introduces immense scenario uncertainty into comparative LCAs. As highlighted by Anderson et al. (2019) [52] and Delem et al. (2019) [53], Module D metrics are inherently volatile and highly speculative, because they are relying on hypothetical market assumptions and future recycling efficiencies that will occur decades into the future, therefore including Module D presents a risk of distorting the results.
- Cut-off criteria. Minor elements such as connectors between structural elements (e.g. screws and nails) have been excluded from the analysis due to their minimal contribution to the building's total environmental impact.

2.4. Methodology of the study

This study adopts a structured approach to performing a Life Cycle Assessment of a prefabricated industrial building. The literature search targeted peer-reviewed scientific articles and publications between 2012 and 2026 and indexed in ScienceDirect and Scopus, chosen for their relevance to life cycle-based methodologies related to building energy performance and building materials sustainability evaluation. The keywords “logistics platform”, “industrial building” and “warehouse” were used interchangeably during research, and in combination with keywords related to sustainability assessment such as “LCA”, “life cycle assessment”, “sustainability”, “GWP”, “carbon footprint”, or “environmental impact”. Only studies explicitly related to industrial

buildings/warehouses or construction materials related to industrial applications through a life-cycle methodology were considered.

While some scientific papers included in the literature view of this study strictly exclude literature on non-industrial sectors to maintain a narrow focus, this research adopted a different approach based on material-level coherence. Publications and scientific articles addressing residential or commercial non-industrial buildings were retained if they investigated material-level optimization, such as eco-sustainable concrete formulations or insulation materials. Since the environmental profile of these materials remains applicable regardless of the building typology, reviewing these papers aligned with the core objectives of this study. This approach ensured a broader foundation for evaluating sustainable material alternatives for the warehouse structure without compromising the industrial relevance of the project.

Certain limitations regarding the literature search must be recognized as well. The scarcity of existing contributions is a limitation which indicates that LCA applications within the industrial building sector are still emerging. Regardless, this thesis serves as a basis for future research, and practical advancements in the field of warehouse buildings, covering certain gaps identified within the current published literature.

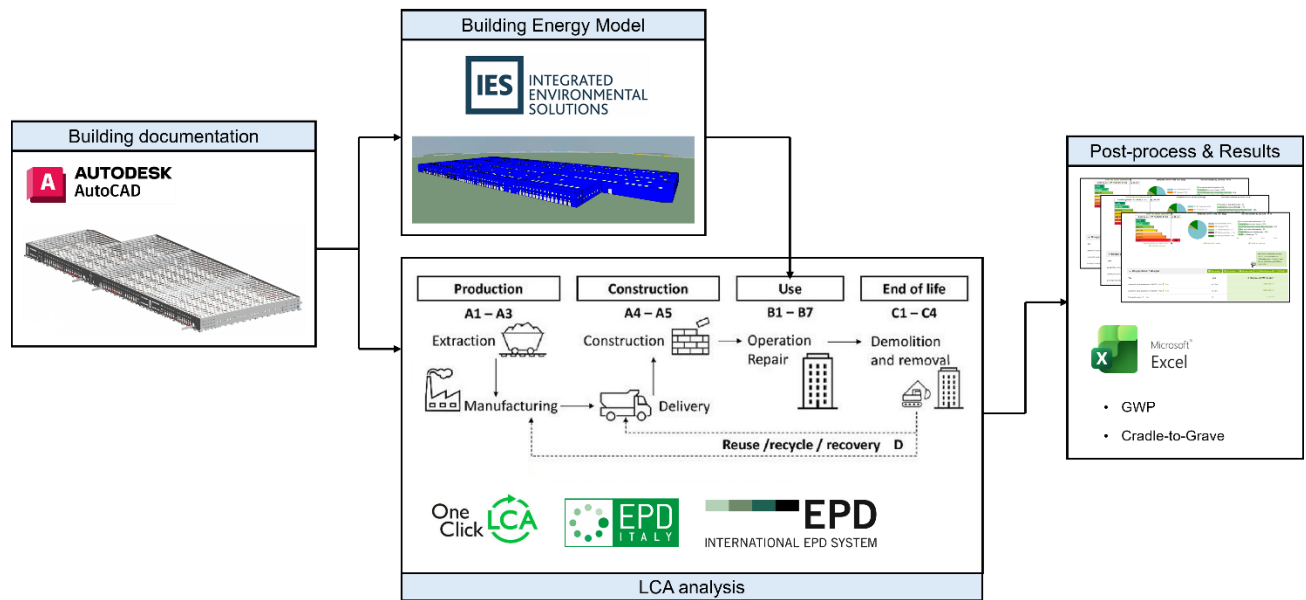


Figure 9: Workflow of the research method.

For what concerns the actual workflow of the analyses performed, it was based on the executive design documentation, including architectural, structural, mechanical, and electrical AutoCAD drawings, together with the project's Bill of Quantities (BoQ). Building geometry, envelope properties, and HVAC system characteristics were used to develop a dynamic energy model in IES Virtual Environment (IESVE). IESVE is an integrated sub-hourly simulation software suite used to analyze building physics, thermal comfort, and HVAC system performance [54]. Using

this software, the building energy demand and HVAC performance was simulated. At the same time, material quantities extracted from the BoQ were imported into One Click LCA to assess the building's life cycle environmental impacts. One Click LCA is a specialized automated life cycle assessment platform designed to calculate the environmental impacts of buildings across different impact categories [55], in accordance with the technical standards outlined in the Chapter 2.1.

The BoQ data formed the basis for the embodied carbon assessment (Modules A1–A5 and C1–C4), while the annual energy consumption obtained from IESVE was used to calculate operational carbon emissions (Module B6). Material mapping within One Click LCA prioritized Italian Environmental Product Declarations (EPDs), including datasets from EPDItaly. Where local data were unavailable, equivalent European EPDs from the One Click LCA database were used. The results from both the LCA and energy simulations were exported to Microsoft Excel for post-processing, comparison, and visualization of the Global Warming Potential (GWP), allowing the evaluation and optimization of the building's overall life cycle performance.

The objective of the study is to perform an optimization of the embodied and operational carbon on the building level throughout the whole life cycle (Cradle to Grave). The optimization is structured to be performed across three axes: reducing the embodied carbon through improving the building structure, reducing the embodied carbon through improving the building envelope, and reducing the operational carbon through implementation of a photovoltaic (PV) system. Matrix of the final output is shown in the following table, outlining the baseline scenario representing the current state of the building according to the available inputs, and seven developed scenarios with the purpose of the whole-life carbon optimization. Scenario number 7 is the final scenario that represents the sinergetic optimization of the building, attempted to be achieved through integration of all three optimization axes.

Table 4: Matrix of GWP optimization axes on the building level, to be performed in the study.

Optimization axis	Scenario #	As-is building structure	Improved building structure	As-is building envelope	Improved building envelope	As-is building energy use	Improved energy use with PV plant
Baseline	Scenario 0	x		x		x	
Embodied carbon	Scenario 1		x	x		x	
	Scenario 2	x			x	x	
	Scenario 3		x		x	x	
Operational carbon	Scenario 4	x		x			x
Whole building carbon	Scenario 5		x	x			x
	Scenario 6	x			x		
	Scenario 7		x		x		x

3. Case study of the warehouse building

3.1. Description of the building's layout and geometry

The case study is a project of a logistics platform facility/industrial building/warehouse located in the municipality of Castel San Pietro Terme, Bologna (BO), within the industrial and commercial area „CA' BIANCA – Poggio Piccolo“. The access to the building is provided from the north-east from the roundabout connecting with Via S. Biagio and Via Ca' Bianca. The building is surrounded by agricultural lands to the north and west, by the Highway A14 to the south and the road Via S. Biagio to the east.

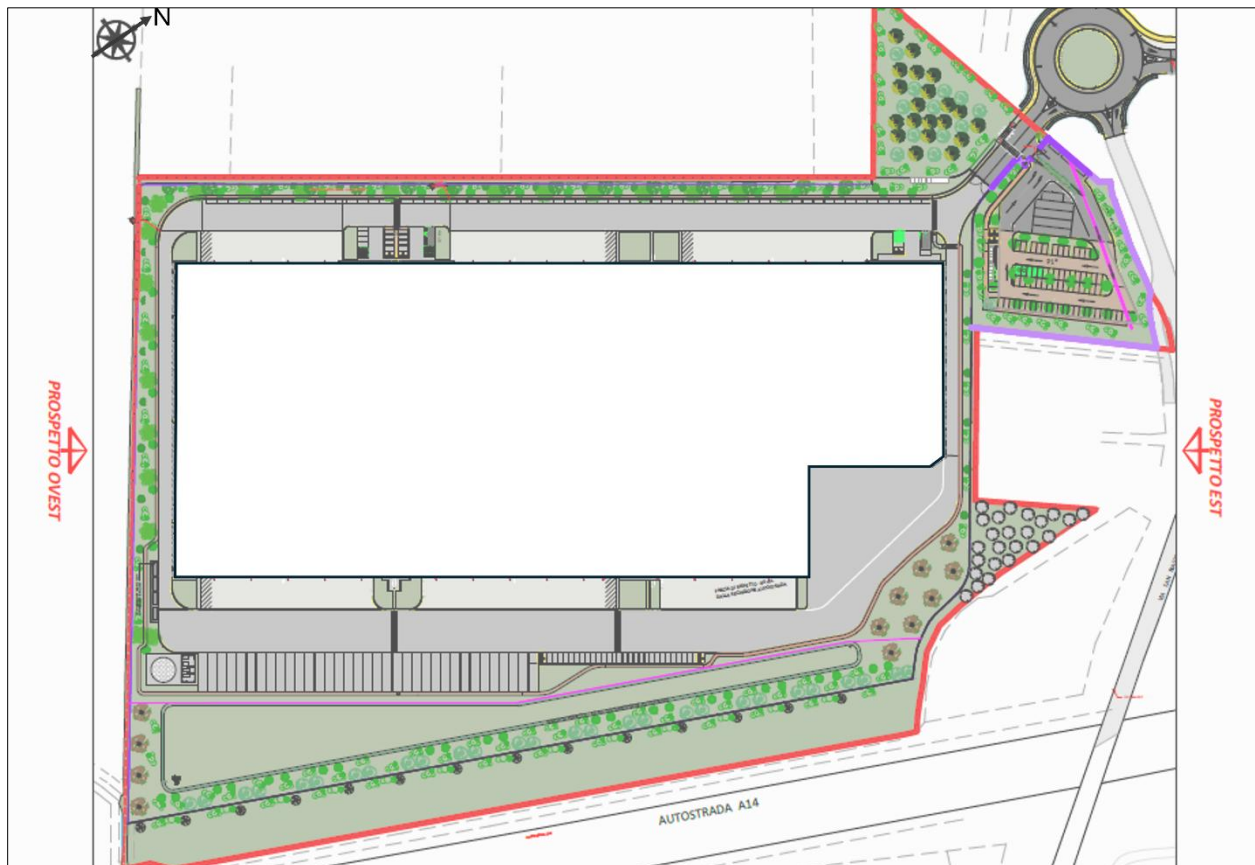


Figure 10: Master plan of the case study building “Castel San Pietro” in Bologna.

This purpose of this warehouse building is to provide safe and secure storage and comprises several actions related to temporary receipt, storage, picking, transport, maintenance, monitoring and shipment of material goods (inventories). The facility operates as a manual warehouse. As introduced in the literature review, the warehouses are divided into manual, semi-automated and automated warehouses. Therefore, this case study is of a warehouse building of the lowest level of automation. The physical handling of goods is performed by personnel using electric forklifts, reach trucks, and manual picking equipment. This operational setup requires unobstructed circulation routes and a controlled indoor environment to ensure efficient and safe working conditions.

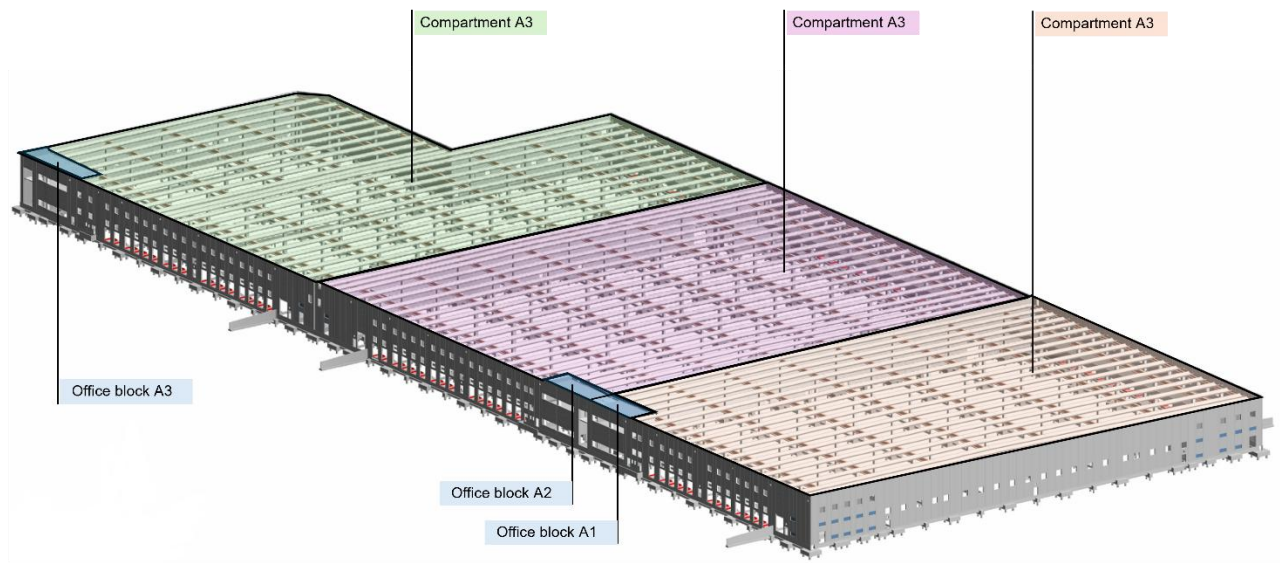


Figure 11: Isometric view of the case study building.

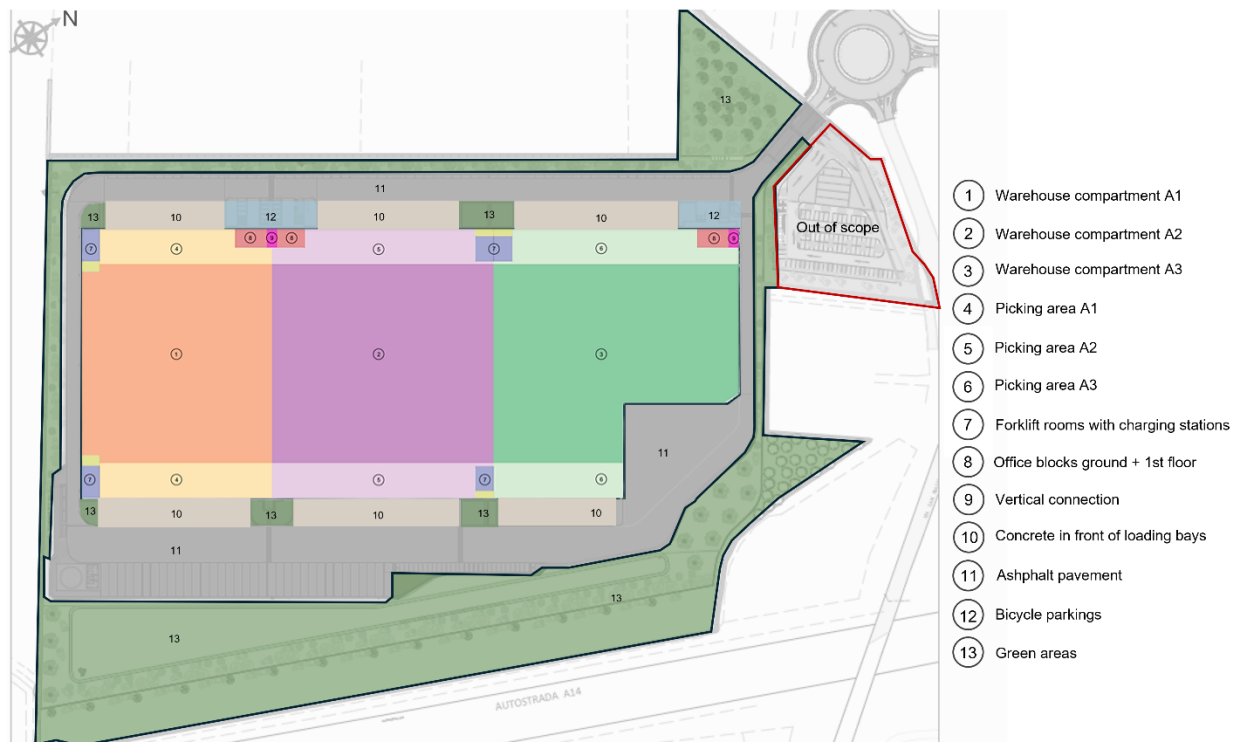


Figure 12: Schematic representation of the building's interior and exterior distribution of spaces.

The warehouse is equipped with 92 loading bays distributed along the north and south façades, where temporary receipt and picking of goods is handled. The building is divided into three independent compartments, primarily for fire safety and operational zoning purposes. Within these compartments, goods are stored in selective pallet racking systems that maximize vertical storage capacity. In addition to the warehouse spaces, the facility includes three dedicated office blocks, each associated with one warehouse compartment. The offices are arranged over two levels (ground floor and first floor) and accommodate administrative, logistics, and management functions.

The building shows a clear geometric contrast between its industrial zones and the administrative sectors, as summarized by the surface area metrics in the following figure. The primary warehouse envelope dominates the site with a footprint of 45,989.3 m² of floor area and 10,452.7 m² of vertical exterior walls, supplemented by a dedicated 1,387.2 m² forklift charging bay. In comparison, the three integrated office blocks occupy in total the footprint of just 953.5 m² of floor area, which represents a 48:1 spatial ratio between the blue-collar logistics floor and white-collar office zones, or 2.1% of office zones out of the total building area.

To optimize natural daylighting across the warehouse, the roof structure incorporates 3,532 m² of polycarbonate skylights. These skylights are fixed, non-openable thermal components during standard operation. Their mechanical actuators are strictly reserved for automated anti-smoke extraction and emergency fire protection workflows.

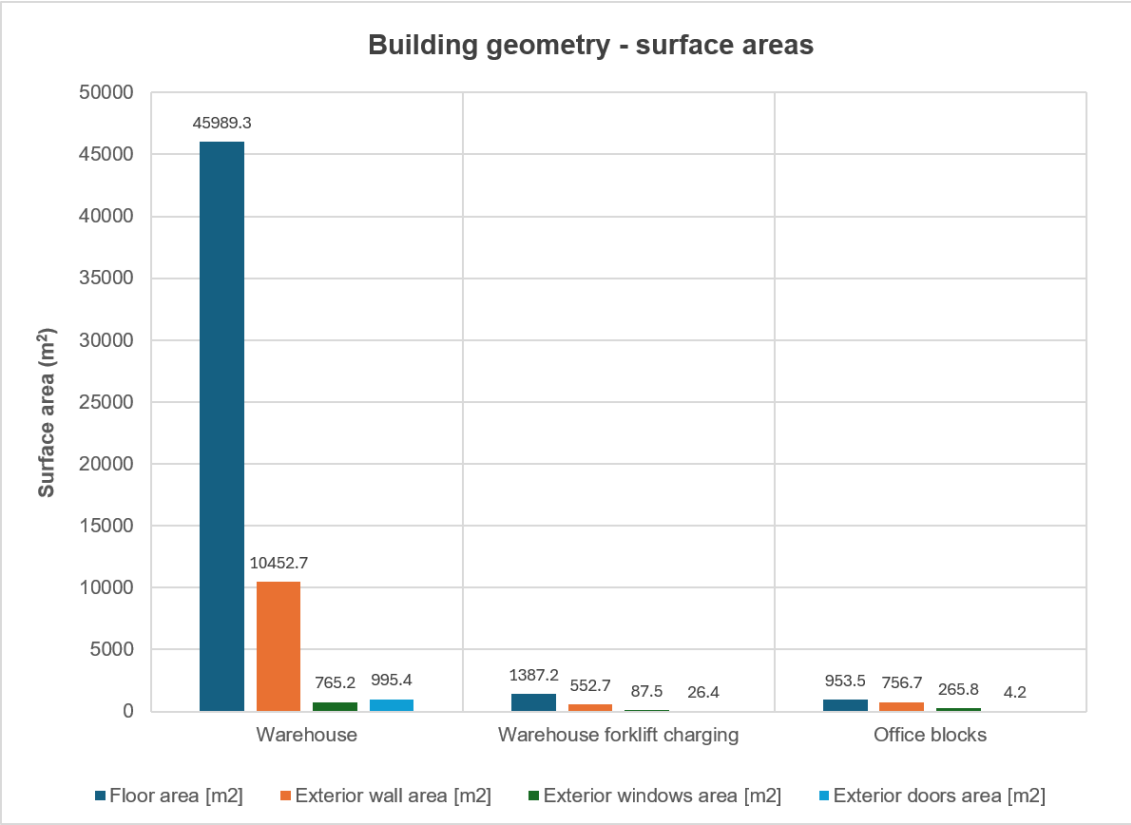


Figure13: Building geometry – surface areas between warehouse and office blocks.

3.2. Climate analysis of the city of Bologna

The city of Bologna, where the case study building is located, falls under the humid subtropical climate category (*Cfa*) according to the Köppen–Geiger climate classification. This classification is characterised by hot, humid summers and cool to cold winters, with no distinct dry season. Average summer temperatures often exceed 30°C, while winter temperatures frequently drop below 0 °C, and precipitation is relatively evenly distributed throughout the year.

Due to the *Cfa* climate, buildings in Bologna are exposed to seasonal as well as daily variations, making both heating and cooling energy demands relevant in the design of a building and its performance analysis. Following diagrams depict the climate of Bologna in terms of its outdoor dry-bulb temperature and irradiance, which will significantly influence the building's loads.

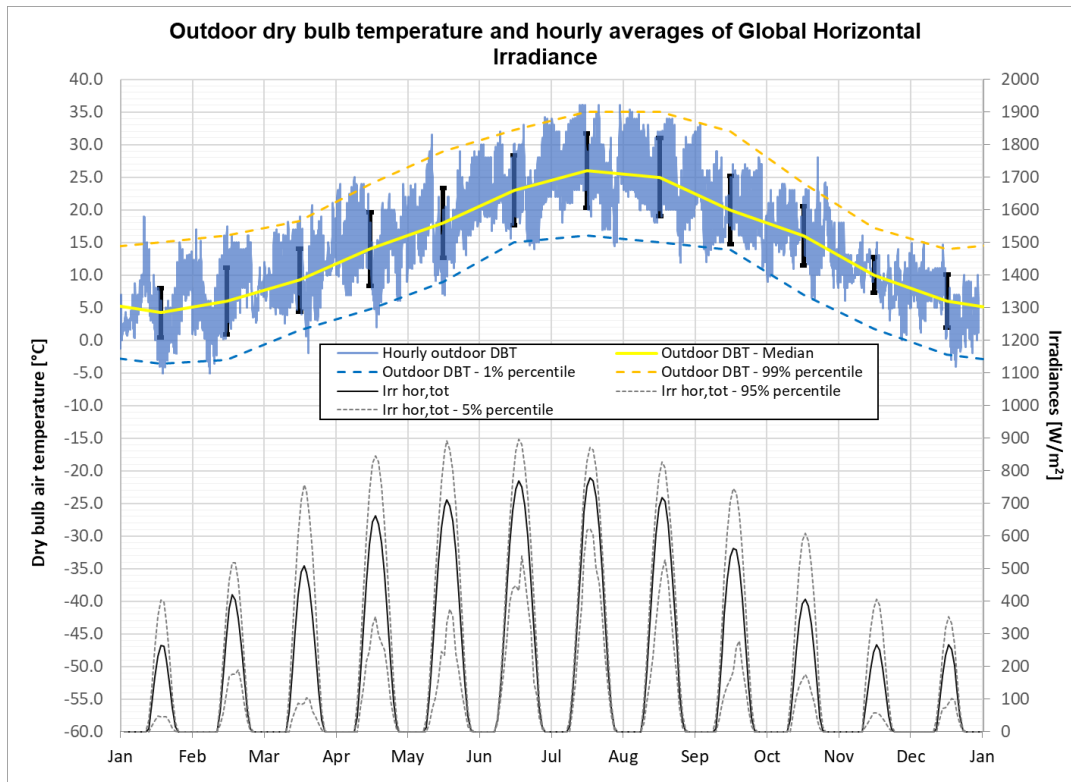


Figure 14: Outdoor dry-bulb temperature and hourly averages of Global Horizontal Irradiance of Bologna.

The chart represented in Figure 4 shows the outdoor dry-bulb temperature and a global irradiance on a horizontal surface. The temperature range is broad, with the absolute lowest temperature being -5°C and the absolute highest 36°C, therefore the temperature ranges for 41°C degrees throughout the year. The 1st percentile (blue dashed line) shows that winter extremes drop below 0°C reaching roughly -4°C, while the 99th percentile shows (orange dashed line) shows that that peak summer days frequently exceed 35°C.

When it comes to global irradiance on a horizontal surface, the peak is reported during the months of May and June, with around 900 [W/m²] considering the 95th percentile, while on average the highest irradiance is reported for mid-day during the month of July. The lowest average irradiance considering the 5th percentile is in the month of January with around 40 [W/m²], similar to December, although the average irradiance reaches up to 250 [W/m²] mid-day during these two months.

To understand temperature oscillations more clearly, Figures 16 and 17 show a closer look of the coldest and warmest week of the year. Hourly oscillations are significant. Both winter and summer days show daily volatility with the temperature difference of minimum 5°C (January 16th) and even up to 11°C (January 17th) in the winter week and up to 13°C (July 15th) in the summer week. For the summer period this could impact the building to not have enough time to “cool down” naturally which leads to cumulative heat gain that remains inside, while for winter the oscillations imply that solar gains could possibly help raise the interior air temperature, considering available roof surface area to exploit the global horizontal irradiance on the roof surface.

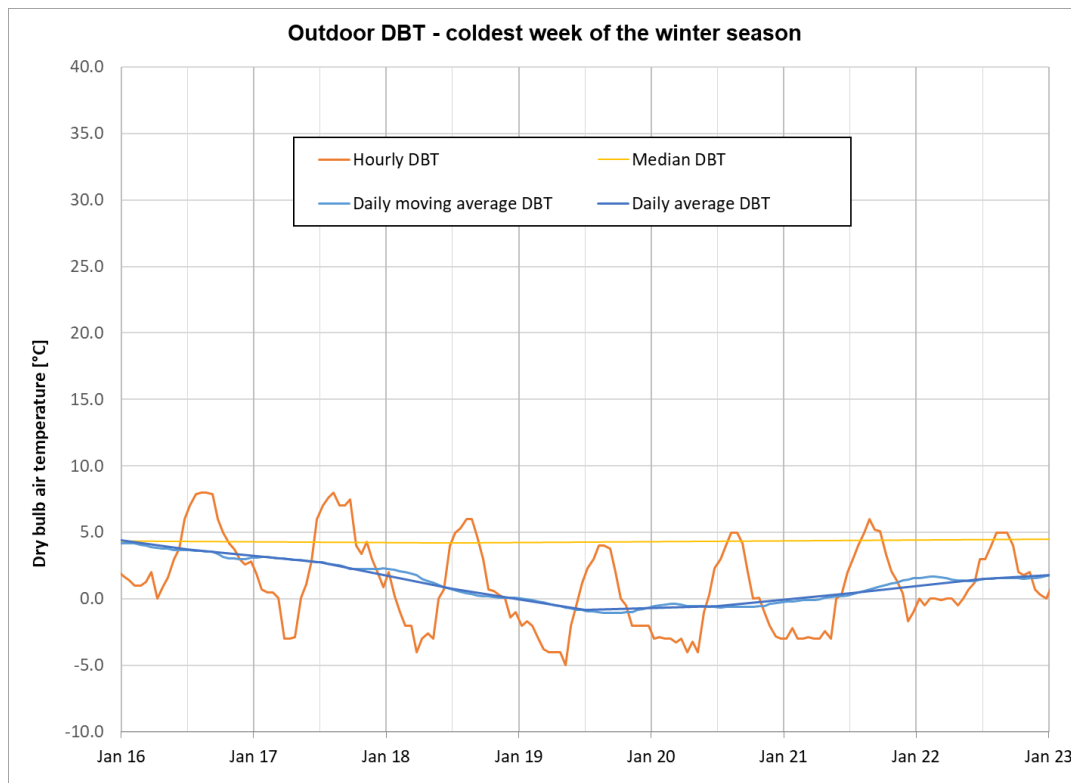


Figure 15: Hourly outdoor dry-bulb temperature of the coldest week of the winter season.

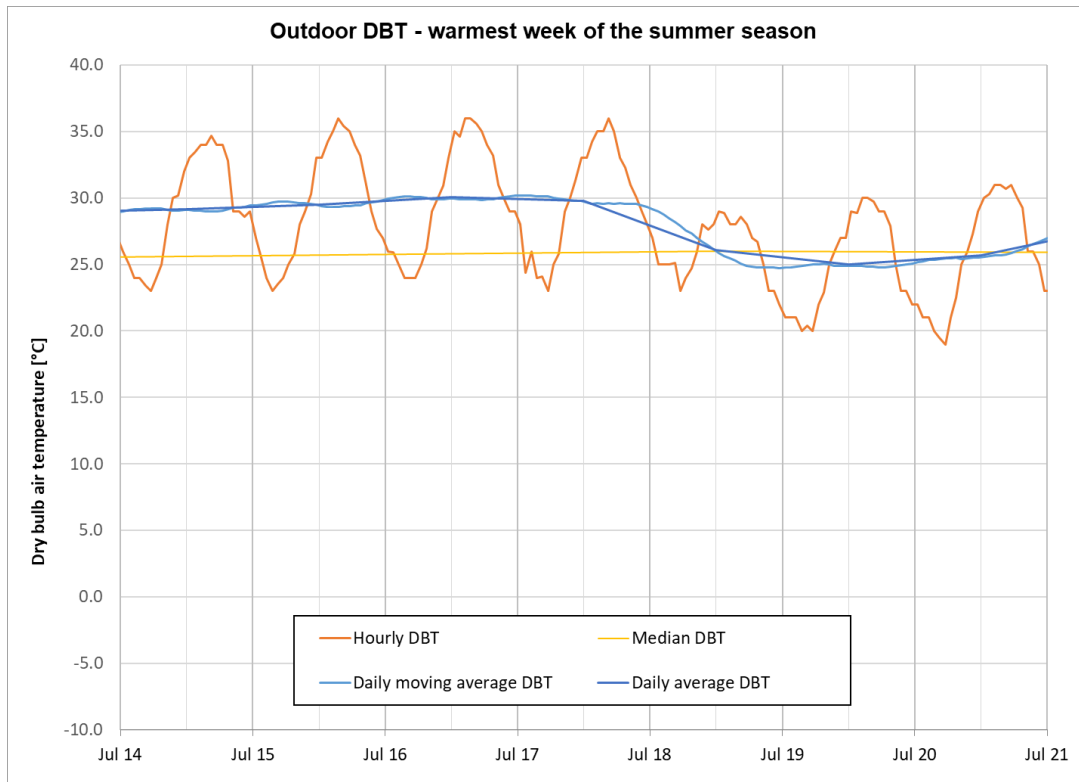


Figure 16: Hourly outdoor dry-bulb temperature of the warmest week of the summer season.

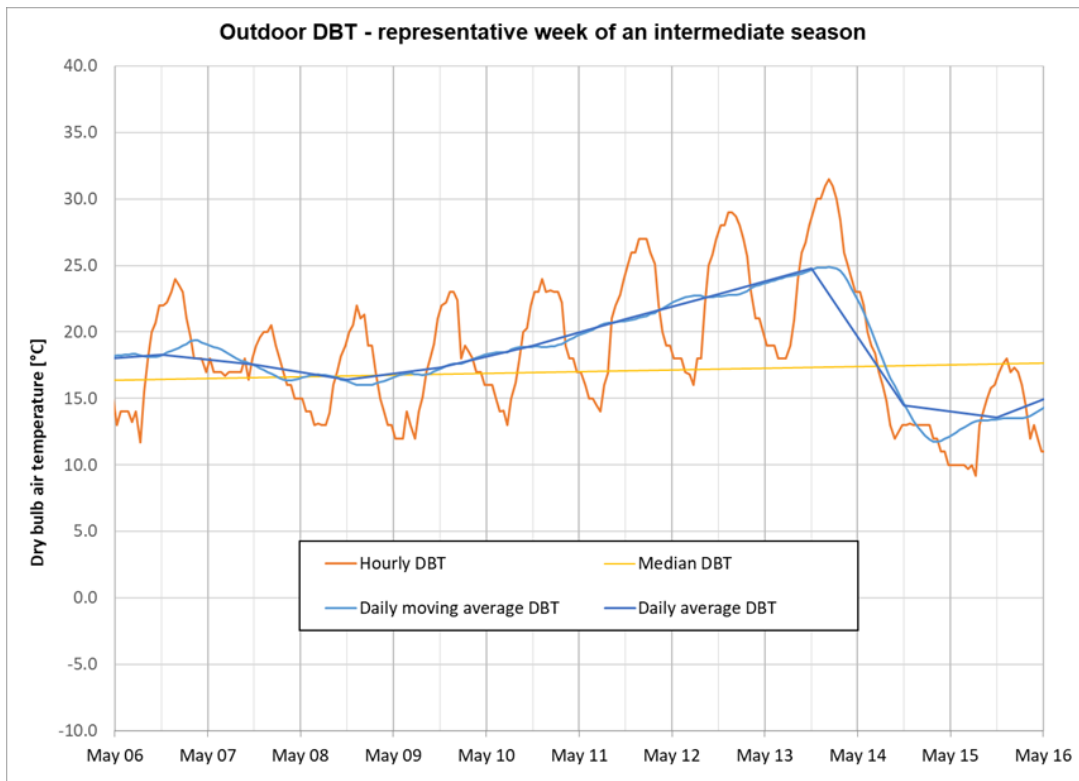


Figure 17: Hourly outdoor dry-bulb temperature of a representative week of an intermediate season in Bologna.

Analysing the share of heating, cooling and neutral hours, the climate is characterized by distinct heating and cooling seasons. Under fixed comfort setpoints that are used for office blocks of the building, heating dominates the annual operation, accounting for approximately 59% of working hours, while cooling is required for about 19%, with the remaining 22% falling within the comfort range without active conditioning. Heating demand is concentrated between October and April, whereas cooling becomes significant from June to September, peaking in July and August.

The adaptive comfort analysis applied to the warehouse zone of the building shows that around 34% of working hours remain comfortable without active systems, while heating and cooling account for approximately 28% and 21%, respectively. Overall, Bologna can be considered a heating-dominated climate with a notable summer cooling season, making winter heat losses and summer overheating both relevant design considerations. The results support the use of conditioned office spaces with dedicated HVAC systems, while the warehouse zones can benefit from more flexible comfort criteria and periods of operation without active heating or cooling.

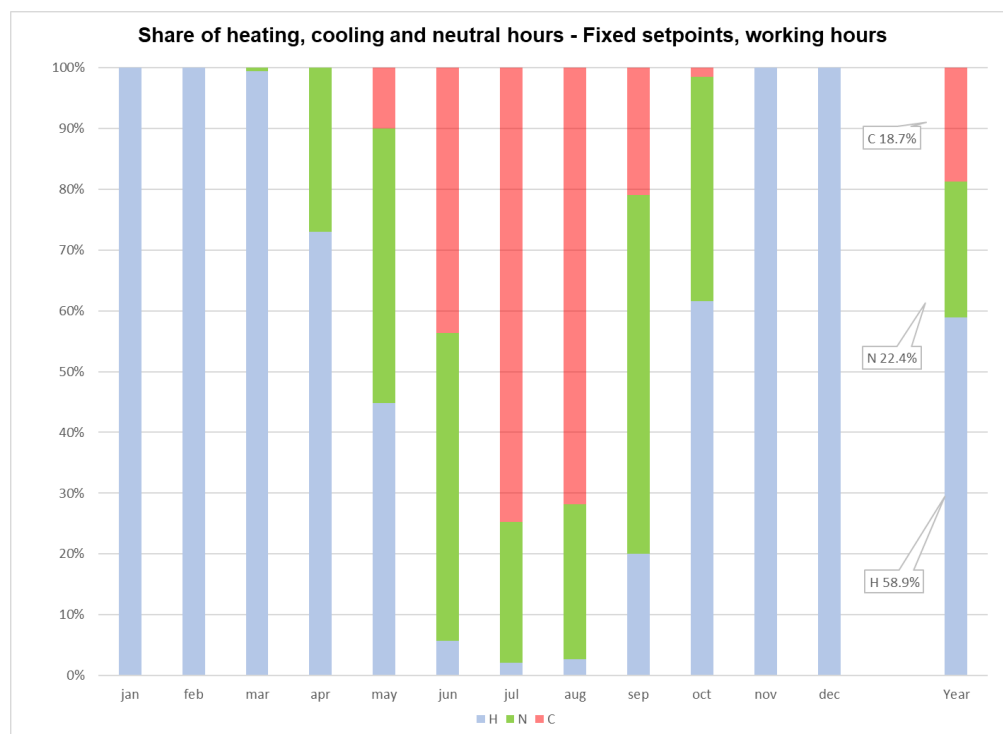


Figure 18: Annual working hours share of heating, cooling and neutral hours with fixed temperature setpoints.

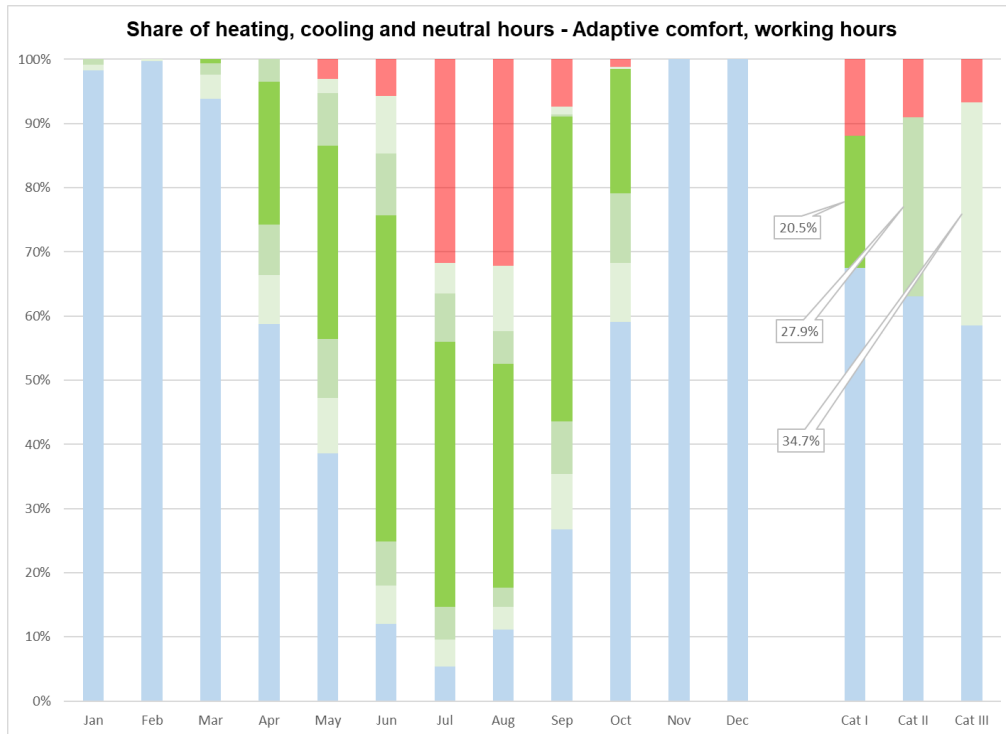


Figure 19: Annual working hours share of heating, cooling and neutral hours following adaptive comfort model.

The monthly irradiance profile shows that Bologna receives the highest solar availability during the summer months, with global horizontal irradiance increasing from approximately 60 W/m² in January to around 280 W/m² in June and July before decreasing towards winter. This trend actually shows the strong potential for photovoltaic electricity generation during periods when cooling demand is also at its highest.

Among the vertical surfaces, the south-facing façade receives the most consistent solar exposure throughout the year, maintaining irradiance levels of approximately 120–150 W/m² even during winter months. East- and west-facing surfaces exhibit intermediate values, with peak irradiance occurring in summer, while the north façade receives significantly lower solar radiation throughout the year. These results indicate that rooftop PV installations are likely to provide the highest energy yield due to the substantially greater horizontal irradiance, especially considering the building's available roof area.

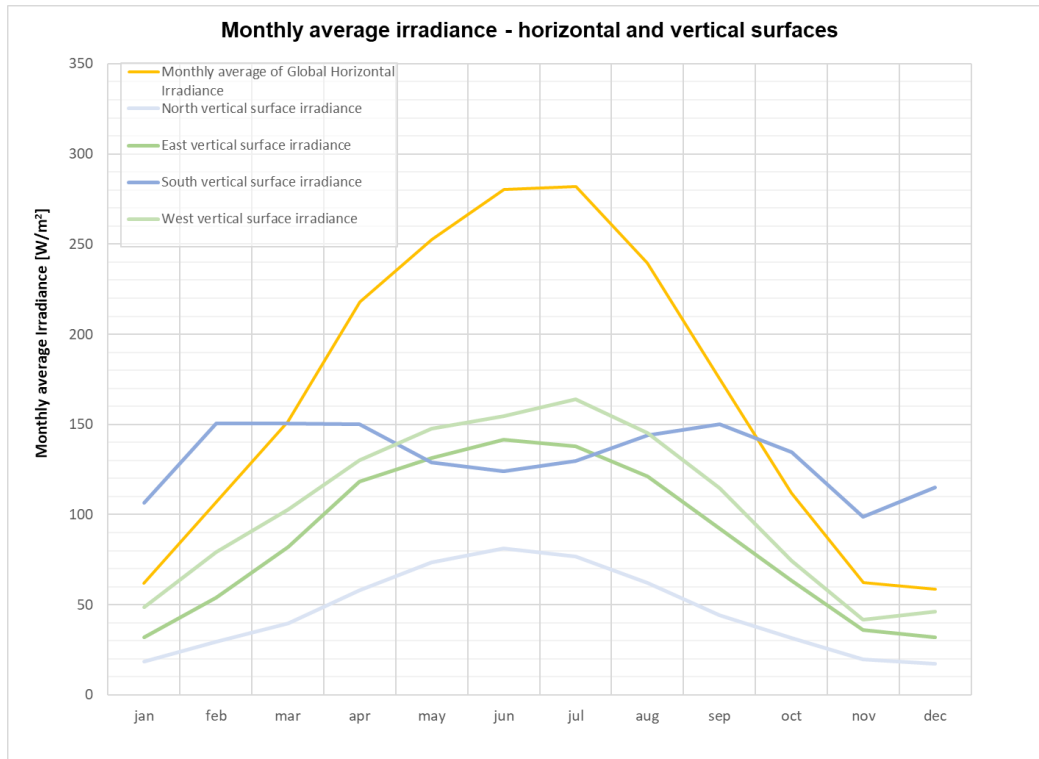


Figure 20: Monthly average of irradiance of horizontal and vertical surfaces.

3.3. Building energy model – Construction inputs

3.3.1. Stratigraphies and construction template

Defining the construction template inside IESVE means assigning the composition/stratigraphies of the envelope components of each thermal zone. In order to properly define thermal transmittances, all the layers will be identified by material category, thickness, thermal conductivity, resistance, and finally U-value of the composition. The standards followed are:

1. EN ISO 6946 – “*Building components and building elements – Thermal resistance and thermal transmittance – Calculation method*”, used for for opaque stratified constructions such as walls, roofs and internal floors [56];
2. EN ISO 10077-1 – “*Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 1: General*”, used for window systems, including frame, glazing and edge spacer [57];
3. EN ISO 13370 – “*Thermal performance of buildings – Heat transfer via the ground – Calculation methods*”, used for ground-contact floors [58].
4. Deliberazione della Giunta Regionale 20 luglio 2015, n. 967: “*Approvazione dell'atto di coordinamento tecnico regionale per la definizione dei requisiti minimi di prestazione energetica degli edifici (artt. 25 e 25-bis L.R. 26/2004 e s.m.)*”, used for defining the maximum allowable thermal transmittances by law [59].

Further chapters of this case study will also deal with thermal bridge analysis of the existing building envelope. The standard the analysis will reference is the following:

1. UNI EN ISO 10211:2017 – “*Thermal bridges in building construction: Heat flows and surface temperatures – Detailed calculations*”, used for calculating linear thermal transmittances across the building envelope [60].

The following table reports the summary of the vertical and horizontal constructions that comprise the building, with indicated thermal transmittances (U-values) and their maximum allowed values in case they delimit a conditioned space, in accordance with the Emilia-Romagna Regional Government Resolution No. 967/2015 (hereafter DGR 967/2015) applied to the Italian climate zone E:

Table 5: Summary of the U-values of the building's vertical and horizontal constructions and transparent openings.

Building element	U-value (W/m²K)	Max. allowed by law (W/m²K)	Compliant
Exterior wall - unconditioned	0.257	-	-
Exterior wall - conditioned	0.179	0.260	Yes
Interior wall between the office block and the warehouse	0.125	0.800	Yes
Interior wall between the office block and the staircase	0.357	0.800	Yes
Interior partition walls of the office block	0.352	-	-
Ground floor slab of the office block, including ground contact	0.108	0.260	Yes
Ground floor slab of the warehouse, including ground contact	0.070	-	-
Interior floor slab between two office floors	0.480	-	-
Warehouse roof	0.613	-	-
Office block roof	0.209	0.220	Yes
Double-glazed window warehouse	1.486	-	-
Double-glazed window office blocks	1.294	1.400	Yes

The compositions and thermal transmittances of the building's walls, slabs and roof are reported in the following pages:

Exterior wall stratigraphy of the warehouse:

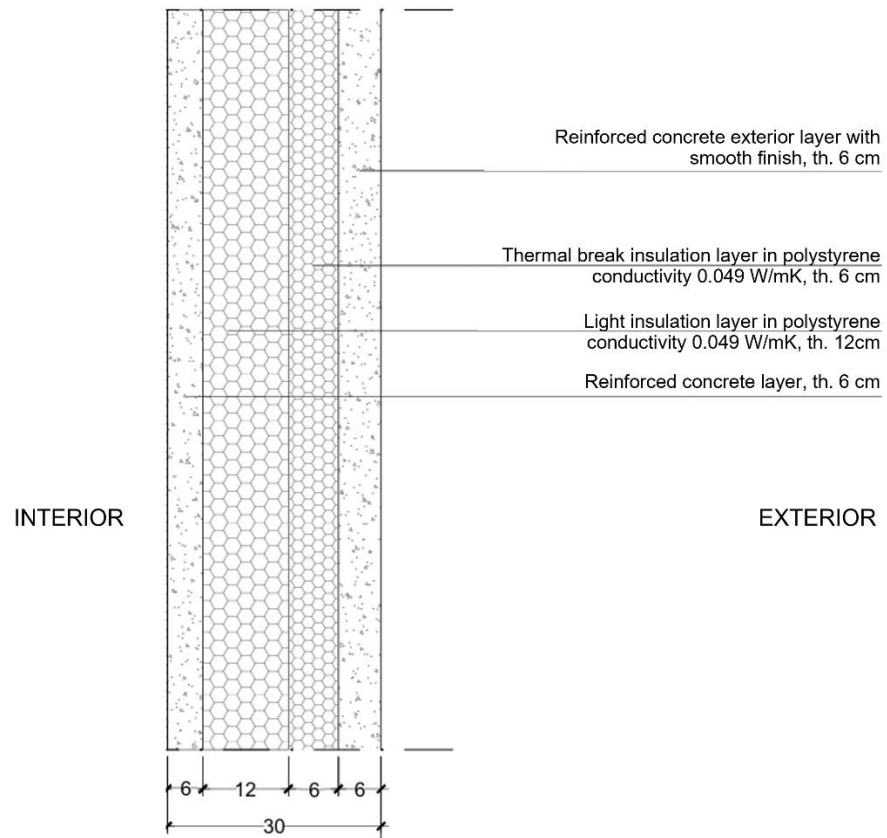


Figure 10: Exterior wall stratigraphy of the warehouse.

Table 6: Thermal transmittance of the exterior wall of the warehouse.

Exterior wall of the warehouse – unconditioned					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.130	0.257
1	Interior concrete layer	60	2.5	0.024	
2	Polystyrene insulation	120	0.049	2.449	
3	Polystyrene - thermal break	60	0.049	1.224	
4	Exterior concrete layer	60	2.5	0.024	
-	External surface resistance	-	-	0.040	

Exterior wall stratigraphy of the office block:

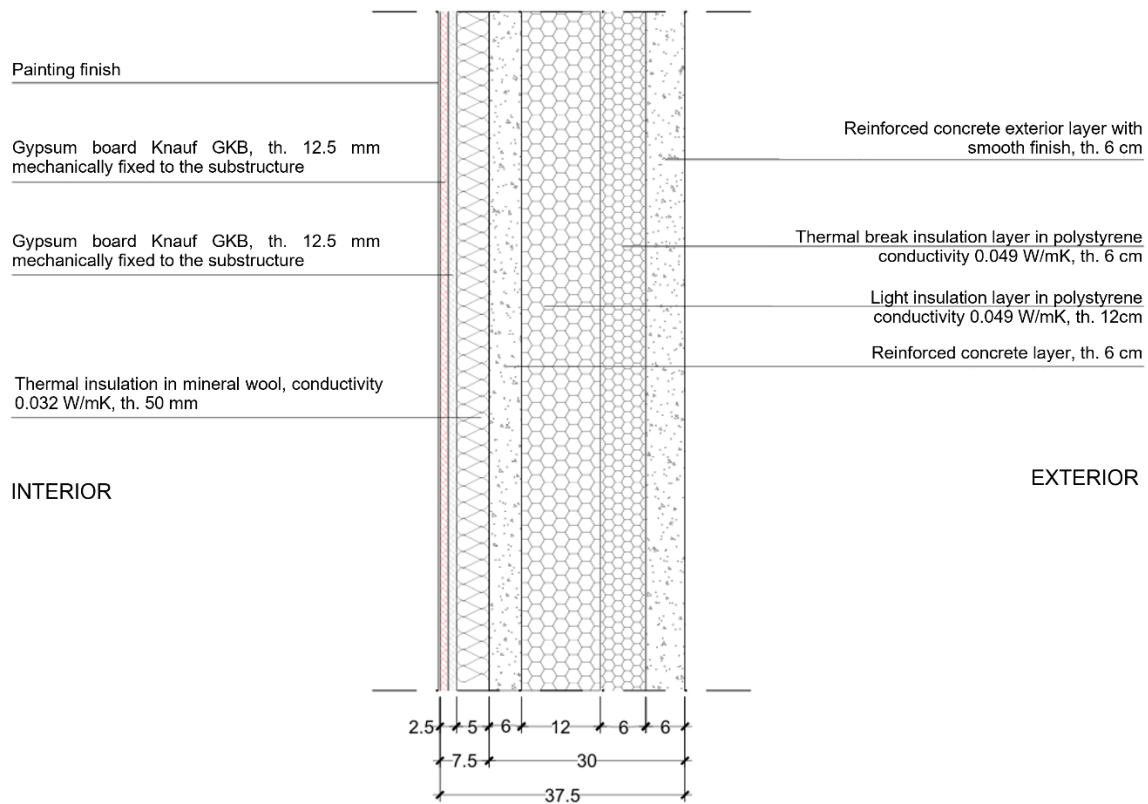


Figure 11: Exterior wall stratigraphy of the office block.

Table 7: Thermal transmittance of the exterior wall of the office block.

Exterior wall of the office block – conditioned					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m²K/W]	U-value [W/m²K]
-	Internal surface resistance	-	-	0.130	0.179
1	Gypsum plasterboard	12.5	0.211	0.059	
2	Gypsum plasterboard	12.5	0.211	0.059	
3	Mineral wool insulation	50	0.032	1.563	
4	Interior concrete layer	60	2.5	0.024	
5	Polystyrene insulation	120	0.049	2.449	
6	Polystyrene - thermal break	60	0.049	1.224	
7	Exterior concrete layer	60	2.5	0.024	
-	External surface resistance	-	-	0.040	

Interior wall stratigraphy between the office block and the warehouse:

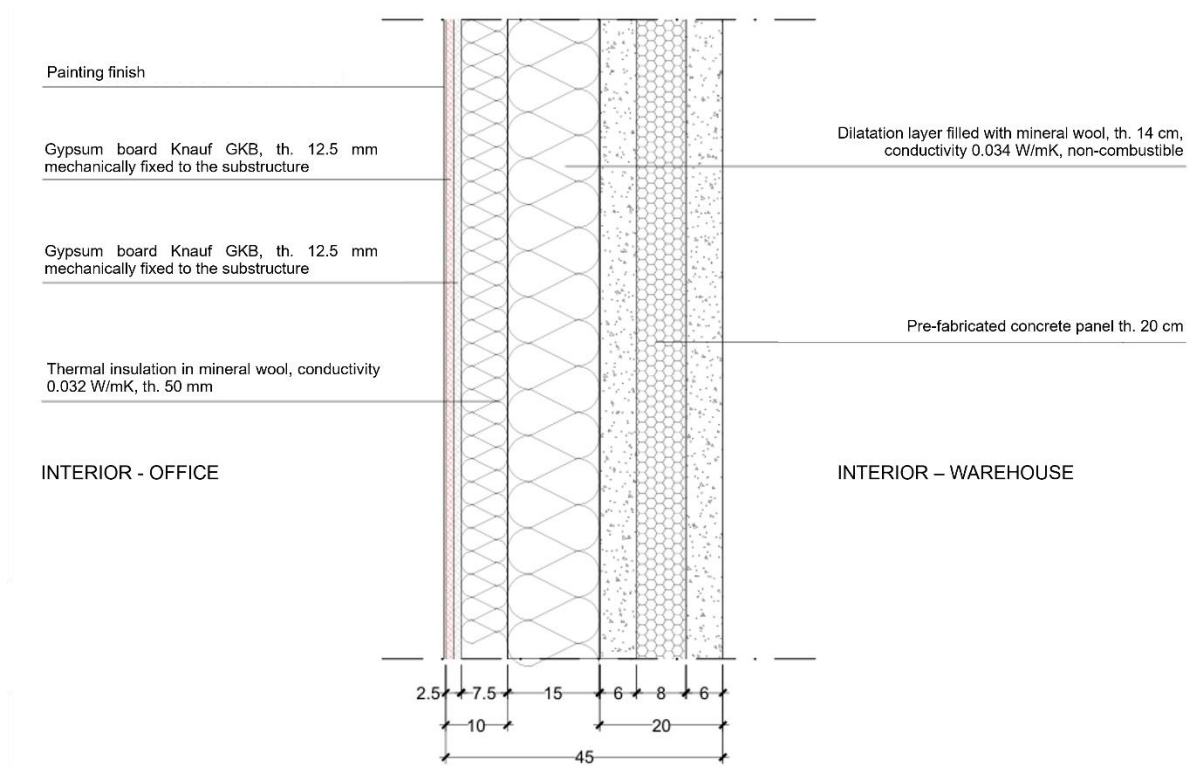


Figure 12: Interior wall stratigraphy between the office block and the warehouse.

Table 8: Thermal transmittance of the interior wall between the office block and the warehouse.

Interior wall between the office block and warehouse					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.130	0.125
1	Gypsum plasterboard	12.5	0.211	0.059	
2	Gypsum plasterboard	12.5	0.211	0.059	
3	Mineral wool insulation	50	0.032	1.563	
4	Mineral wool insulation	140	0.032	4.375	
5	Interior concrete layer	60	2.5	0.024	
6	Polystyrene insulation	80	0.049	1.633	
7	Interior concrete layer	60	2.5	0.024	
-	Internal surface resistance	-	-	0.130	

Interior wall stratigraphy between the office block and staircase:

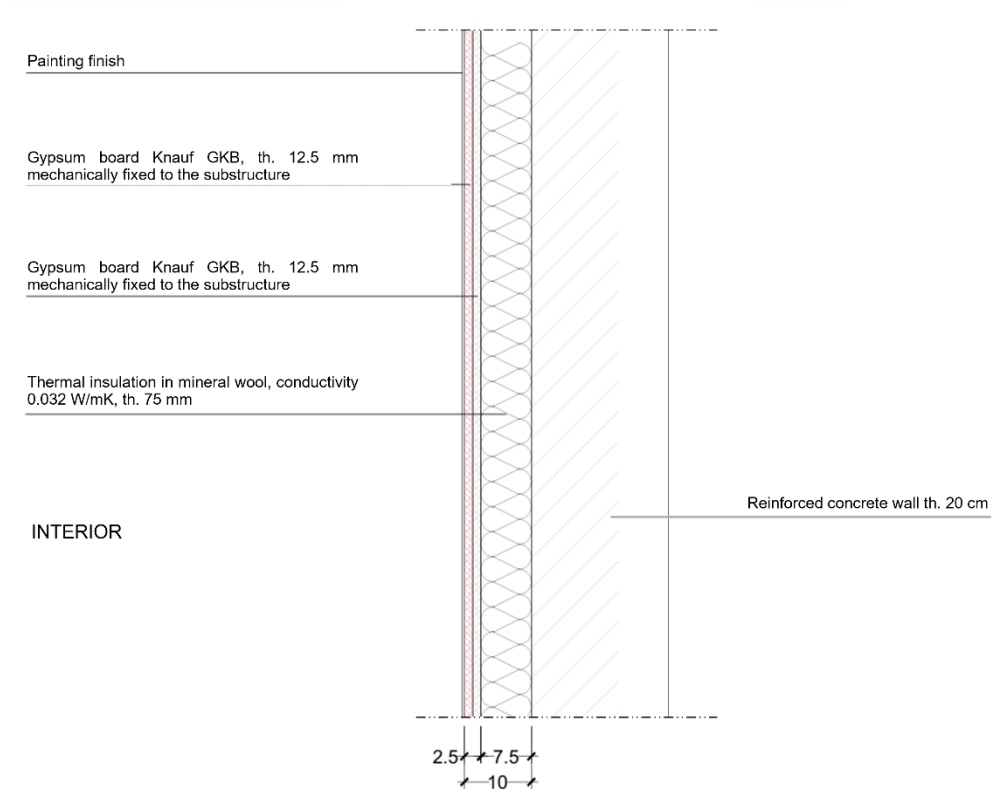


Figure 13: Interior wall stratigraphy between the office block and staircase.

Table 9: Thermal transmittance of the interior wall between the office block and staircase.

Interior wall between the office block and staircase					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.130	0.357
1	Gypsum plasterboard	12.5	0.211	0.059	
2	Gypsum plasterboard	12.5	0.211	0.059	
3	Mineral wool insulation	75	0.032	2.344	
4	Concrete wall	200	2.5	0.080	
-	Internal surface resistance	-	-	0.130	

Partition walls stratigraphy within the office blocks:

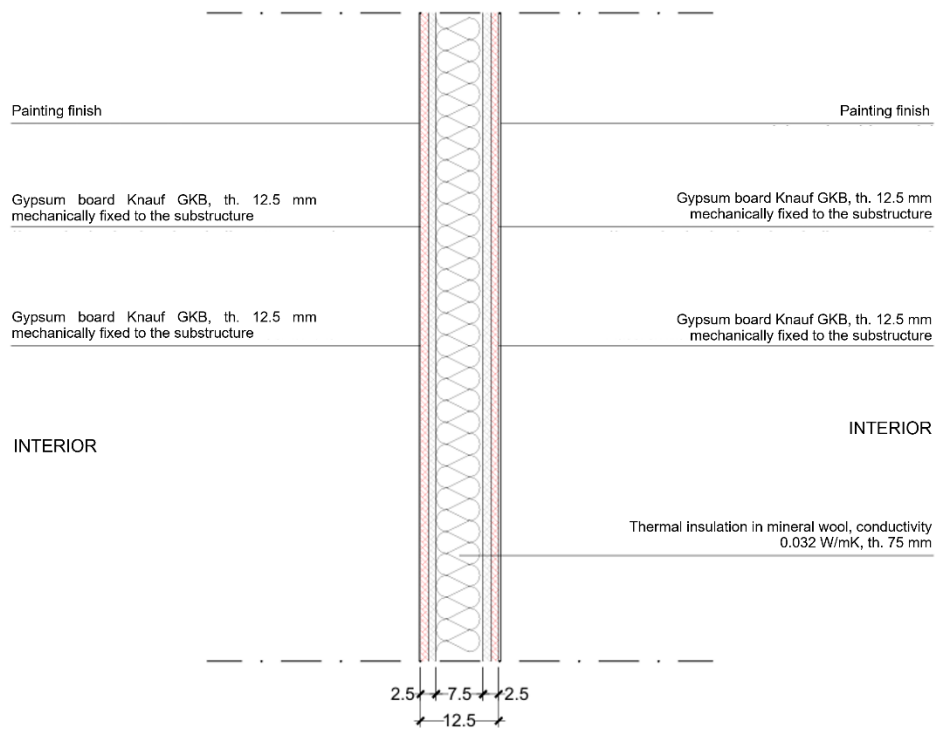


Figure 14: Partition walls stratigraphy within the office blocks.

Table 10: Thermal transmittance of the interior partition walls within the office blocks.

Interior partition walls of the office block					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.130	0.352
1	Gypsum plasterboard	12.5	0.211	0.059	
2	Gypsum plasterboard	12.5	0.211	0.059	
3	Mineral wool insulation	75	0.032	2.344	
4	Gypsum plasterboard	12.5	0.211	0.059	
5	Gypsum plasterboard	12.5	0.211	0.059	
-	Internal surface resistance	-	-	0.130	

Ground floor slab stratigraphy of the warehouse:

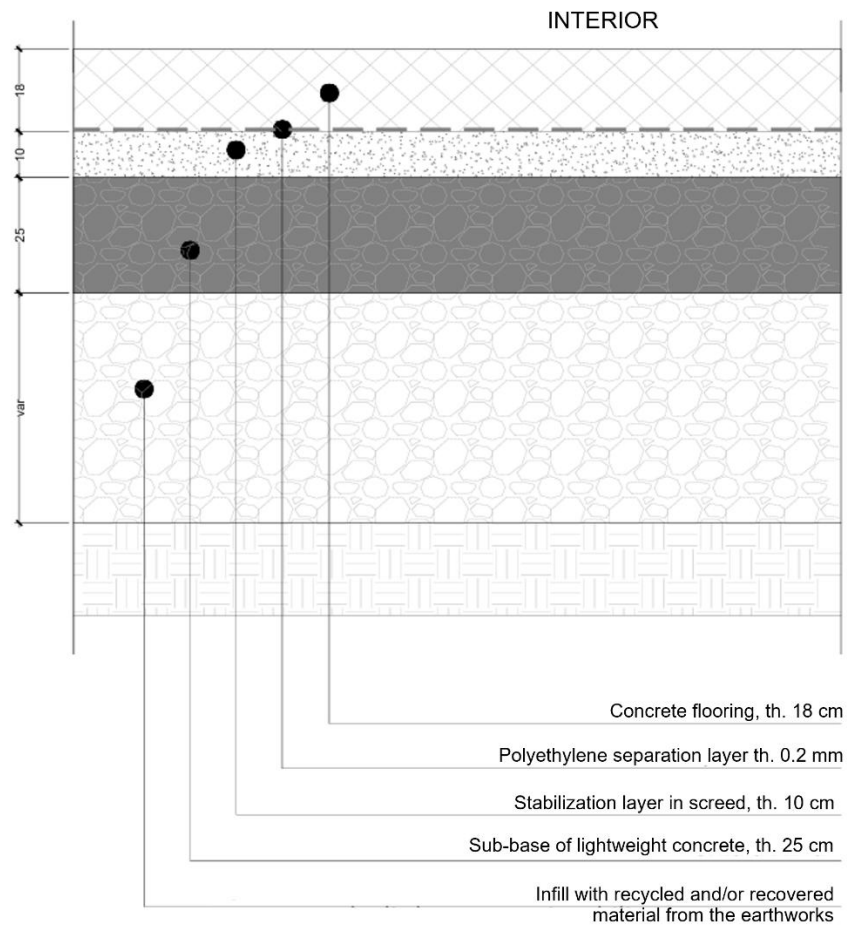


Figure 15: Ground floor slab stratigraphy of the warehouse.

Table 11: Thermal transmittance of the ground floor slab of the warehouse, considering the ground contact.

Ground floor slab of the warehouse					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value _with ground contact [W/m ² K]
-	Internal surface resistance	-	-	0.170	0.070
1	Reinforced concrete (2% steel)	180	2.5	0.008	
2	Cement screed for floor finish	100	1.49	0.034	
3	Sub-base of lightweight concrete	250	0.9	2.167	
4	Coarse gravel layer	450	1.2	4.167	
-	External surface resistance	-	-	0.040	

Ground floor slab stratigraphy of the office blocks:

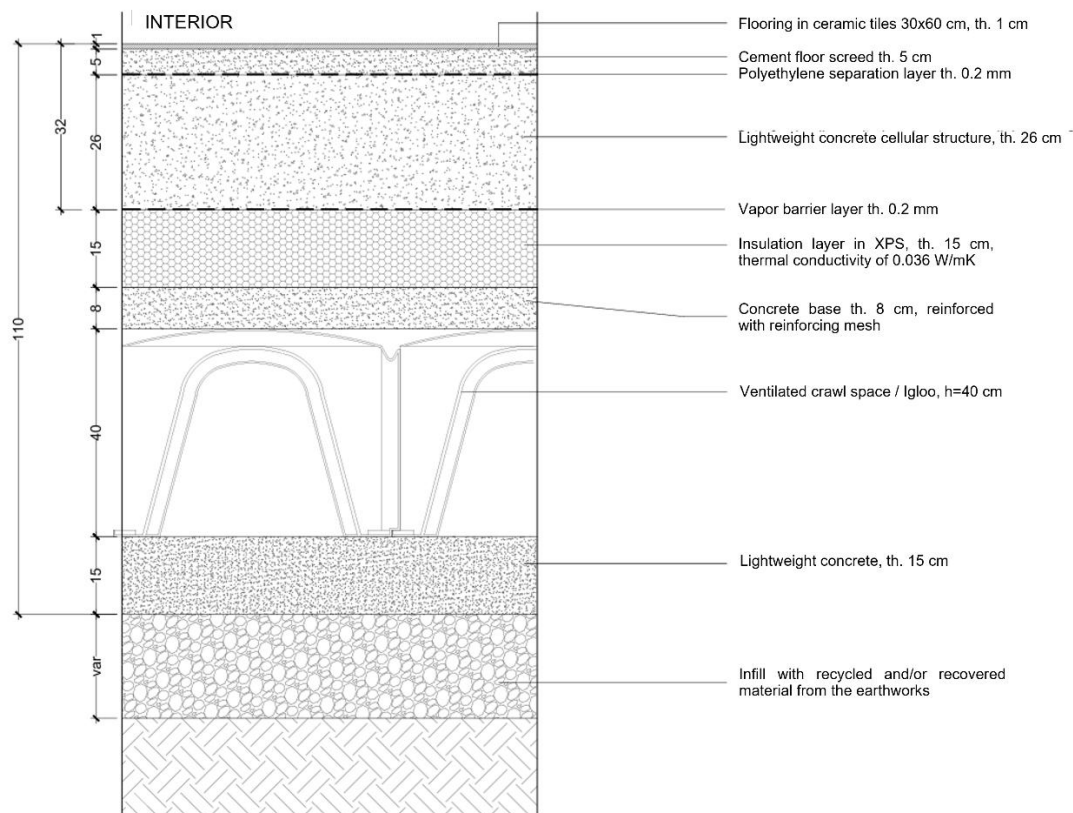


Figure 16: Ground floor slab stratigraphy of the office blocks.

Table 12: Thermal transmittance of the ground floor slab of the office block, considering the ground contact.

Ground floor slab of the office block					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value_with ground contact [W/m ² K]
-	Internal surface resistance	-	-	0.170	0.108
1	Ceramic tiles	10	1.30	0.008	
2	Cement screed with mesh reinf.	50	1.49	0.034	
3	Lightweight cellular concrete	260	0.12	2.167	
4	Extruded polystyrene (XPS)	150	0.036	4.167	
6	Concrete base with mesh reinf.	80	2.30	0.035	
7	Ventilated crawl space (Igloo)	150	-	-	
8	Lightweight concrete sub-base	150	0.70	0.214	
9	Gravel infill	250	1.20	0.208	
-	External surface resistance	-	-	0.040	

With regards to the ground floor thermal transmittance, contact with the soil must be taken into account, considering that the floor is not exchanging heat with the external environment such as the external walls and the roof do, but with the soil with a particular thermal conductivity. For this reason, EN ISO 13370 standard must be followed. For the shallow subsoil beneath the warehouse (ground-contact floor), soil is between silty and gravelish, which is typical of the Emilia-Romagna plain near Bologna.

The first step of verifying the correct equivalent thermal transmittance of the ground floor slab is finding the equivalent thickness that shall be calculated in the following way:

$$d_f = d_{w,e} + \lambda_g \cdot (R_{si} + R_{f;b} + R_{se}) , \text{ where:}$$

d_f – the total equivalent thickness in $[m]$;

$d_{w,e}$ – the full thickness of the walls of the building at ground level, including all layers;

$R_{f;b}$ – the thermal resistance of the floor slab, including that of any all-over insulation layers above, below or within the floor slab, and that of any floor covering, in $[m^2K/W]$;

R_{si} – the thermal resistance of the internal surface, in $[m^2K/W]$; $R_{si} = 0.17 [m^2K/W]$, considering an unheated zone;

R_{se} – the thermal resistance of the external surface, in $[m^2K/W]$; $R_{se} = 0.04 [m^2K/W]$;

λ_g – the thermal conductivity of the ground, in $[W/mK]$.

The standard also provides the possible thermal conductivities of the ground. As the soil has been already identified as clay or silt, the value of $\lambda_g = 2.0 [W/mK]$ is taken, as reported in the following table taken from the standard.

Table 13: Soil thermal conductivity according to soil type, EN ISO 13370.

Category	Description	Thermal conductivity λ_g $W/(m \cdot K)$	Heat capacity per volume ρc $J/(m^3 \cdot K)$
1	clay or silt	1,5	$3,0 \times 10^6$
2	sand or gravel	2,0	$2,0 \times 10^6$
3	homogeneous rock	3,5	$2,0 \times 10^6$

Knowing these values, it is possible to calculate the equivalent floor thermal transmittance in the following way:

$$U_{fg;b} = \frac{2 \cdot \lambda_g}{\pi \cdot B + d_f + 0.5 \cdot z} \cdot \ln \left(\frac{\pi \cdot B}{d_f + 0.5 \cdot z} + 1 \right)$$

$$B = \frac{A}{0.5 \cdot P}$$

where:

B – the characteristic dimension of the floor, in [m];

z - depth of basement floor below ground level, in [m];

A – area of the floor slab, in [m²];

P – the exposed perimeter of the floor slab, in [m].

The calculated equivalent U-value for the basement floor in contact with the ground is 0.070 [W/m²K] for the warehouse, while for the office floor slab it is 0.108 [W/m²K]. The difference is explained by the geometrical scale reflected in the characteristic dimension of the floor, consequently significantly decreasing the U-value of the warehouse ground floor slab. Values of each parameter of the equation are reported in the following tables:

Table 14: Corrected U-value of the ground floor slab of the warehouse and the office blocks according to EN ISO 13370.

Warehouse			Office blocks		
Parameter	Unit	Value	Parameter	Unit	Value
dw,e	m	0.30	dw,e	m	0.30
λg	W/mK	2.00	λg	W/mK	2.00
Rsi	m ² K/W	0.17	Rsi	m ² K/W	0.17
Rfb	m²K/W	0.47	Rfb	m²K/W	6.46
Rse	m ² K/W	0.04	Rse	m ² K/W	0.04
df	m	1.66	df	m	13.65
A	m ²	47222.19	A	m ²	563.79
P	m	1012.60	P	m	156.25
B	m	93.27	B	m	7.22
z	m	0.00	z	m	0.00
Ufg,b	W/m²K	0.070	Ufg,b	W/m²K	0.108

Interior intermediate floor slab between two floors of the office blocks:

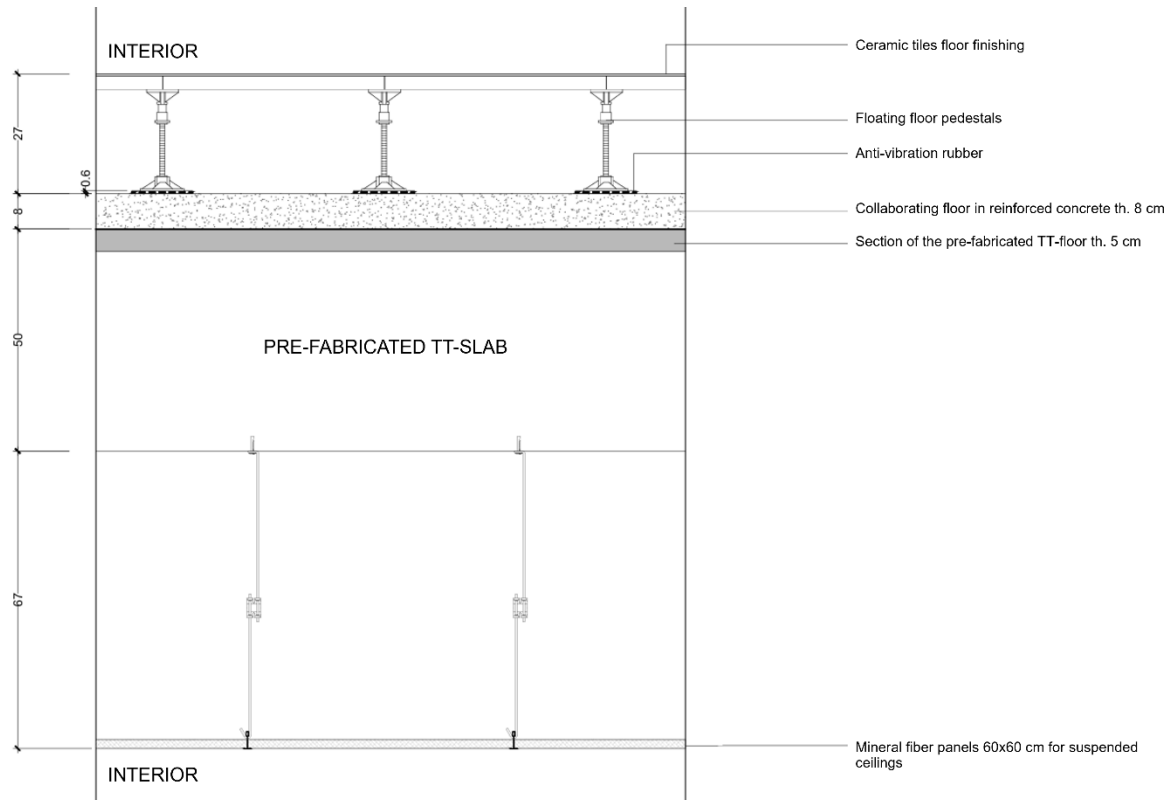


Figure 17: Interior intermediate floor stratigraphy between two floors of the office blocks.

Table 15: Thermal transmittance of the interior floor slab between two office floors.

Interior floor slab between two office floors					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.130	0.480
1	Ceramic tiles	10	1.3	0.008	
2	Floating floor pedestals	270	-	0.160	
3	Concrete base	80	2.5	0.032	
4	Reinforced concrete (2% steel)	50	2.5	0.020	
5	Plenum space	1170	-	-	
6	Mineral fiber ceiling board	12	0.065	0.185	
-	Internal surface resistance	-	-	0.130	

Roof stratigraphy above the warehouse:

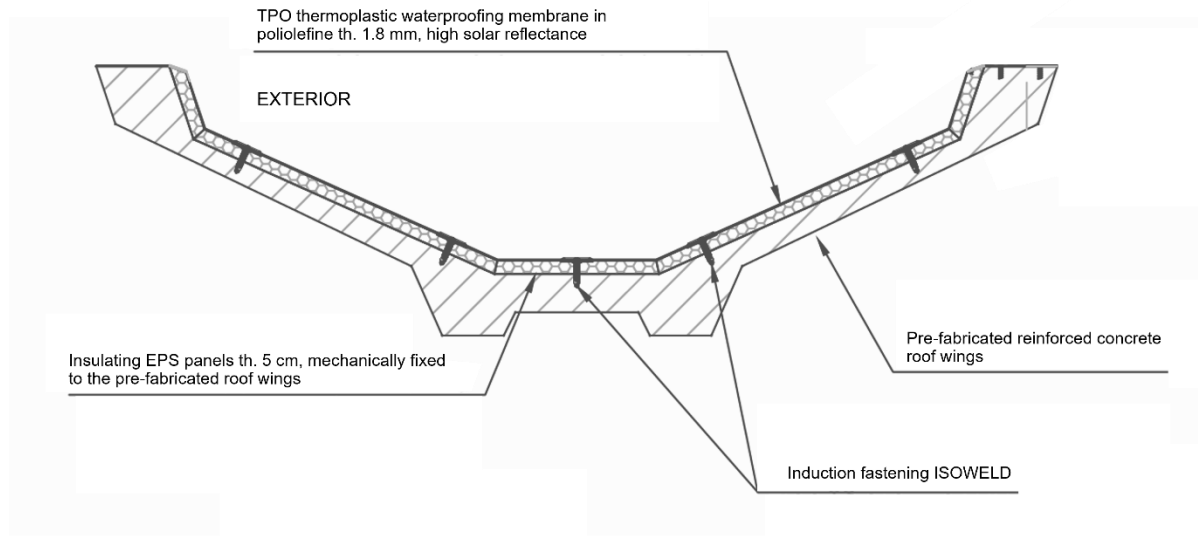


Figure 18: Roof stratigraphy above the warehouse.

Table 16: Thermal transmittance of the roof above the warehouse.

Warehouse roof					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.100	0.613
1	Reinforced concrete (2% steel)	80	2.5	0.032	
2	Insulating EPS panel	50	0.035	1.429	
3	TPO waterproofing membrane	1.8	0.17	0.011	
-	External surface resistance	-	-	0.060	

Roof stratigraphy above the office blocks:

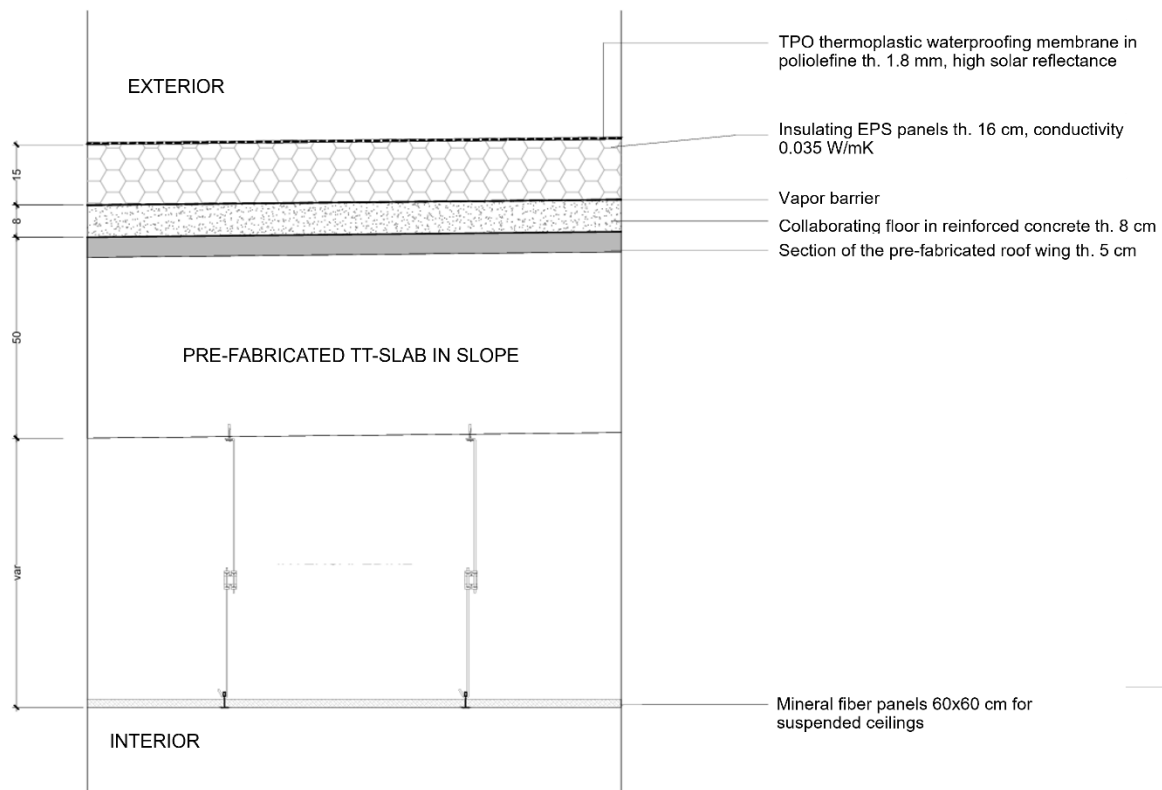


Figure 19: Roof stratigraphy above the office blocks.

Table 17: Thermal transmittance of the roof above the office blocks.

Office block roof					
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	U-value [W/m ² K]
-	Internal surface resistance	-	-	0.100	0.209
1	Reinforced concrete (2% steel)	50	2.5	0.020	
2	Concrete base	80	2.5	0.032	
3	Insulating EPS panel	160	0.035	4.571	
4	TPO waterproofing membrane	1.8	0.17	0.011	
-	External surface resistance	-	-	0.060	

Exterior windows stratigraphy:

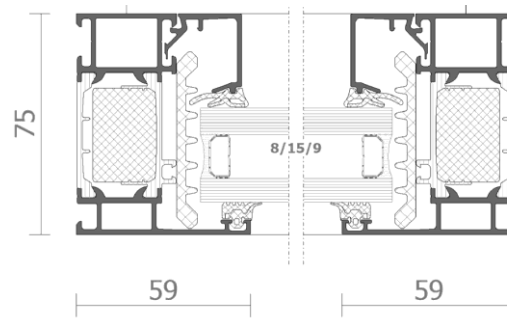


Figure 20: Horizontal section showing the window frame and glass profile of the warehouse.

Table 18: Thermal transmittance of the exterior windows of the warehouse.

Double-glazed warehouse window							
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	Resistance - frame [m ² K/W]	Glazing U-value [W/m ² K]	Total U-value [W/m ² K]
1	Outer pane	9	1.00	0.009	0.574	1.285	1.486
2	Air Cavity	15	-	0.532			
3	Inner pane	8	1.00	0.008			

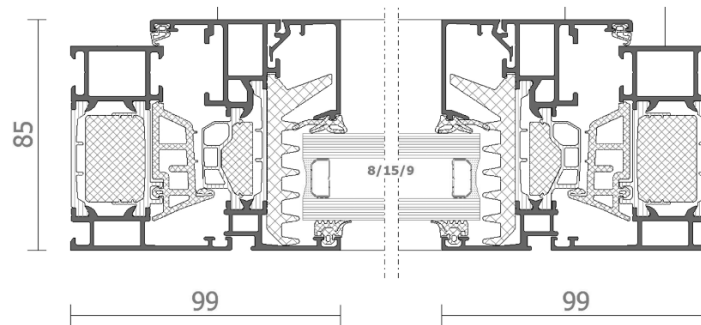


Figure 21: Horizontal section showing the window frame and glass profile of the office blocks.

Table 19: Thermal transmittance of the exterior windows of the office blocks.

Double-glazed warehouse window							
Layer no.	Layer name	Thickness [mm]	Conductivity [W/mK]	Resistance [m ² K/W]	Resistance - frame [m ² K/W]	Glazing U-value [W/m ² K]	Total U-value [W/m ² K]
1	Outer pane	9	1.00	0.009	0.806	1.285	1.291
2	Air Cavity	15	-	0.532			
3	Inner pane	8	1.00	0.008			

Skylights on the roof of the warehouse:

Skylights made out of polycarbonate are integrated with the curved corrugated metal sheets spanning over the length of the warehouse roof. Thermal transmittance of the 20mm thick polycarbonate sheets is 1.80 [W/m²K].

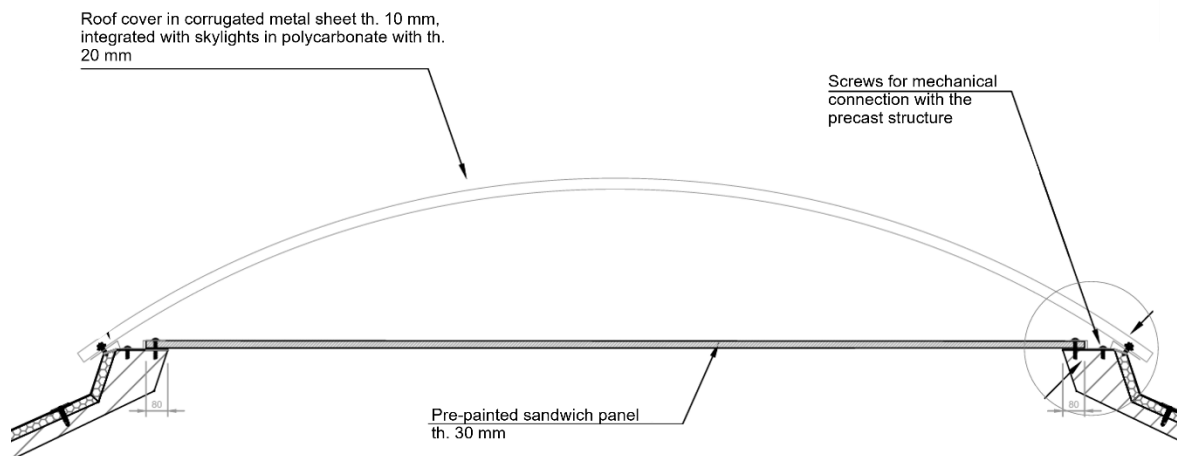


Figure 22: Skylights detail on the roof of the warehouse.

POLIFORM LUCERNARI s.p.a. Via Benetton, 21 - 43010 Fontanafredda (PVI)
 ph. +39 0521 611110 r.a. - tx. +39 0521 611111 - www.poliformlucernari.com
 P. IVA 02052940349 - Numero REA 207152 - Capitale Sociale 119.000,00 i.v.

Materiale	LASTRE IN POLICARBONATO ALVEOLARE		
Spessore	16 mm	20mm	25mm
Peso	2,55 Kg/m ²	3,10 Kg/m ²	3,30 Kg/m ²
Trasmittanza termica	2,1 W/m ² K	1,8 W/m ² K	1,6 W/m ² K

Figure 23: Thermal transmittance of a 20mm thick polycarbonate skylight.

According to the available architectural layouts it was possible to construct the geometry in IESVE as accurately as possible. From the project documentation it was possible to see that the roof has a very low slope (1%, the minimum to assure rainwater drainage). In this case study, the simplification has been made in IESVE with a roof completely flat.

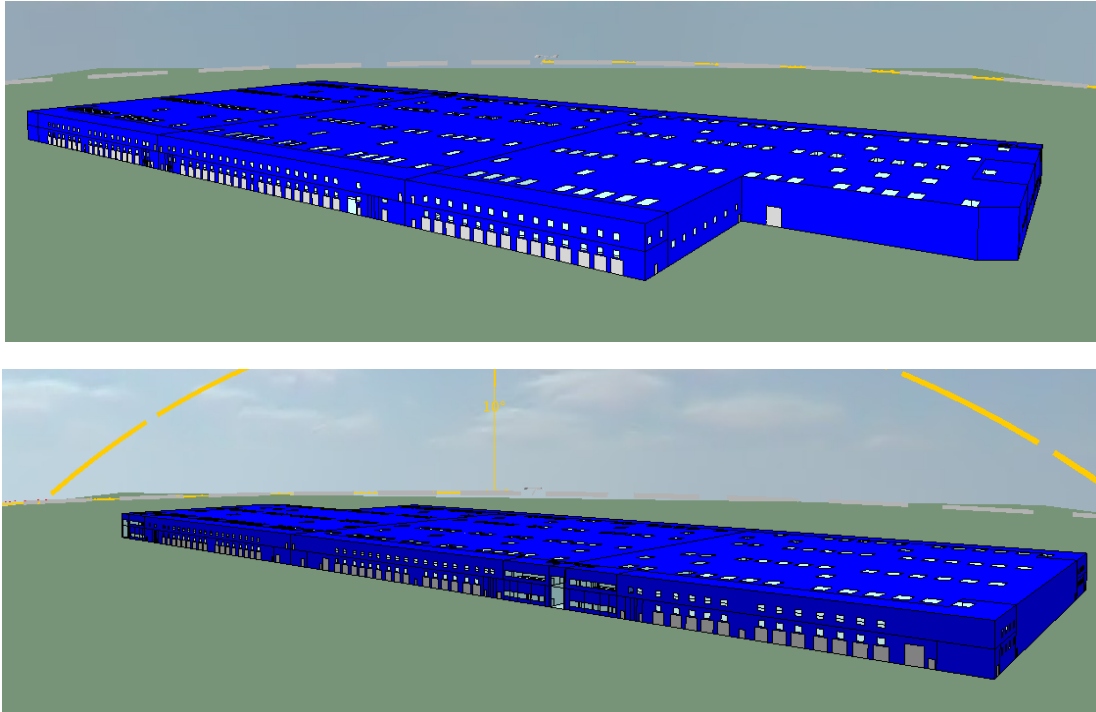


Figure 24: South-east and north-west perspective from the IES-VE model.

3.4. Building energy model – thermal inputs

3.4.1. Defining thermal templates

After defining the building constructions, the next step is to develop the thermal template of each building zone, which includes heating and cooling conditions and systems modelling, internal gains (people, equipment and lighting gains) and air exchanges (infiltration and natural ventilation). To define the thermal template, the following inputs are required:

- HVAC system – refers to the mode of input for HVAC calculation. Inside IESVE the user is prompted to assign HVAC methodology, choosing between ApSys and ApHVAC². For this project ApHVAC methodology is followed.
- Design conditions – the user is prompted to provide information about heating and cooling setpoints, setback temperatures and operational schedules that the setpoints and setbacks correspond with.³ Setpoints can be: constant, follow a time (daily, weekly or yearly profile), and refer to two-values. We chose the two-values setpoint choice because it allows to define separate comfort settings for heating and cooling and setbacks for non-operational periods. Operational schedule accompanied with choosing two-values

² The difference between ApSys and ApHVAC is in the level of detail and complexity of the HVAC model. While ApSys allows simplification for quick sizing and calculations of the energy needs, ApHVAC is based on a detailed plant model simulation (component by component).

³ Domestic hot water (DHW) generation too is a plant component to be taken into account in the energy model of a building; however, for this project we considered DHW out of scope.

setpoints is „System extended hours“. For heating, the setback was set 2°C below the occupied setpoint (18°C vs. 20°C), while for cooling the setback was set 2°C above the occupied setpoint (28°C vs. 26°C) to reduce cooling loads while preventing excessive indoor heat buildup. The following table summarizes the space conditions of rooms assigned to be conditioned:

Table 20: Definition of the heating and cooling main setpoints and setback points.

Thermal template "Space Conditions" definition	
Setpoint type	Two-value
Heating main setpoint	20
Heating setback	18
Cooling main setpoint	26
Cooling setback	28

3.4.2. Internal gains

Internal gains are divided into gains coming from lighting, people and appliances/equipment, therefore the gains are expressed as lighting power density [W/m²], equipment power density [W/m²], and occupation density [m²/person].

Internal gains are defined according to ANSI/ASHRAE/IES Standard 90.1-2016, Appendix G [61]. ASHRAE 90.1-2016 provides baseline values of internal gains according to the space-by-space method. Namely, the space-by-space method in ASHRAE 90.1 is a compliance approach used to calculate power allowances of building internal gains. It involves assigning lighting power densities, equipment and occupancy densities to each individual space or room based on its specific function. Assigning a certain “Space Type” to a space/room within the energy model, automatically creates a thermal template for that space. Therefore, the following tables represent internal gains for assigned spaces – equipment power density and occupation density are defined by default, while lighting power density is calculated from project documentation. Each “Space Type” has a different daily operational schedule for lighting, occupancy and appliances, also assigned by default, aligned with ASHRAE 90.1-2016.

The building is separated between the warehouse and office blocks. Office blocks consist of different spaces, each with a dedicated thermal template. The following schemes visually present these spaces on a floor plan layout of a typical office block of the ground floor and the first floor.



Figure 25: Scheme of the Space type assignment – example for one office block of the ground floor.

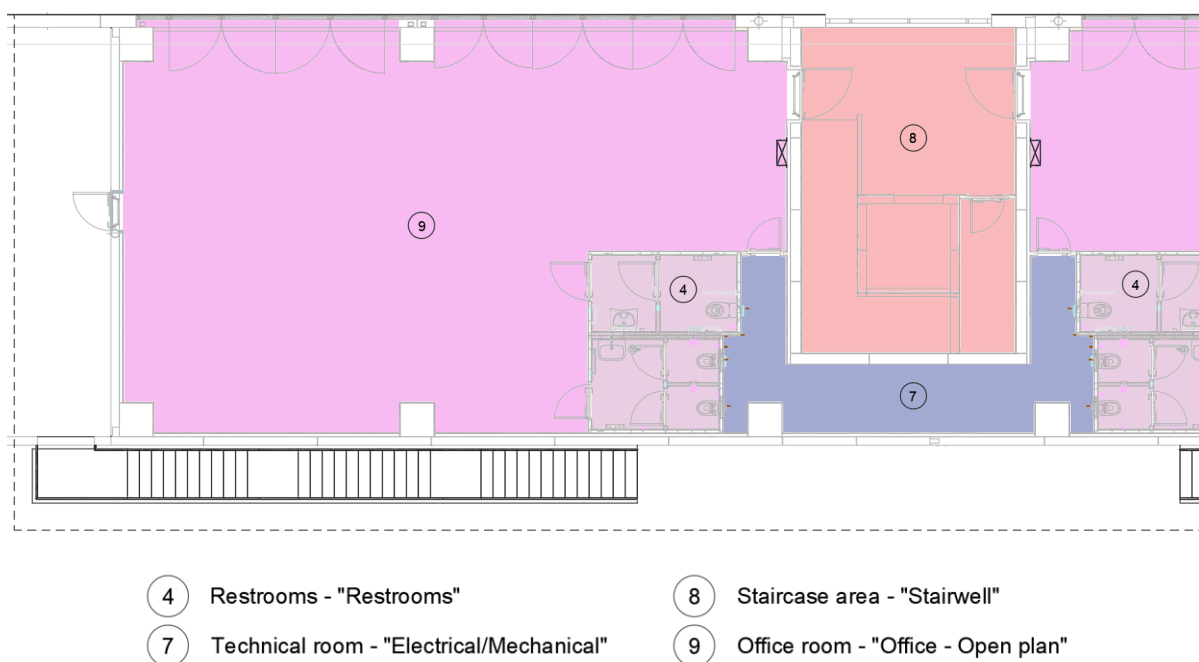


Figure 26: Scheme of the Space type assignment – example for one office block of the first floor.

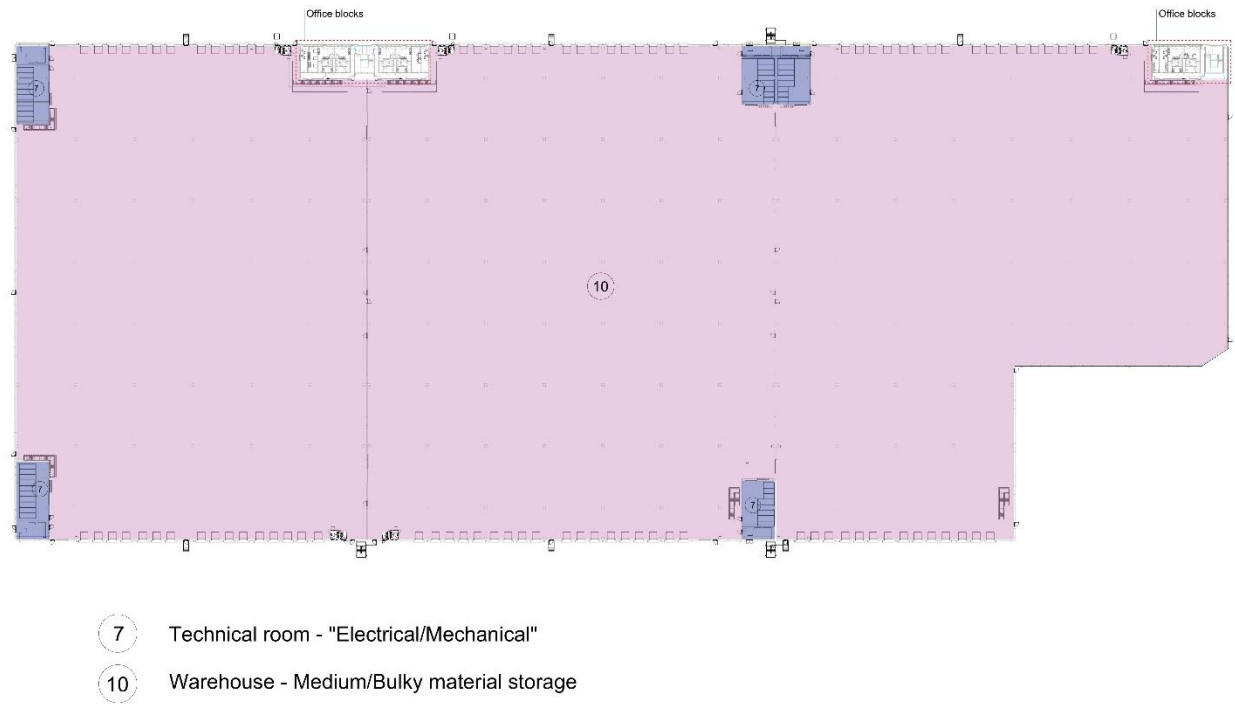


Figure 27: Scheme of the Space type assignment – warehouse zone, ground floor.

Table 21: Surface areas of the referenced building space types.

Building space	Surface area (m ²)
Corridor - All Other Corridors	154.9
Dining area - All Other	161.1
Electrical/Mechanical	1,364.9
Locker room	208.9
Office - Enclosed	135.5
Office - Open plan	138.8
Restrooms	74.2
Stairwell	94.7
Storage - $\geq 50\text{ft}^2$	16.4
Warehouse - Medium/Bulky material storage	45,862.9

As explained, the values for each space are automatically assigned according to the assignment of the “Space Type” within the standard ASHRAE 90.1:2016; however, for case study, the lighting power density was calculated by taking into consideration the luminaires planned to be installed inside the building, developed during the design stage. Overall, we can differentiate between the warehouse zone and the office blocks zone, in terms of lighting. The summary of the luminaires is the following:

Table 22: Types of luminaires to be installed in the building. Source: available project documentation.

Building space	Luminaire name	Luminaire power (W)	Number installed	Total power (W)
Warehouse	TECTON C LED16000-940 L2000 WB LDE WH	104	238	24,752
	TECTON C LED16000-940 L2000 NB LDE WH	104	262	27,248
	TECTON C LED16000-940 L2000 WB LDE WH	65	40	2,600
	TECTON C LED16000-940 WB EM	104	219	22,776
Total			759	77,376
Warehouse zone area: 47,184.3 m²				
Office blocks	LED quadrato Thorn modello Beta 2	33	102	3,366
	LED rotondo Classe II, IP65, IK10	16.3	16	260.8
	TECTON C LED1500 WH	104	6	624
	AQFPRO L 8000 MB	55.5	4	222
Total			128	4,472.8
Office blocks area: 953.51 m²				

Following the identification and counting of all the luminaires, calculation has been performed then by assigning the total power for each building space type individually. The following table therefore shows the lighting power densities of the defined spaces:

Table 23: Lighting power density – default Space-by-Space method. ASHRAE values vs. project values.

Building space	Lighting power density	
	LPD ASHRAE 90.1:2016 [W/m ²]	LPD Case Study [W/m ²]
Corridor - All Other Corridors	5.38	5.11
Dining area - All Other	9.69	4.62
Electrical/Mechanical	16.15	3.87
Locker room	6.46	4.01
Office - Enclosed	11.84	3.76
Office - Open plan	11.84	3.33
Restrooms	9.69	5.02
Stairwell	6.46	2.78
Storage - ≥50ft ²	8.61	11.44
Warehouse - Medium/Bulky material storage	9.69	1.75

Table 24: Equipment power density – default Space-by-Space method. ASHRAE values vs. project values.

Building space	Equipment power density	
	EqPD ASHRAE 90.1:2016 [W/m ²]	EqPD Case Study [W/m ²]
Corridor - All Other Corridors	2.15	2.15
Dining area - All Other	5.38	5.38
Electrical/Mechanical	2.15	2.15
Locker room	5.38	5.38
Office - Enclosed	10.76	10.76
Office - Open plan	16.15	16.15
Restrooms	0.00	0.00
Stairwell	10.76	10.76
Storage - ≥50ft ²	2.15	2.15
Warehouse - Medium/Bulky material storage	2.15	2.15

The difference between the LPD values coming from ASHRAE and from the case study comes from the way that baseline from the standard is created. The standard ASHRAE 90.1:2016 assigns maximum allowable LPD values to individual space types according to their intended function, occupancy characteristics, and illumination requirements. The prescribed LPD limits represent code-compliant reference conditions that provide adequate lighting quality in reference to typical design practices and operational requirements for a particular space type. However, it is important to underline that this standard considers fluorescent lighting for its baseline LPD, while the case study utilizes exclusively LED lighting, commonly known for its energy-efficient characteristics such as a higher luminous efficacy, light beam shaping, lower ballast losses and its easy integration with dimming and control systems. The comparison therefore quantifies the reduction in installed lighting power achieved through the implementation of high-efficiency lighting technology relative to a reference standard for code compliance.

In terms of equipment power density, it stays unchanged between the standard and the case study. For the office blocks, equipment gains encompass PCs and monitors, printing machines, breakroom appliances (microwaves, coffee and vending machines). For the warehouse compartment, equipment includes forklift battery-charging stations and localized mechanical handling automation.

Automatically by assigning the space types, their operational schedules for lighting, equipment and occupancy are assigned as well. There are two different operational schedules, namely, for regularly occupied spaces and non-regularly occupied spaces. According to the ASHRAE standard, their definition are following:

- Regularly occupied spaces: areas designed for routine human occupancy and activity, where occupants are expected to spend significant periods of time under normal operating conditions. For this case study, those include all offices, dining rooms and locker rooms (due to the presence of showers).

- Non-regularly occupied spaces: areas accessed only occasionally for maintenance, storage, circulation, or support functions, and are therefore not intended for prolonged occupancy. For the case study, those include all the rest.

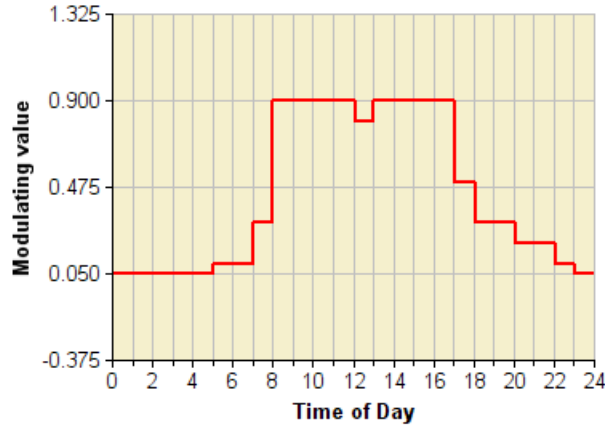


Figure 28: Lighting and equipment operational profile for regularly occupied spaces.

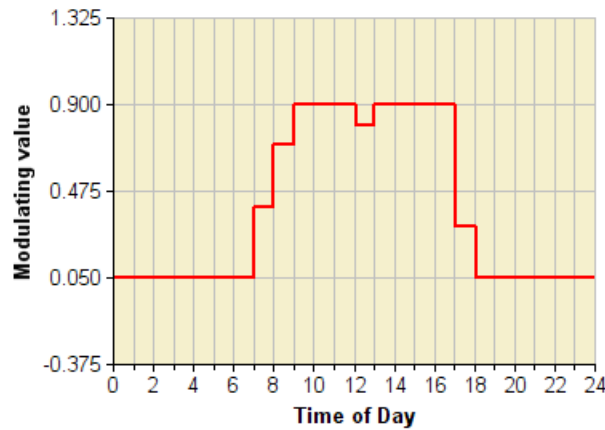


Figure 29: Lighting and equipment operational profile for non-regularly occupied spaces.

When it comes to occupancy profiles, presence of workers is considered only for regularly occupied spaces (offices and break rooms). As the expected occupancy does not change in any phase of the project, the default values of occupation density and the values of the case study remain equal.

Table 25: Occupation density – default Space-by-Space method. ASHRAE value vs. project values.

Building space	Occupation density	
	Occ. Density ASHRAE 90.1:2016 [m ² /person]	Occ. Density Case Study [m ² /person]
Corridor - All Other Corridors	0.00	0.00
Dining area - All Other	1.33	1.33
Electrical/Mechanical	0.00	0.00
Locker room	9.29	9.29
Office - Enclosed	18.58	18.58
Office - Open plan	18.58	18.58
Restrooms	0.00	0.00
Stairwell	0.00	0.00
Storage - ≥50ft ²	0.00	0.00
Warehouse - Medium/Bulky material storage	0.00	0.00

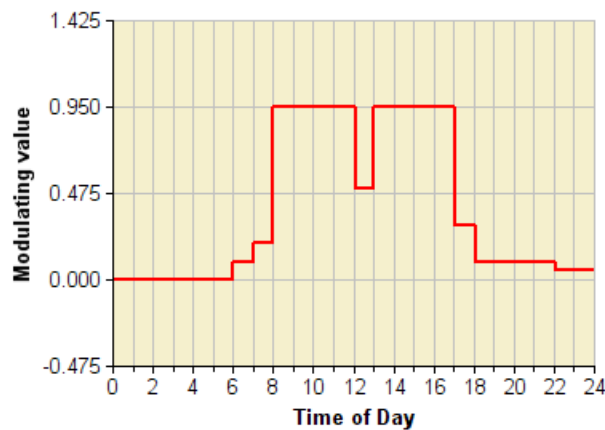


Figure 30: Occupancy operational profile for regularly occupied space.

3.4.3. Air exchanges

Building air exchanges in the energy simulation are defined in the thermal template and they encompass natural ventilation and infiltration.

Natural ventilation was not considered as a ventilation strategy within the warehouse thermal model. Although the building is equipped with loading bay doors, these openings are operated exclusively for logistical activities associated with the loading and unloading of goods. Their opening frequency and duration depend on vehicle arrivals, operational schedules, and warehouse throughput, which makes these schedules highly variable, also depending on the tenant and their specific needs. Energy modeling in this case study is performed without considering one particular tenant. This is why natural ventilation air change rate is not considered

as a controllable design parameter in this case study. Consequently, the loading bays cannot be considered a reliable source of natural ventilation capable of possible contribution to indoor thermal comfort.

Furthermore, no dedicated operable façade openings are provided within the warehouse volume. Roof-mounted skylights serve exclusively as smoke and heat exhaust devices for fire safety purposes and are not intended for routine ventilation during normal operation. While operable windows are available within the office areas, these spaces are mechanically conditioned, and natural ventilation was not included in the baseline energy model to ensure consistency with the HVAC operating assumptions (introduced in the following chapter). Therefore, the warehouse was modelled as a mechanically operated building in which air exchange occurs through envelope infiltration rather than intentional natural ventilation.

Infiltration was modelled in accordance with the ASHRAE 90.1:2016 Appendix G methodology. The standard defines a baseline envelope air leakage rate of 0.4 cfm/ft² (which is approximately 2.0 L/s·m²) at 75 Pa pressure differential, according to the Section G3.1.1.4. It is possible to calculate the infiltration rate, knowing the geometric properties of the building:

Table 26: Input parameters to define the building's infiltration rate.

Parameter	Value	Unit
Vertical and horizontal envelope area	58,049	m ²
Leakage rate at 75 Pa (Appendix G)	2.0	L/ s·m ²
Warehouse volume	541,183	m ³

The total leakage flow expressed in (L/s) at the pressure of 75 Pa is:

$$Q_{75} = 2.0 \cdot 58,049 = 116,098 \frac{L}{s}$$

$$Q_{75} = 116.1 \frac{m^3}{s}$$

A pressure of 75 Pa is a testing pressure that is equivalent to a continuous, direct wind blowing at around 40 km/h against every square meter of the structure simultaneously. To translate the leakage rate into standard, daily operational conditions, a pressure of 4 Pa is considered. Therefore, the infiltration is scaled down using the following equation:

$$Q_4 = C \cdot \Delta P^n$$

$$Q_4 = Q_{75} \cdot \left(\frac{4}{75}\right)^{0.65} = 17.3 \frac{m^3}{s}$$

Where:

Q_4 – infiltration flow rate at 4 Pa;

Q_{75} – infiltration flow rate at 75 Pa;

$n = 0.65$ – average flow exponent, indicating the degree flow turbulence.

The equivalent air change rate (ACH) can be calculated dividing the infiltration flow rate with the total volume of the building:

$$ACH = \frac{Q_4 \cdot 3,600}{V}$$

$$ACH = \frac{17.3 \frac{m^3}{s} \cdot 3,600}{541,183 m^3} = 0.115 \frac{1}{h}$$

Therefore the infiltration rate considered for the case study is 0.115 1/h with a continuous profile.

3.4.4. Exterior lighting

Exterior lighting was evaluated in accordance with ASHRAE Standard 90.1:2016, Section 9.4, which establishes maximum allowable lighting power for outdoor applications based on the characteristics of the site and the intended function of the illuminated areas. The standard classifies projects into five Lighting Zones, from LZ0 to LZ4. The warehouse was classified as Lighting Zone 3 (LZ3), considering that the warehouse is located in a zone with a developed industrial context, therefore with the need to provide safe vehicle circulation, loading operations, and pedestrian access during evening hours. This classification represents areas with moderate to high ambient lighting levels where exterior illumination is necessary for safety, security, and operational purposes.

Table 27: Table 9.4.3A from ASHRAE 90.1:2016 – Exterior Lighting Zones.

Lighting Zone	Description
0	Undeveloped areas within national parks, state parks, forest land, rural areas, and other undeveloped areas as defined by the <i>authority having jurisdiction</i>
1	Developed areas of national parks, state parks, forest land, and rural areas
2	Areas predominantly consisting of <i>residential</i> zoning, neighborhood business districts, light industrial with limited nighttime use and <i>residential</i> mixed use areas
3	All other areas
4	High activity commercial districts in major metropolitan areas as designated by the local jurisdiction

ASHRAE 90.1 distinguishes between tradable and non-tradable exterior lighting applications when determining the allowable lighting power:

- Tradable surfaces are areas for which lighting power may be redistributed within the site, provided that the total installed power does not exceed the overall allowance. They include uncovered parking areas, building grounds (driveways, pedestrian circulation routes), outdoor sales. This approach provides design flexibility by allowing lighting power to be concentrated where greater illumination is required. In this case study, tradable surfaces applicable are considered under the uncovered parking areas category.

- Non-tradable surfaces are applications with fixed power allowances that cannot be exchanged with other site lighting categories. These include façade lighting, main entrances, emergency doors, security-sensitive areas, and other specific functions identified by the standard. In this case study, non-tradable surfaces are building facades.

Table 28: Exterior lighting power of applicable tradeable and non-tradeable surfaces for Exterior Lighting Zone 3.

Surface type	Category	Surface area/linear length	Unit	Lighting power (W)	Power density/per lin. meter	Unit
Uncovered parking areas	Tradeable surface	22173.9	m ²	1473.5	0.07	W/m ²
Building facades	Non-tradeable surface	994.72	m	3445.7	3.46	W/m

3.4.5. Building's HVAC system

Introduction to the building's Heating, Ventilation & Air-Conditioning (HVAC) systems will be split into space conditioning (including heating and cooling) and mechanical ventilation. Inputs for the building's HVAC system is based on the available technical documentation that covered the layouts, functioning schemes and models for each type of the system, including the domestic hot water (DHW), that in this case study is out of scope. The following illustration summarizes the types of systems used in the building, that are split into two major zones: warehouse zone and office blocks.

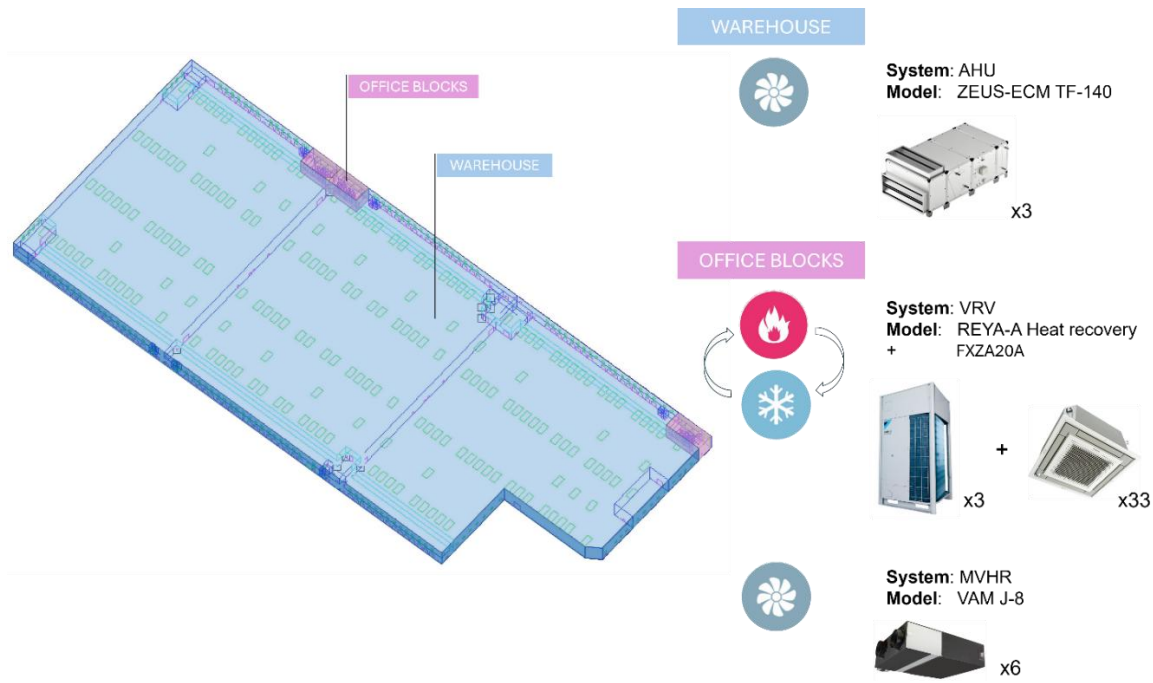


Figure 31: Illustrative summary of the HVAC systems of the building.

All the HVAC systems present in the building operate based on the fixed operational schedules as defined in the ApHVAC systems modeling. Systems' schedule is based on the occupancy schedule expected from the workers, divided into blue collar (warehouse workers) and white collar (workers of the office block). Warehouse is operating longer than the office block, starting earlier and finishing later, because the logistics team requires an extra hour in the morning to prepare, stage, and load incoming freight before the corporate workday begins, and extra time in the evening to process final daily shipments and secure the loading bays after administrative operations close. Warehouse operation time is therefore:

Weekdays	☐	☒	06:30	18:30	12hrs
Weekend	☐	☒	10:00	16:00	6hrs

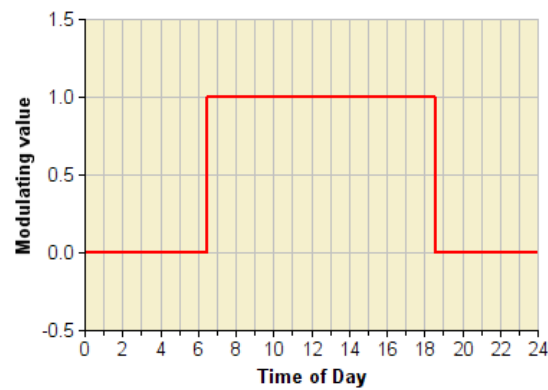


Figure 32: Operational profile of the HVAC system – warehouse.

Operational time of the office zone of the building is the following:

Weekdays	☐	☒	08:00	18:00	10hrs
Weekend	☐	☒	10:00	16:00	6hrs

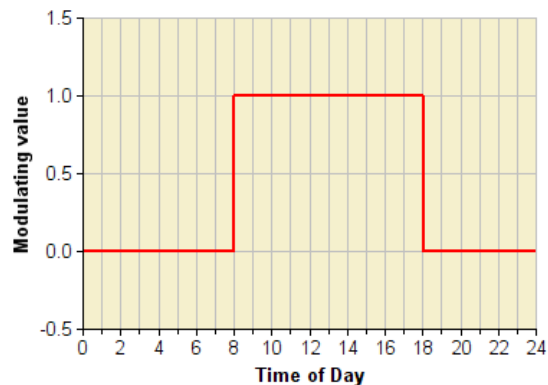


Figure 33: Operational profile of the HVAC system – office blocks.

3.4.5.1. Space conditioning system

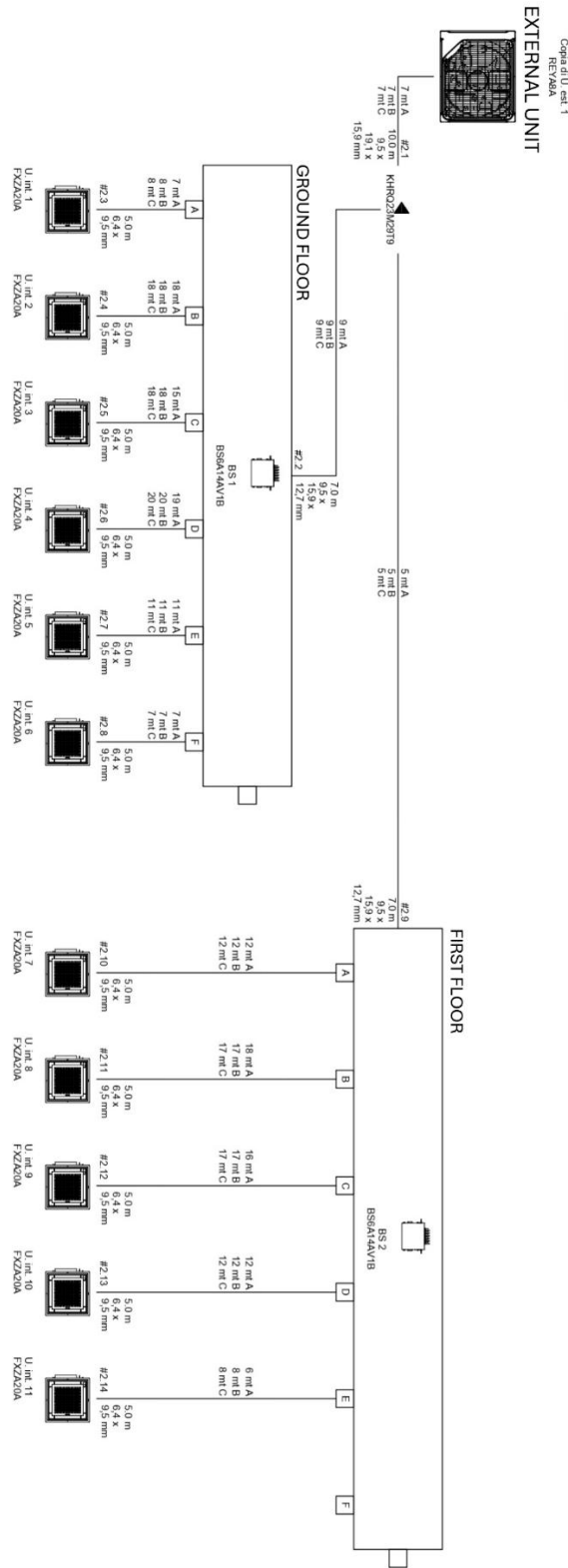


Figure 34: Space conditioning scheme.

In terms of space conditioning, only office blocks are heated and air-conditioned. As represented in the introductory illustrative scheme, the Variable Refrigerant Flow (VRF or VRV) system is implemented. VRV is a high-efficiency space conditioning technology that uses a direct expansion (DX) refrigerant cycle to provide both cooling and heating, depending on the demand, both heating and cooling to different zones simultaneously. It is composed of an outdoor unit which performs a refrigerant-based DX cycle, branch distribution boxes and multiple indoor terminal units. Great advantage of this system is its ability to modulate the volumetric flow rate of the energy carrier, supplying each indoor unit separately and independently, according to the flow rate required for that indoor unit particularly.

For the case study building, the air-sourced VRV system is implemented. One branch box is assigned per each office block, with the total of six (three compartments per floor, applied to ground floor and first floor). From each branch box, refrigerant lines branch towards the designated indoor terminal units, which are the fully flat cassette fan coils. It is considered as an energy-efficient system because of its ability of varying the refrigerant flow rates according to demand, leading to possible zonal energy savings, as it is a demand-responsive system. The following scheme represents this system for one office compartment, covering its ground floor and first floor. The same scheme is applied to all three compartments.

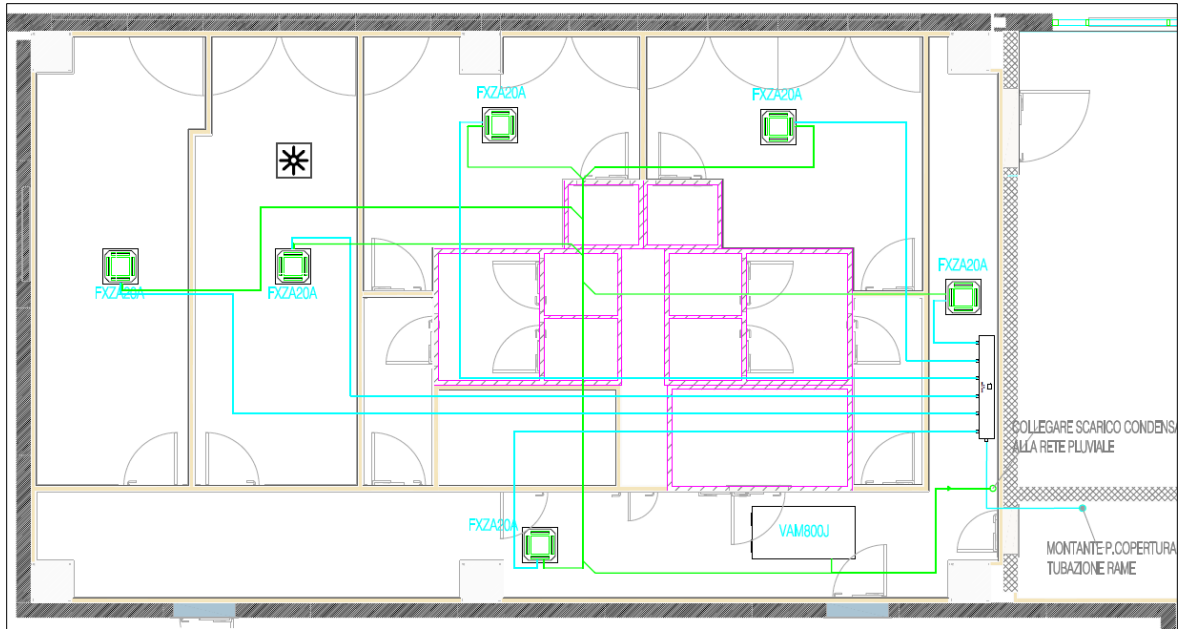


Figure 35: Space conditioning scheme – one office block, ground floor.

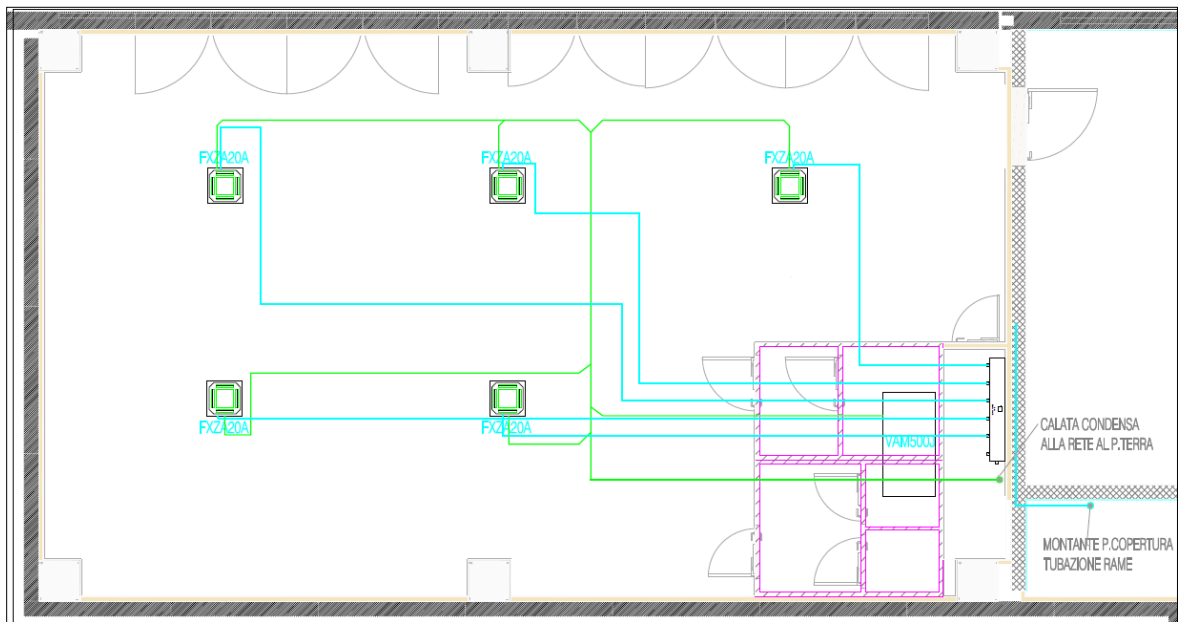


Figure 36: Space conditioning scheme – one office block, first floor.

3.4.5.2. Mechanical ventilation system

As illustrated in the introductory scheme of the building's HVAC systems, there are two types of mechanical ventilation systems implemented for this building:

- a. Mechanical ventilation with heat recovery (MVHR) – serving office blocks,
- b. Air handling unit (AHU) – serving warehouse zones.

Their definitions are the following:

- a. The MVHR system is a solution that provides a continuous supply of fresh outdoor air and exhaust of the stale indoor air, while also recovering heat from the outdoor air taken by the exhausts to pre-heat or pre-cool the incoming air to be supplied, depending on the season. Fresh outdoor air is drawn into the MVHR unit where it is passed through a heat exchanger, absorbing thermal energy from the return (outgoing) air, but without mixing the air streams. The incoming air is then supplied to the occupied zones, as determined by design, reducing the energy required to condition the space due to the air already being pre-heated/pre-cooled.

Using this system for the office blocks of the warehouse is an efficient approach, because in these spaces a continuous fresh air supply with indoor air quality (IAQ) control is required, therefore MVHR reduces peak energy demands in terms of heating and cooling loads, while also improving the occupant comfort. Ultimately, the heat recovery process not only improves the Indoor Air Quality (IAQ) but also reduces the ventilation energy loss [62].

- b. AHU system on the other hand, can serve a larger net floor area, suitable for spaces such as warehouse areas where each compartment is larger than 10,000 m². Considering that there are multiple air handling units separately serving the warehouse zones, the system can be described as a zone-based semi-centralized ventilation approach, allowing for an optimized airflow distribution. AHUs are used in the warehouse compartments instead of MVHR used for the offices, since warehouses have low occupancy density as already presented, therefore meaning that an MVHR unit would be excessive.

As it has been presented for the space conditioning, ventilation schemes are shown in the three following figures, showing a typical ventilation layout of one office block on the ground floor, one office block on the first floor and a warehouse ventilation, respectively.

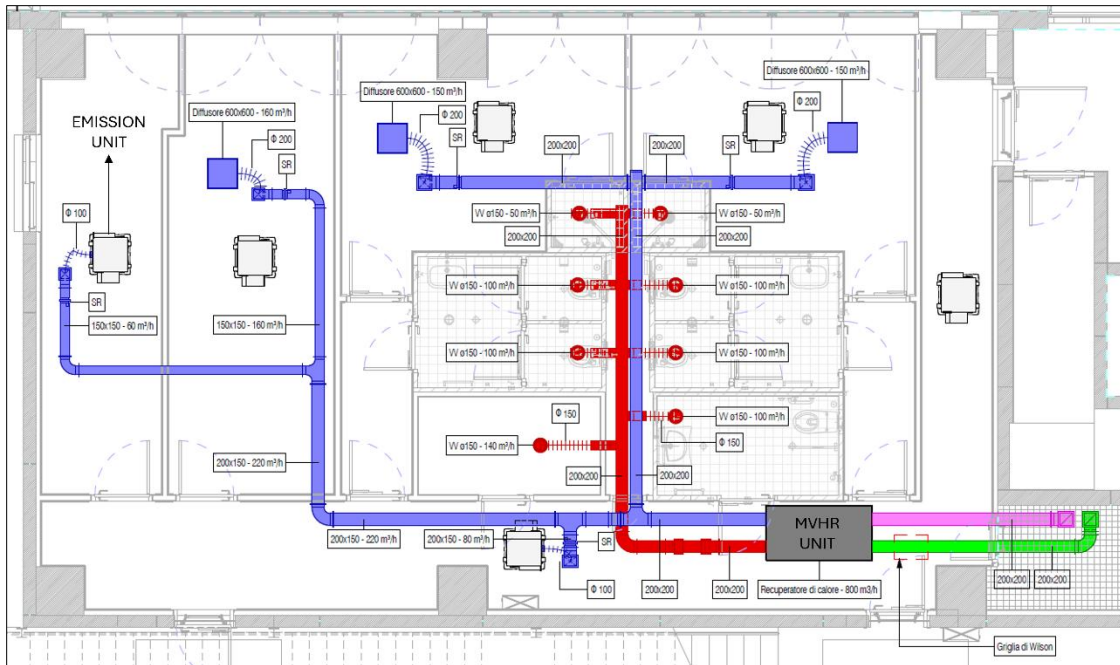


Figure 37: Mechanical ventilation scheme – one office block, ground floor.

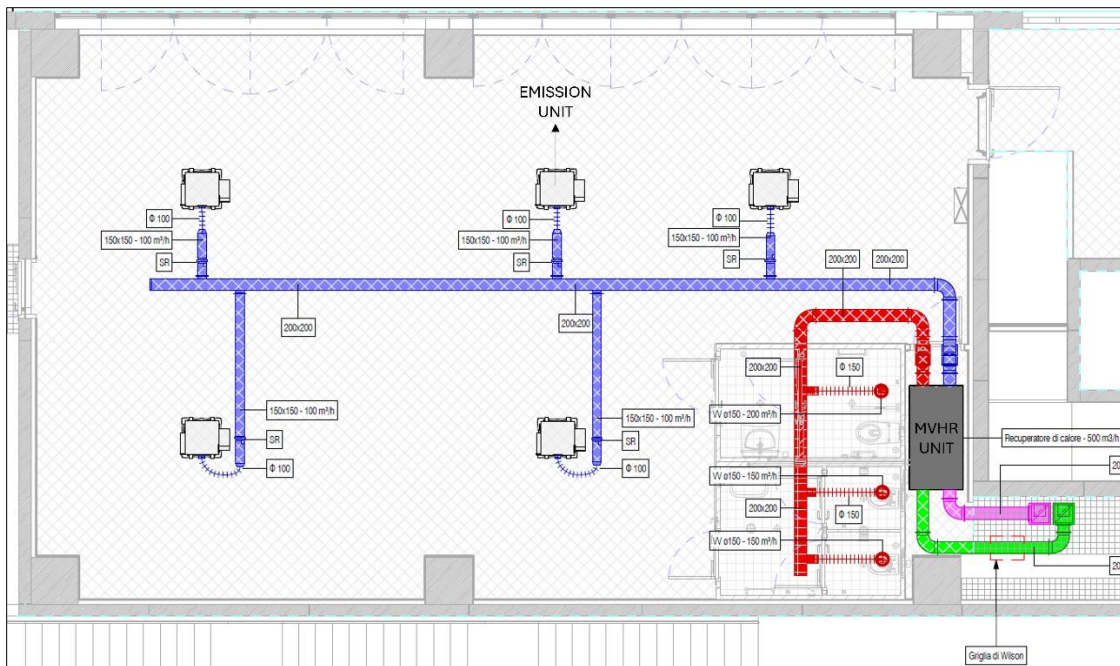


Figure 38: Mechanical ventilation scheme - one office block, first floor.

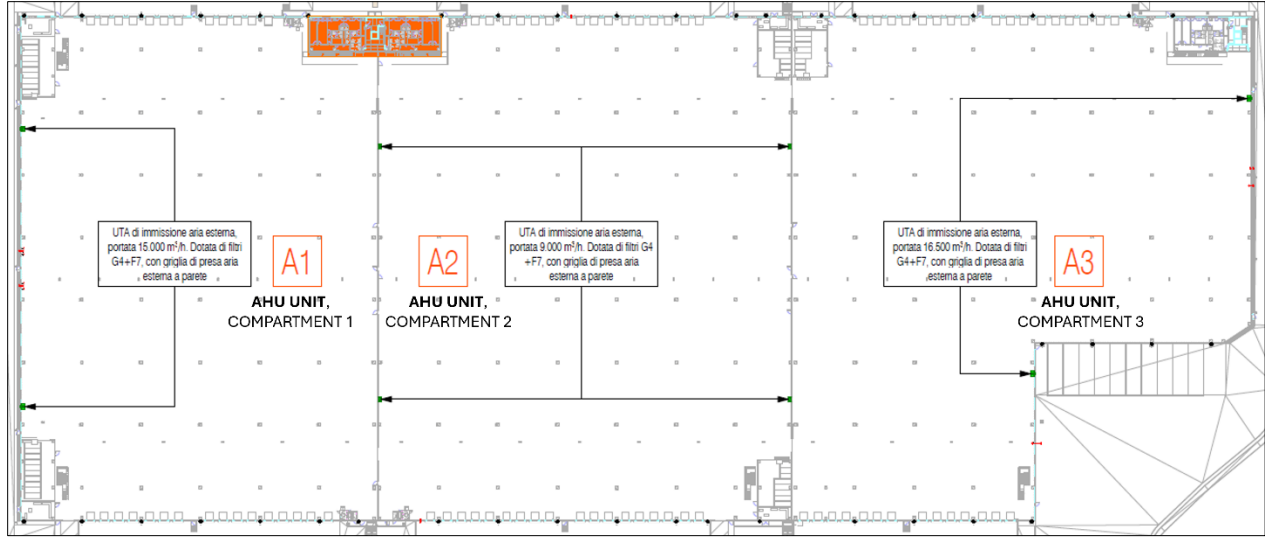


Figure 39: Mechanical ventilation scheme – warehouse.

The standard followed to define the air flow rates of the thermal zones is ANSI/ASHRAE 62.1-2016. Firstly, the minimum required air flow rate should be verified to assure compliance for each Space type identified, and then the proposed values which directly come from design of the mechanical ventilation system from the available project documentation. ASHRAE 62.1 proposes the minimum ventilation flow rate in the breathing zone, and it is based on minimum fresh air rate per person or area, depending on the occupancy category.

For each of the office blocks, one MVHR unit is assigned, with the capacity to supply the zones of ground floor 800 [m³/h] per unit, while on the first floor their capacity is designed with 500 [m³/h]. For the AHU supplying the warehouse, 2 emission units are supplying the A1 compartment with 15,000 [m³/h] each, 4 units are supplying the A2 compartment with 9,000 [m³/h] each, and 2 emission units supplying the A3 compartment with 16,500 [m³/h]. Each AHU unit includes an external air intake grille and a direct air supply grille.

In order to verify and compare the minimum requirement with the design values, Zone outdoor airflow is defined, which is a function of the Breathing zone outdoor airflow and the Zone air distribution effectiveness, as represented in the following formula:

$$V_{oz} = \frac{V_{bz}}{E_z}$$

where:

V_{oz} – design airflow of the thermal zone [l/s];

V_{bz} – breathing airflow requirement [l/s];

E_z – air distribution effectiveness of the thermal zone [-].

Furthermore, zone outdoor airflow is a function of the minimum required airflow per person and per unit area, expressed in the following way:

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$$

where:

R_p – outdoor airflow rate required per person [l/s/person];

P_z – zone population: number of people in the ventilated zone during typical usage [persons];

R_a – outdoor airflow rate required per unit area [l/s/m²];

A_z – zone floor area: the net occupiable floor area of the ventilated zone [m²].

These parameters are based on the occupation category; however, zone air distribution effectiveness is based on the type of the ventilation system implemented. Therefore, for this case study the assigned value of effectiveness E_z is 0.8 [-]. It is defined according to ASHRAE 62.1 as “Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return”.

The following table summarizes the minimum required ventilation flow rate (zone outdoor airflow) for each space. Spaces are marked as compliant if the air flow rate of the supplied primary air exceeds the minimum required air flow rate according to the standard:

Table 29: Summary table of the minimum required vs. project-provided primary air supply flow rates.

Building zone	Building space	Occupancy category (ANSI/ASHRAE 62.1 - 2016)	Req. by ASHRAE 62.1	Zone outdoor airflow - proposed by design		Compliance
			Voz [l/s]	Voz [m³/h]	Voz [l/s]	
Office block A1 GF	Principal corridor	Corridors	16.17	80.00	22.22	YES
	Locker room 1	Break rooms (general)	22.52	180.00	50.00	YES
	Locker room 2	Break rooms (general)	22.38	180.00	50.00	YES
	Break room	Break rooms (general)	33.34	180.00	50.00	YES
	Office space	Office space	13.12	60.00	16.67	YES
	Unit capacity		107.54	800.00	222.22	
Office block A2 GF	Principal corridor	Corridors	16.25	80.00	22.22	YES
	Office space	Office space	49.31	180.00	50.00	YES
	Locker room	Break rooms (general)	22.42	180.00	50.00	YES
	Break room	Break rooms (general)	33.27	180.00	50.00	YES
	Office space	Office space	13.03	60.00	16.67	YES
	Unit capacity		134.29	800.00	222.22	
Office block A3 GF	Principal corridor	Corridors	16.14	80.00	22.22	YES
	Locker room	Break rooms (general)	22.10	180.00	50.00	YES
	Office space	Office space	13.42	180.00	50.00	YES
	Break room	Break rooms (general)	32.40	180.00	50.00	YES
	Office space	Office space	12.91	60.00	16.67	YES
	Unit capacity		96.97	800.00	222.22	
Office block A1 1 ST floor	Office - open space	Office space	89.36	500.00	138.89	YES
	Unit capacity		89.36	500.00	138.89	
Break room 1 ST floor	Break room	Break rooms (general)	89.55	500.00	138.89	YES
	Unit capacity		89.55	500.00	138.89	
Locker room 1 ST floor	Locker room	Break rooms (general)	86.78	500.00	138.89	YES
	Unit capacity		86.78	500.00	138.89	
Warehouse A1-A2-A3	Warehouse zone	Warehouses	17,348.63	99,000.00	27,500.00	YES
	Units capacity		17,348.63	99,000.00	27,500.00	

Since all the spaces comply with the minimum required primary air supply flow rates according to ASHRAE 62.1:2016, these flow rates are taken as the input for ventilation modeling inside of the energy model.

3.4.5.3. Prototype HVAC systems in ApHVAC

Having all the inputs of the building's HVAC systems, it was possible to proceed with the systems modelling following the ApHVAC methodology. To ensure that the systems are modelled accurately and follow a code-compliant methodology, the available system prototypes (templates) were implemented. These templates assigned are defined in accordance to ASHRAE 90.1-2016, App. G PRM (Appendix G – Performance Rating Method), provided to the user. To model both the conditioned and ventilated (office blocks) and the unconditioned but ventilated (warehouse) spaces, the following two templates were used:

- 09 p DOAS - Air-Source VRF System – representing space conditioning and mechanical ventilation of the office blocks;
- 09 m Heat and Vent only [OA and ER coil] – representing mechanical ventilation of the warehouse.

Both air-source VRV and systems are available in the Prototype Library as systems 09p and 09m, respectively.

The air-source VRV system prototype named “09 p DOAS - Air-Source VRF System” includes a Dedicated Outside Air System (DOAS) for ventilation. By default, this ventilation unit is connected to the building's primary VRF network, which provides the necessary heating or cooling to condition the incoming fresh outdoor air before it enters the occupied spaces. The prototype is configured to deliver ventilation air to the zones in parallel with the heating and cooling from the VRF indoor unit.

Mechanical ventilation prototype system named "09 m Heat and Vent only [OA and ER coil]" is a system that couples outdoor air (OA) intake with an electric resistance heating coil to temper ventilation air during cold periods. However, to isolate the pure electrical consumption of the ventilation fans, the electric resistance heating loop was disabled from the loop. Consequently, the component functions strictly as a constant fresh-air supply network, so that indoor air quality standards are met without introducing thermal energy to the warehouse's load profile.

Finally, the following table is a summary of the HVAC systems and applied energy modelling methodology to all the Space types defined in the model:

Table 30: Summary of the HVAC systems applied to each Space type in the energy model.

Building space	Space conditioning, system, methodology	Mechanical ventilation, methodology
Corridor - All Other Corridors	Conditioned, VRV, ApHVAC	Air supply, MVHR, ApHVAC
Dining area - All Other	Conditioned, VRV, ApHVAC	Air supply, MVHR, ApHVAC
Electrical/Mechanical	Unconditioned, /, /	No mech. ventilation
Locker room	Conditioned, VRV, ApHVAC	Air supply, MVHR, ApHVAC
Office - Enclosed	Conditioned, VRV, ApHVAC	Air supply, MVHR, ApHVAC
Office - Open plan	Conditioned, VRV, ApHVAC	Air supply, MVHR, ApHVAC
Restrooms	Unconditioned, /, /	Air exhaust, MVHR, /

Stairwell	Unconditioned, /, /	No mech. Ventilation, /
Storage - $\geq 50\text{ft}^2$	Unconditioned, /, /	Air exhaust, MVHR, /
Warehouse - Medium/Bulky material storage	Unconditioned, /, /	Air supply, AHU, ApHVAC

Following the building energy simulation, it was possible to extrapolate the building's energy consumption, which is completely electrical energy, since no generators with natural gas are used in the project. The results of the energy consumption will be discussed in the following chapter.

4. LCA Baseline results

After defining all the building's constructions, stratigraphies and mechanical systems, it was possible to obtain the results of the baseline embodied and operational carbon emissions. The initial results are extrapolated from the One Click LCA platform. Since all the materials used as the input inside of the platform have an assigned geographic location, this means various distances from the construction site, that contribute to carbon emissions due to transportation of the materials to the site. Additionally, all the materials are assigned a service life, which implies a potential repair year, as well as their handling the end of life and waste management. Therefore, the following input details on the building level are outlined below:

- Transportation: Measured in kilometers, transport distance defines how far materials travel from production sites to the construction site. Default distance and transport mode values reflect typical local conditions for each product type. In known, users may input specific transport distances and modes. Return trips and transport infrastructure are excluded from the calculations. Transport impacts are included in the stage A4 and, for replacement cycles, in stages B4-B5. In this case study, the maximum distance of materials adopted within the Life Cycle Inventory is 370 km. Furthermore, in the model there are three modes of transportation: delivery truck of 9 ton capacity, trailer of a 40 ton capacity for heavier and larger materials such as precast structure, and concrete mixer truck for concrete cast in-place.



Concrete mixer truck, approximately 8 m³, 100% fill rate



Trailer combination, 40 ton capacity, 100% fill rate



Large delivery truck, 9 ton capacity, 100% fill rate

- Service life: For most materials, the assumed service life matches that of the building, defined as 50 years. Service life indicates the time a product functions before replacement. If a product's default lifespan equals the building's lifetime, in the One Click LCA model it is noted as "As Building." Other components are replaced based on their expected service

frequency, with no replacements occurring in the final year of the assessment period. Replacements are accounted for under life cycle stages B4-B5.

- End-of-life (EoL) treatment: The disposal method for each material defines impacts across the final life cycle stages. This selection affects stages C (excluding demolition, C1) and D (if applicable). Within this analysis, EPD data was used to define the EoL treatment of each material, rather than modifying it within the model, in order to be methodologically consistent and rely on the declarations published and available online.

4.1. Embodied carbon results

The results of the embodied carbon were obtained for the entire built area of the site, including not only the building area but also the exterior works. Life cycle inventory is based on the project's bill of quantity (BoQ) reflecting the real quantities of the built building and exterior area. The total number of materials input for the calculation equals to 154. To have a clear and standard analysis of the environmental impact results, LEVEL(s) framework is followed. It divides all the elements into three main categories:

1. Shell (substructure and superstructure),
2. Core (fittings, furnishings and services), and
3. External works.

LEVEL(s) is a European framework of core sustainability indicators for buildings [63]. Choosing a LEVEL(s) framework for presenting the environmental impact of all the building materials of the life cycle inventory means having in mind different project actors and having following potential advantages:

- Project design team – focusing on the performance of the whole building starting from the design stage and having a simple structure to present the data;
- Clients and investors – priority aspects are set clearly and transparency is ensured with the regards to methodology of reporting environmental data, ensuring reliability;
- Public policy makers and procurers – highlighted main building sustainability aspects of direct interest to public authorities, i.e. reducing operating and maintenance costs by evaluating operational carbon of the use stage of a building.

As introduced in the methodology of this study, the analysis will be limited in scope of assessment to Global Warming Potential (GWP) impact category. GWP is the main metric that is required by the LEVEL(s) framework already discussed, EU Taxonomy, as well as within the Energy Performance of Buildings Directive (EPBD) focusing on whole-life carbon reporting. For example, LEVEL(s) reports that GWP, its core indicator, has a potential influence on increasing future revenues due to the market recognition and demand.

Finally, the consistency of reporting the environmental impact categories is another reason why the primary focus of analyses is on GWP, as the global warming impacts can be more readily

quantified compared to others [51]. This robustness in quantifiability contributes to its reliability as an environmental indicator [64].

A baseline model has been built using the environmental product declarations available for the building's materials. Cradle-to-Grave assessment is performed and according to the baseline results, the product stage A1-A3 is overwhelmingly dominant. On average for all the LEVEL(s) Building Parts, the contribution of the product stage is 86.7%. Two building parts that show the highest contribution of other life cycle stages are 1.3.1. Ground floor slab and 1.5.2. Weatherproofing. In case of the ground floor slab, the second dominant life cycle stage is C1-C2 – Waste demolition and transport, with 4.3% of contribution, followed by A5 – Construction stage with 3.5%. The reason is the on-site casting of concrete for the ground floor slab that covers 47,823.73 m² of net floor area. For the rest of the building parts, all the other life cycle stages represent less than 5% of contribution each, with the production stage remaining the overwhelmingly dominant stage.

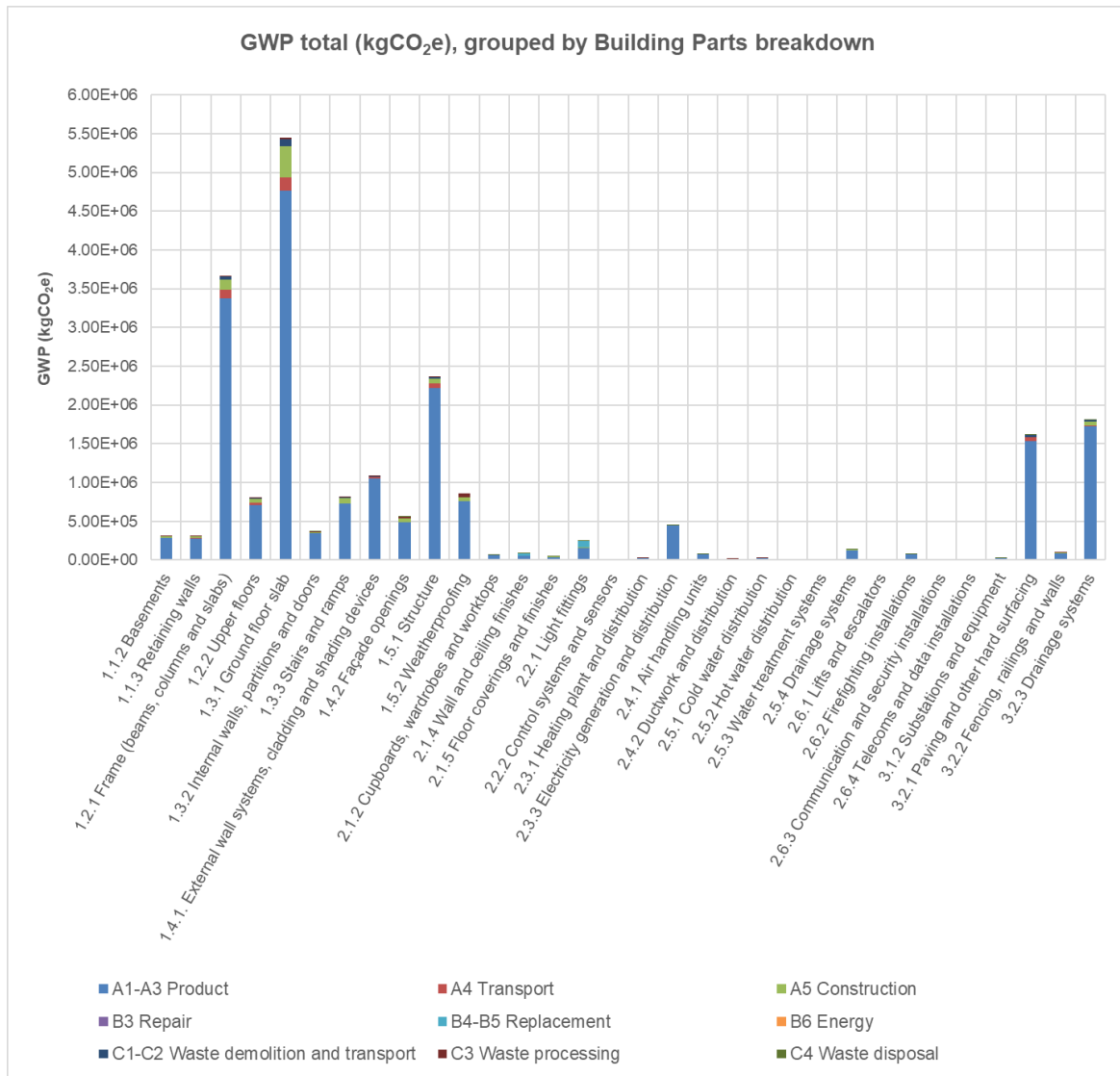


Figure 40: Total Cradle-to-Grave GWP impact of the building, grouped by LEVEL(s) Building Parts breakdown.

As it has been stated in the Methodology section, the functional unit of the building can be considered both as Global Warming Potential expressed per gross floor area of the building or per gross volume of the building. Total embodied carbon of the baseline scenario considering the Cradle-to-Grave approach equals to 392.1 kgCO₂e/m² or 39.3 kgCO₂e/m³.

Table 31: Contribution of different life-cycle stages to the whole-life building's GWP.

Life-cycle stage	GWP total (kgCO₂e)	% of contribution
A1-A3 Product	18,733,690	86.7%
A4 Transport	475,230	1.9%
A5 Construction	837,799	3.5%
B3 Repair	0.00	0.0%
B4-B5 Replacement	110,600	0.5%
B6 Energy	0.00	0.0%
C1-C2 Waste demolition and transport	991,925	4.3%
C3 Waste processing	459,130	2.1%
C4 Waste disposal	1,190	0.0%
Total impact (kgCO₂e)	21,609,565	
Total impact per gross floor area (kgCO₂e/m²)	392.1	
Total impact per gross volume (kgCO₂e/m³)	39.3	

Considering such a high impact of the A1-A3 product stage, more attention is therefore dedicated to the analysis of the most impacting Building Parts and materials within this LCA stage. It is apparent that dominantly the highest impacts are due to the building's structural frame made of precast reinforced concrete, but also non-load bearing elements, which include the ground floor slab that covers completely the warehouse compartments, as well as the mezzanines on the first floor. Other significant impact is visible for the roof structure, as it is also composed of precast wing tile structural elements. Finally, a high carbon footprint is also emitted due to the materials of landscaping, that include asphalt surfaces of the exterior site and concrete paving in front of the loading bays, but also the drainage system made out polyethylene (PE) piping. This information shows us that not including the building exterior works on the site would undermine the total impacts of the entire construction of the facility, not only the building itself. For a more detailed look into the material inventory and which single material is assigned to which category exactly, please refer to the attachments in the Appendix chapter of the document.

Table 32: Contribution to the GWP of A1-A3 product stage of different Building Parts according to LEVEL(s) framework.

Building parts LEVEL(s)	GWP (kgCO ₂ e), A1-A3	Percentage % of contribution to GWP (kgCO ₂ e), A1-A3
1.1. Foundations (substructure)	468,751	2.89
1.2. Load bearing structural frame	4,071,996	21.02
1.3. Non-load bearing elements	5,494,668	29.99
1.4. Facades	1,544,033	7.94
1.5. Roof	2,975,762	15.30
2.1. Fittings and furnishings	157,096	0.81
2.2. In-built lighting system	158,543	0.82
2.3. Energy system	463,015	2.38
2.4. Ventilation system	84,710	0.44
2.5. Sanitary systems	149,329	0.77
2.6. Other systems	71,640	0.37
3.1. Utilities	20,000	0.10
3.2. Landscaping	3,318,612	17.19
Total	18,733,690	100.0

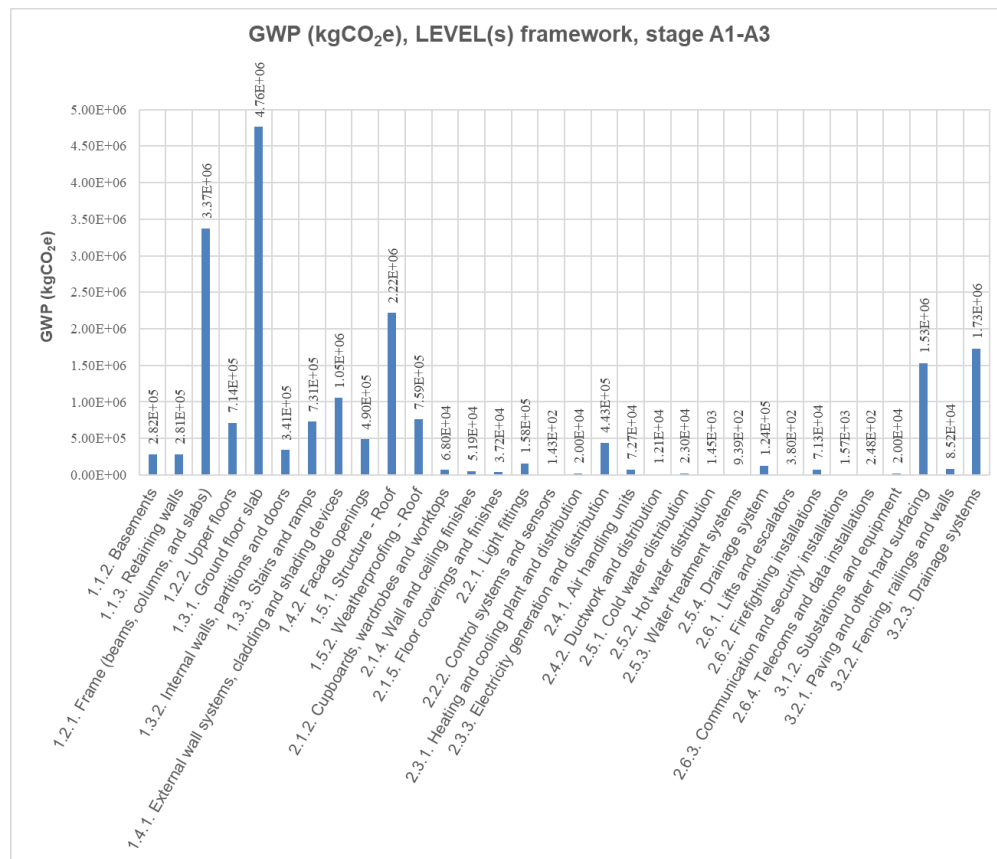


Figure 41: GWP impact of the building in the A1-A3 product stage, grouped by LEVEL(s) Building Parts breakdown.

Having structured the results according to LEVEL(s) framework and understanding which Building Parts are the most critical in terms of carbon emissions, it is also interesting to isolate the single elements and obtain information which materials are the most impacting ones. As expected from previous results, the most impacting material is a prefabricated (precast) structure made out of reinforced concrete, followed by ready-mix concrete poured on-site, that included foundations, ground floor and upper floor slabs. The structure is followed by exterior paving in asphalt and drainage systems and piping consisting of HDPE pipes, precast concrete manholes and PVC piping for sewage, while prefabricated facade and reinforcing steel used for the in-situ concrete are the 5th and 6th most contributing materials.

Table 33: Most contributing materials to the GWP within the A1-A3 product stage.

Material n#	Material	GWP (kgCO ₂ e), A1-A3 production stage	Percentage % of contribution to GWP (kgCO ₂ e), A1-A3
1	Prefabricated structure 30.05%	5,573,701	30.05
2	Ready-mix concrete 28.13%	5,216,358	28.13
3	Exterior paving 5.75%	1,066,822	5.75
4	Drainage and sewage systems 5.64%	1,045,900	5.64
5	Prefabricated facade 4.33%	859,120	4.33
6	Reinforcing steel 3.17%	586,985	3.17
7	El. equipment 3.00%	556,302	3.00
8	Steel staircase 2.79%	517,000	2.79
9	Black steel piping 2.65%	492,000	2.65
10	EPS insulation 2.39%	443,827	2.39
11	Structural joints 1.96%	363,710	1.96
12	TPO roof 1.43%	265,000	1.43
13	Polycarbonate 1.16%	216,000	1.16
14	Loading bays 0.96%	178,330	0.96
15	Others 6.58%	1,220,712	6.58
Total		18,733,690	100.00

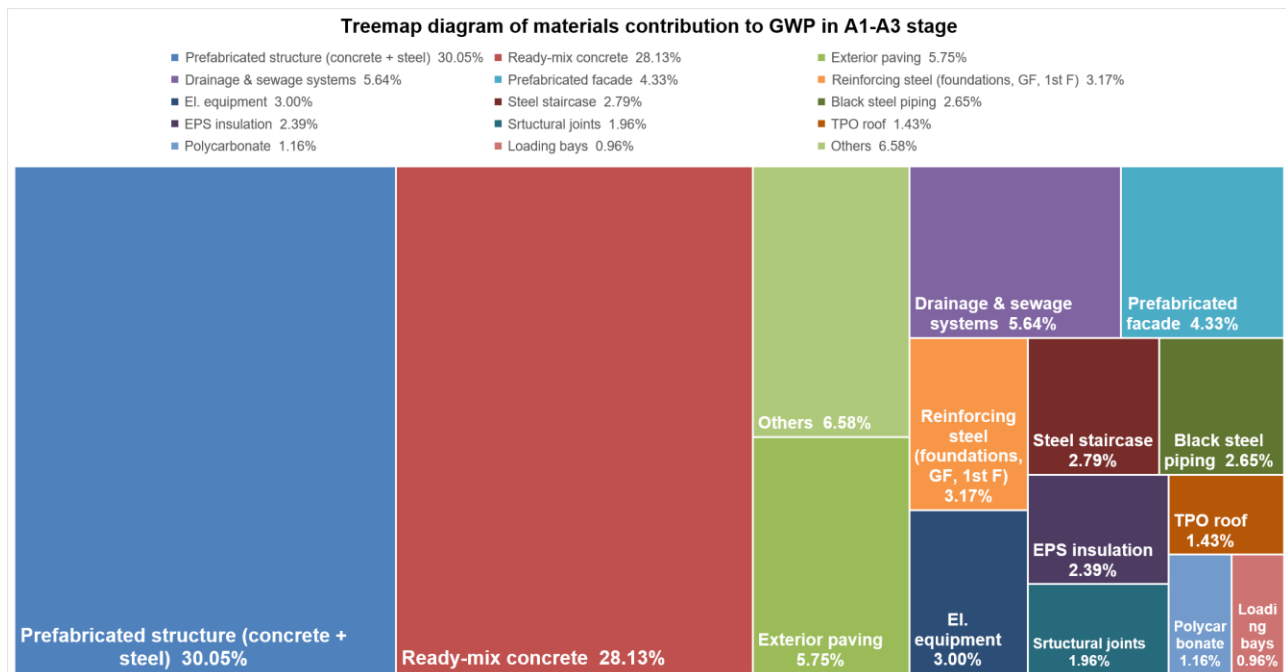


Figure 42: Tree-map diagram of materials contribution to GWP in A1-A3 product stage.

4.2. Operational carbon results

Thanks to the building energy model created using the IESVE software, building energy consumption on annual basis is exported and post-processed in terms of energy use for interior and exterior lighting, space heating and cooling, mechanical ventilation, elevators and office equipment electrical energy consumption. Based on the annual consumption expressed in kWh, operational carbon emissions in kgCO₂e are obtained by multiplying the consumption with the emission factor, taken as the national residual mix factor of 0.522 kgCO₂e/kWh. The result is then further divided with the functional units of the analysis.

The highest consumption is reported due to office equipment, that includes plug loads coming from computers and monitors, printers, scanners, breakroom appliances such as microwaves, refrigerators and coffee machines, but also communication and IT gear like servers, routers and telecom racks, connected to the building's BMS system. Second highest contribution is due to interior lighting, then followed by mechanical ventilation. Space conditioning is significantly less impactful than ventilation, which is a consequence of warehouse space being ventilated, but not conditioned. Space conditioning represents in fact only 4.46% of the total annual energy consumption, and represents just slightly more than one fifth (1/5) of the consumption due to mechanical ventilation.

Table 34: Results of operational carbon emitted due to the building's energy consumption.

LIGHTING	Energy use [kWh]	Energy demand [kW]	Hours ON [h]
Interior lighting	270,027.10	92.75	2,911
Exterior lighting	28,766.66	4.92	5,847
Total lighting	298,793.76	97.67	3,059
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Operational carbon - lighting	156,627.69	kgCO₂e	
Operational carbon - lighting	3.42	kgCO ₂ e/m ²	
CONDITIONING	Energy use [kWh]	Energy demand [kW]	Hours ON [h]
Space heating	18,596.87	16.73	1,112
Space cooling	18,438.47	17.07	1,080
Total space conditioning	37,035.34	33.8	1,096
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Operational carbon - conditioning	19,413.93	kgCO₂e	
Operational carbon - conditioning	94.88	kgCO ₂ e/m ²	
MECH. VENTILATION	Energy use [kWh]	Energy demand [kW]	Hours ON [h]
Fans interior	165,400.85	30.41	5,439
Heat rejection	1,176.42	1.09	1,079
Total ventilation	166,577.27	31.5	5,288
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Operational carbon - ventilation	87,319.80	kgCO₂e	
Operational carbon - ventilation	1.90	kgCO ₂ e/m ²	
EQUIPMENT	Energy use [kWh]	Energy demand [kW]	Hours ON [h]
Elevators	2,539.53	5.56	457
Office equipment	324,572.08	111.48	2,911
Total equipment	327,111.61	117.04	2,795
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Operational carbon - equipment	171,471.91	kgCO₂e	
Operational carbon - equipment	3.59	kgCO ₂ e/m ²	
TOTAL EL. ENERGY	Energy use [kWh]	Energy demand [kW]	Hours ON [h]
Total energy consumption	829,517.98	280.01	2,962
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Total Operational carbon, annual	434,833.33	kgCO₂e	
Total Operational carbon, annual	103.79	kgCO ₂ e/m ²	
Total Operational carbon, 50 years	21,741,666.5	kgCO₂e	

Total Operational carbon, 50 years	394.50 kgCO ₂ e/m ²
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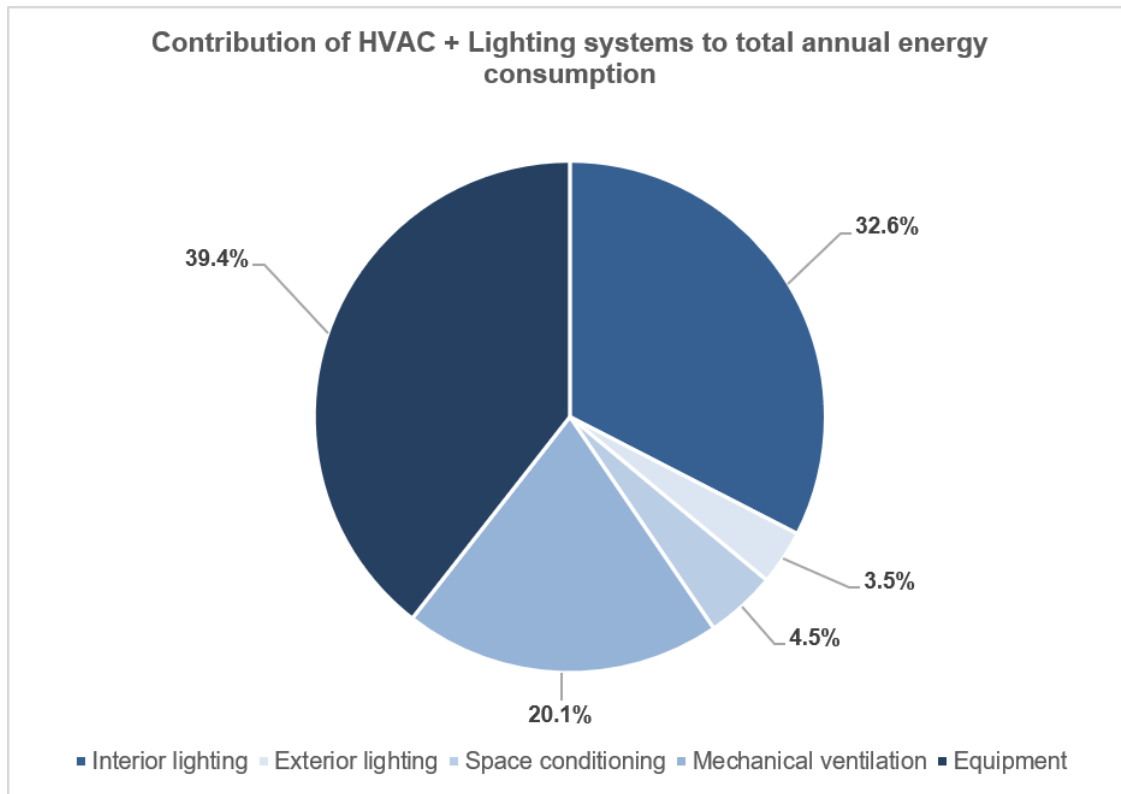


Figure 43: Percentage of contribution of HVAC + Lighting systems of the building to the total annual building's electrical energy consumption.

Comparing the final results of the baseline scenario between total embodied and operational carbon during the building's service life, the ratio between them is almost 50-50, where embodied carbon impacts are released upfront in year 0 (in which the construction ends and building operation begins) with 392.1 kgCO₂e/m² of GWP, while operational carbon is emitted over 50 years, finally resulting in 394.5 kgCO₂e/m² by the EoL, being just slightly higher than the embodied carbon. This baseline scenario will be therefore used for further optimizations.

Table 35: Summary of the baseline scenario 50-years embodied, operational carbon and total building carbon, expressed as a total sum, per gross floor building area and gross volume of the building.

Environmental impact	Value	Unit
Total Embodied carbon, 50 years	21,609,565.2	kgCO ₂ e
	392.1	kgCO ₂ e/m ²
	39.3	kgCO ₂ e/m ³
Total Operational carbon, 50 years	21,741,666.5	kgCO ₂ e
	394.5	kgCO ₂ e/m ²
	39.5	kgCO ₂ e/m ³
Total building carbon, 50 years	43,351,231.7	kgCO ₂ e
	786.6	kgCO ₂ e/m ²
	78.8	kgCO ₂ e/m ³

5. Optimization of embodied and operational carbon

The following chapter will present discussion of results obtained with the attempt to optimize the whole-life total building's carbon by implementing different strategies on material- and whole-building-level. First and foremost, optimization of the embodied carbon will be shown, that will be performed only for specific parts of the building, according to the baseline results. The following table highlights the materials that will be included in the discussion.

Reasoning for the choice of these building elements in particular is due to the strong presence of concrete and steel within their composition, the most common building construction materials that due to their potential in prefabrication are highly used in warehouse buildings. It was decided to not pursue an analysis related to exterior paving and drainage materials although their impact is non-negligible; however, their representation renders the LCA analysis more accurate and complete.

Table 36: Focus on the most contributing materials to GWP for optimization analysis.

Material n#	Material	GWP (kgCO ₂ e), A1-A3 production stage	Percentage % of contribution to GWP (kgCO ₂ e), A1-A3
1	Prefabricated structure 30.05%	5,573,701	30.05
2	Ready-mix concrete 28.13%	5,216,358	28.13
3	Exterior paving 5.75%	1,066,822	5.75
4	Drainage & sewage systems 5.64%	1,045,900	5.64
5	Prefabricated facade 4.33%	859,120	4.33
6	Reinforcing steel 3.17%	586,985	3.17
7	El. equipment 3.00%	556,302	3.00
8	Steel staircase 2.79%	517,000	2.79
9	Black steel piping 2.65%	492,000	2.65
10	EPS insulation 2.39%	443,827	2.39
11	Structural joints 1.96%	363,710	1.96
12	TPO roof 1.43%	265,000	1.43
13	Polycarbonate 1.16%	216,000	1.16
14	Loading bays 0.96%	178,330	0.96
15	Others 6.58%	1,220,712	6.58
Total		18,733,690	18,733,690

As it has been introduced, the following embodied carbon optimization will be focused on the most impacting common building materials that can be summarized into three main frontlines, which are: precast concrete structural elements, on-site concrete structural elements and precast envelope. Naturally, two materials that both the precast and on-site structural elements are composed of are concrete and steel. Therefore, the analysis will be separated into:

- Concrete and steel embodied carbon optimization, and
- Building envelope embodied carbon optimization.

5.1. Building structure embodied carbon optimization

5.1.1. Concrete embodied carbon optimization

Two main distinct technologies in building the structural system of the case study building are the precast technology and on-site cast concrete. The following table provides a summary of the GWP impact of different precast vs. cast on-site elements for the production stage Cradle-to-Gate (A1-A3). The impacts are almost equally divided between the two building technologies with concrete,

with precast elements being slightly more dominant with 48.1% of impact. In terms of the volume, precast elements represent 44.5% of all the concrete elements (with around 10,000m³ of precast concrete). It is noteworthy mentioning that results include GWP contributions of both concrete and steel. Further analyses will report a more detailed breakdown of their separate contributions.

Table 37: Summary of the GWP impacts of different precast concrete elements vs. cast on-site concrete elements.

Precast reinforced concrete elements		Cast on-site reinforced concrete elements	
Element	GWP (kgCO ₂ e), A1-A3	Element	GWP (kgCO ₂ e), A1-A3
Concrete pillars	875,414.5	Pile foundations for pillars	235,757.2
Primary beams	955,064.3	Retaining walls for facade panels	231,194.6
Secondary beams	119,265.8	Ground floor slab	4,053,386.1
Precast TT-floors	1,328,065.4	Mezzanine slab floor finishing	731,527.7
Wing-shaped roof beams	2,259,572.9	Concrete in front loading bays	551,451.7
Total	5,573,701.3	Total	5,803,317.3

As it has been discussed in the literature review, substituting the traditional concrete with a more sustainable solution is not a straight-forward solution, as it is a heterogeneous material that has a structural role, therefore improving its sustainability also has implications on the structural performance that must be addressed in order to have a more complete picture if a chosen sustainable solution is viable in real-life construction. Instead of focusing solely on the carbon intensity of concrete per cubic meter, improving concrete strength implies less production of concrete, meaning that there is an important interaction between concrete strength, its carbon footprint due to the binder content and total material volume. Research papers such Bacelara et al. (2022) [65] have already demonstrated that by increasing the compressive strength of a building's columns, a reduction of the environmental impact can be achieved.

Therefore, it was decided to pursue the same analysis. Out of all the precast concrete elements listed, the following analysis will focus on optimization of the volume of concrete columns. To evaluate the possible real-world material savings for concretes of various compressive strengths, the structural volume optimization in this study was restricted exclusively to vertical load-bearing elements (columns). Horizontal flexural elements, such as beams and slabs, were omitted from the geometric reduction analysis. This scope is explained by the fact that columns are predominantly axial compression members, meaning that their load-bearing capacity is in direct relation with the concrete compressive strength. The relation between the increase in compressive strength and reduction in the required cross-sectional area is linear.

Keeping the same horizontal flexural elements unchanged ensures to have the same compressive axial force N_{Rd} on the columns. Considering the columns' height of 11.5m, the resisting compressive axial force is a function of the column cross-section area, design compressive strength, as well as the buckling reduction factor:

$$N_{Rd} = \frac{X \cdot A_c \cdot f_{cd}}{\gamma_M}$$

Since the height of the columns is a non-variable parameter and the compressive axial force does not vary from the baseline, the areas of two columns with different compressive strength of concrete can be expressed in the following way:

$$A_1 = \frac{N_{Ed}}{X \cdot f_{cd,1}}$$

$$A_2 = \frac{N_{Ed}}{X \cdot f_{cd,2}}$$

It is therefore possible to cancel out the buckling reduction factor and the design compressive axial force, which simplifies the proportion in the following way:

$$\frac{A_2}{A_1} = \frac{f_{cd,1}}{f_{cd,2}}$$

The research paper of Bacelara et al. [65] also brings into analysis another index for evaluation of concrete sustainability, which is the concrete eco-efficiency, that is a function of its environmental impact and compressive strength, expressed through the following equation:

$$ECO_c = \frac{GWP (t CO_2e)}{f_{ck} (MPa)}$$

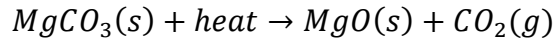
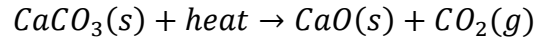
This index gives us a valuable input to understand how structurally efficient is a concrete solution with respect to its carbon footprint, especially when comparing different concrete solutions that contain different binder compositions and various values of compressive strengths. The lower the value is, the concrete mix is considered as more efficient. As the primary objective of this analysis is to couple Life Cycle Assessment data with material efficiency, represented by an index of concrete eco-efficiency, isolating the direct impact of concrete strength on the volume of columns means avoiding the secondary structural redundancies (such as the frame action stiffness redistributions) that a full FEM model would introduce.

The analysis will proceed by presenting various concrete mix solutions containing different binders and different compressive strengths. Concrete mix solutions that will be presented are references from collected research papers related to sustainable concrete and are cited in the literature review. Since the carbon footprint of production of concrete is heavily impacted by the production of cement, a short introduction to cement types and production route is provided.

5.1.1.1. Introduction to cement types and production

Production of cement includes several procedures, such as quarrying, transportation, high-temperature pyroprocessing, clinker cooling, finish milling, grinding and bending. The critical environmental point occurs within the rotary kiln, where raw material (which is primarily limestone) is heated to approximately 1450°C.

This extreme thermal processing triggers the chemical calcination of limestone, as well as magnesite, a reaction that inherently releases carbon dioxide as a process byproduct:



Clinker production is a highly energy- and carbon-intensive process, as the pyroprocessing part of the production represents 88% of the total fuel used, 91% of the total energy used for the entire cement production process and up to 75% of the total carbon footprint of clinker manufacturing, according to Gao et al. (2024) [66]. The authors also argue that focusing on reducing CO₂ emissions during this intensive process and using less clinker can lead to a more efficient and effective cement production process.

Furthermore, while mechanical optimization and alternative fuels can reduce the thermal energy demands of the kiln, the primary driver of the industry's carbon footprint must be mitigated, which is the clinker production in the kiln. This is why using secondary raw materials can reduce emissions by 30% according to Durastanti et al. (2024) [67], starting from 2.9 Gt CO₂/year, which is about 7% of global anthropogenic CO₂ emissions. Secondary Cementitious Materials (SCMs) such as blast furnace slag, fly ash, natural pozzolana, limestone filler, and calcined clays replace a significant portion of the carbon-intensive clinker, utilizing latent hydraulic or pozzolanic reactions to bind the concrete matrix without the associated calcination footprint.

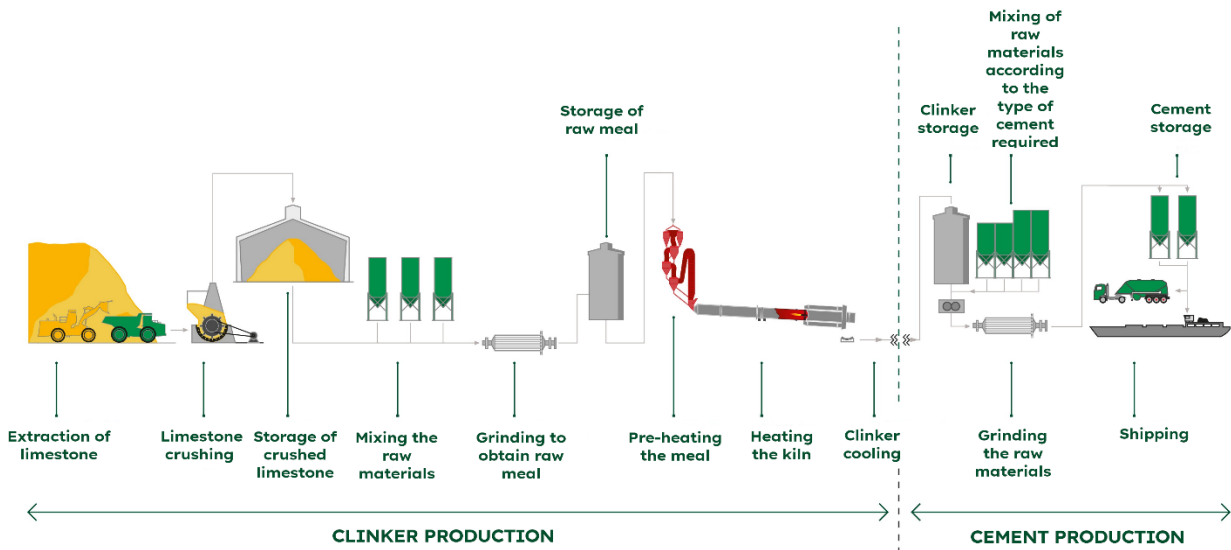


Figure 44: Illustration of clinker and cement production process.

To understand systematically the common type of cements, the categorization of cements is presented in the table below, according to the technical standard UNI EN 197-1: Part 1 Composition, specifications and conformity criteria for common cements.

Table 38: Categorization of cements according to UNI EN 197-1: Part 1.

Main Types	Types of cements		Composition (percentage by mass)										Minor additional constituents
			Main constituents										
			Clinker	Blast- furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calcareous				
K	S	D	P	Q	V	W	T	L	LL				
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland-pozzolana cement	CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
	Portland limestone cement	CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland-composite cement	CEM II/B-M	65-79	←----- 21-35 -----→									0-5
		CEM II/C-M*	50-64	←----- 36-50 -----→									0-5
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic cement	CEM IV/A	65-89	-	←----- 11-35 -----→					-	-	-	0-5
		CEM IV/B	45-64	-	←----- 36-55 -----→					-	-	-	0-5
CEM V	Composite cement	CEM V/A	40-64	18-30	-	←----- 18-30 -----→			-	-	-	-	0-5

It is noteworthy mentioning that cements such as CEM II/C-M and composite cement type CEM VI are referenced in the edition of the standard UNI EN 197-5: Part 5: Portland-composite cement CEM II/C-M and composite cement CEM VI.

5.1.1.2. LCA of various concrete mixes

Having introduced briefly the cement classification according to the European standard, the following paragraphs will present the comparative analysis of concrete mixes containing various cement types and having different compressive strengths. The purpose of this work is to demonstrate which type of concrete mix shows the lowest environmental impact, taking the concrete mix recipes directly from literature review based on the research papers dealing with the topic of concrete eco-sustainability.

For evidence of the recipe of each concrete mix and its reference from a peer-reviewed research paper, please refer to the attachments in the Appendix of this document. In total, 46 recipes were analyzed, as well as the recipe used for the baseline. The summary of the baseline impacts are reported in the table below. The baseline column cross-section geometry is 70x70cm, taken directly from the available project documentation.

Table 39: Summary of the GWP impact of the baseline scenario for precast reinforced concrete pillars, for the Cradle-to-Gate stage A1-A3.

Element	GWP (kgCO ₂ e), A1-A3	Total columns' volume (m ³)	GWP (kgCO ₂ e/m ³), A1-A3
Concrete pillars, concrete	829,269.1	1,668.7	496.9
Concrete pillars, rebars ⁴	46,145.4	42.8	-
Total for reinforced concrete pillars, 70cm x 70cm	875,414.5	1,711.5	511.5

To isolate the environmental impacts that are driven strictly by binder chemistry and material optimization, the life cycle stages were split into A1 stage (primary foreground system), i.e. impacts being results of various mixes, A2-A3 stages (standardized, representative system of typical values for concrete and steel related to these stages), and A4-A4, C1-C4 stages (standardized, representative system of typical values of a precast reinforced concrete precast pillar). More precisely, the workflow was executed as follows:

1. *Step 1* Material-level inventory (Module A1): for each of the 46 evaluated concrete mixes sourced from peer-reviewed experimental literature, the precise mass of all constituents was compiled in terms of kg/m³ of a concrete sample. Then the material emission factors expressed in kgCO₂e/kg were applied for each constituent within a particular concrete mix to yield the footprint of one cubic meter of a concrete mix, expressed in kgCO₂e/m³, representing the Module A1 for each of the 46 solutions. As already stated, in a process as complex as concrete making, cement production represents the highest impact. Therefore, it must be underlined that carbon impacts of a particular cement produced is already included in the results, and impacts of other raw materials for concrete making added to the sum. Concisely, the A1 product stage for reinforced concrete includes:
 - Clinker production impacts (from raw extraction of limestone to thermal kiln processes to finished clinker)
 - Impacts of all the rest raw materials for concrete
 - Steel rebars production impacts (from furnace to billets to ribbed bars)
2. *Step 2* Volumetric structural scaling: as it has been introduced in previous chapters, volume of the precast pillars is a direct function of the compressive strength. Based on the strength reported from the experimental lab results found in the respective literature, the column dimensions were adapted for each mix. The total mass-based GWP expressed in kgCO₂e for the building's columns was obtained by multiplying each mix's A1 carbon footprint by the calculated structural volume of columns created with each mix according to its compressive strength.

⁴ The GWP impact of rebars is traditionally expressed in the functional unit of mass (kg or t), therefore there will be a dedicated chapter to environmental impact of steel. Here although it is reported for completeness as a precast element contains steel as well, the analysis focuses on concrete.

3. **Step 3** Transport and internal plant operations (Modules A2 and A3): Utilizing the results reported in EPDs of established concrete and steel bars Italian producers, the impacts of raw material transit to the plant and plant-specific mixing carbon footprint were extrapolated to complete the cradle-to-gate A1-A3 impacts.
4. **Step 4** Finally, once the pillars are produced and ready to be transported to the construction site, for the rest of their life cycle until the C4 stage, the modules were modeled using fixed, uniform values extracted from a verified EPD of a representative Italian precast concrete pillar element. In this way it is ensured that stages beyond the production stage are a fixed parameter, and the focus is on the impacts of concrete production.

The following illustration summarizes the workflow of modelling the LCA of a precast reinforced concrete pillar element:

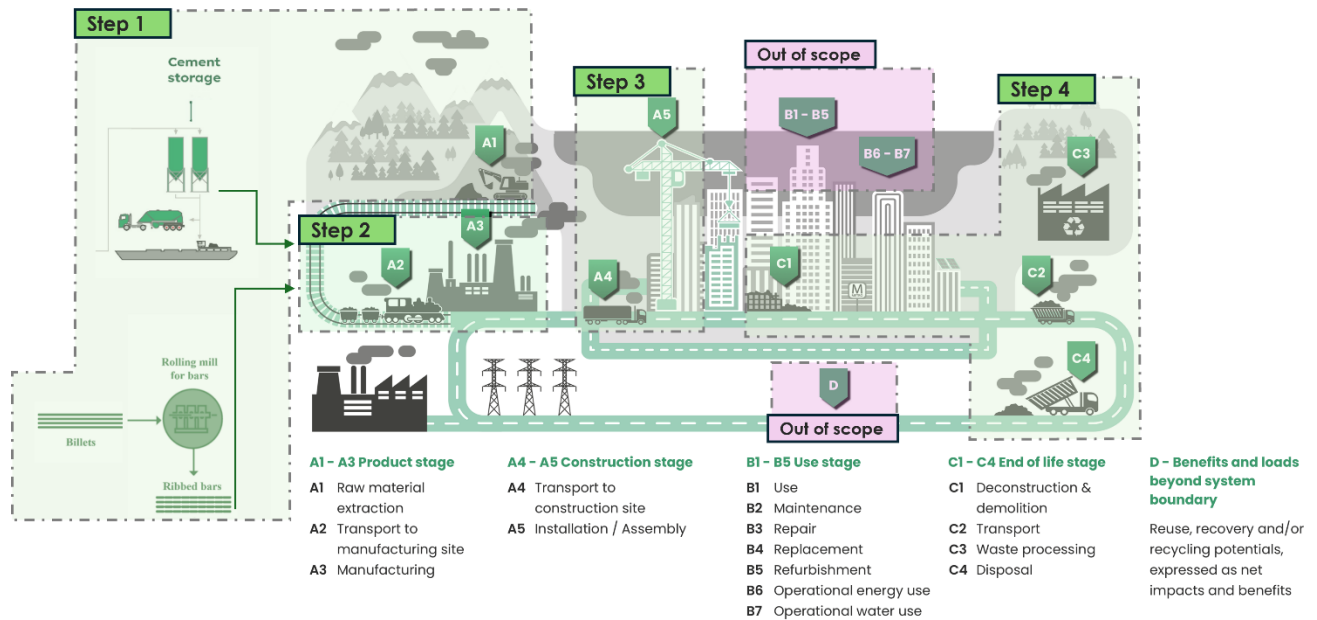


Figure 45: Illustration summarizing the LCA modelling workflow of a prefabricated reinforced concrete pillar element.

Concrete mixes included in the following analysis contain besides clinker, aggregates and water, also the following SCMs: ground-granulated blast furnace slag (GGBS), fly ash, calcined clay, limestone powder and mineral natural gypsum, as well as admixtures such as superplasticizers to improve workability, which is especially relevant for higher-strength concretes with lower water-to-binder ratios. Carbon emission factors of the elements of the concrete mix taken as input for the analysis are reported in the following table:

Table 40: Input data in terms of GWP impact per kg of the materials, with source and database indicated.

Concrete mix part	Element of the concrete mix	GWP (kgCO ₂ e/kg)	Source/database
Clinker	Clinker 1 - CEM I 52.5 R	0.940	EPD-IES-0028242:001
	Clinker 2 - CEM I 42.5 R	0.930	S-P-03386
SCMs	Ground Granulated Blast Furnace Slag (GGBS), economic allocation (One Click LCA)	0.0561	One Click LCA
	Fly ash, calculated average for Italy (One Click LCA)	0.0497	One Click LCA
	Calcined clay	0.29	EPD HUB-1883
	Limestone powder (One Click LCA)	0.062	One Click LCA
	Gypsum	0.04	ÖKOBAUDAT 1.1.03
Aggregates Addition	River sand and gravel	0.00322	EPD-IES-0031355:001
	Superplasticizer	1.53	EPD-IES-0031598:001

The following tables report results of the A1 stage of concrete mixes carbon footprint, therefore addressing the point *Steps 1 and 2* of the presented workflow. Impacts of steel rebars will be analyzed separately.

Table 41: Results of the analysis of A1 GWP impacts for top 15 most sustainable concrete solutions vs. the baseline case.

Ranking	Concrete mix	Total GWP of the pillars (t CO ₂ e)	Total concrete pillars volume (m ³)	28d compressive strength (N/mm ²)	GWP of the mix (kgCO ₂ e/m ³)
1	Concrete with composite cement, CEM V/B (S-V)	125.85	1033.2	50.9	121.8
2	Blast furnace slag concrete, CEM III/B	133.89	973.9	54.0	137.5
3	Concrete with composite cement, CEM VI (S-V-L)	137.71	1158.3	45.4	118.9
4	Concrete with composite cement, CEM VI (S-L)	150.09	1288.9	40.8	116.5
5	Low-binder concrete LC3, C70	152.69	755.6	69.6	202.1
6	Low-binder concrete LC3, C60	171.10	885.3	59.4	198.5
7	Blast furnace slag concrete, CEM III/B	172.16	1314.7	40.0	130.9
8	Low-binder concrete LC3, C50	175.73	1058.1	49.7	161.7
9	Concrete with pozzolanic cement, CEM IV/B (V)	186.06	757.8	69.4	245.6
10	Blast furnace slag concrete, CEM III/B	193.98	939.1	56.0	206.6
Baseline	Concrete with Portland CEM I, C30	776.68	1753.0	30.0	460.8

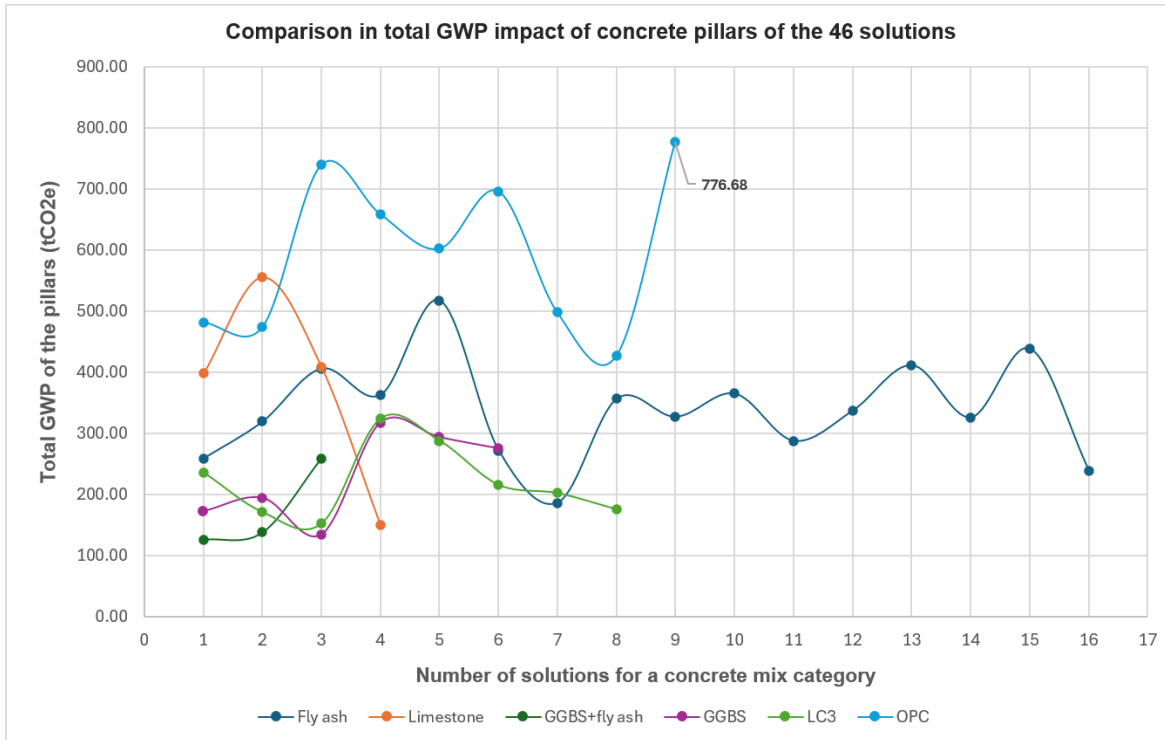


Figure 46: Comparison of total GWP impacts of concrete pillars of all the 46 solutions.

The final ranking of solutions is based on a single parameter that combines the effect of both the concrete mix and the compressive strength, which is the total, cumulative GWP impact of all the pillars, considering their entire volume in the building. If we were to look at the GWP expressed per cubic meter of a concrete mix, we will see that the order does not correspond with the ranking of the best solutions in terms of total GWP, which means that GWP per cubic meter of a mix only tells us about the sustainability of the concrete mix, but neglects the structural performance which is an important factor in terms of the building volume.

Although compressive strength is important, the results reveal that overall performance is fundamentally driven by binder chemistry and clinker substitution. As illustrated in the comprehensive mapping of all 46 solutions, concrete solutions with composite cements, specifically CEM V/B containing siliceous fly ash and blast furnace slag (GGBS), achieved the lowest carbon footprints, resulting in a GWP of 128.85 tCO₂e (or 121.8 kgCO₂e/m³) for a 50.9 MPa concrete mix. This represents a carbon reduction of nearly 74% compared to the baseline CEM I design that has the impact of 460.8 kgCO₂e/m³. Even the concretes with cements such as CEM III/B containing high percentage of GGBS and composite cements CEM VI that contain significant percentage of limestone powder, show the overall better performance than LC3 C70 concrete. The LC3 C70 concrete among the top 5 solutions shows the substantially reduced volume of columns. Regardless, although the total binder content of concrete mixes with composite cements V and VI is even higher compared to LC3 concrete, the total GWP is lower, which emphasizes the importance of clinker reduction and increase in SCM content of the binder mix.

However, we also observe an interesting pattern with solutions of LC3 concrete of different compressive strengths. In terms of the ratio of the components within the binder composition, the mixes are quite similar. However, the mix with the highest compressive strength (LC3 C70) shows the lowest total GWP in kgCO₂e, although its GWP expressed per cubic meter of the concrete mix is the highest, with 202.1 kgCO₂e/m³ compared to LC3 C50 concrete that shows 161.7 kgCO₂e/m³. Increasing the compressive strength requires an increase in the total binder content, although the ratio between the components of the binder might not change. This is exactly the reason why per cubic meter, the total GWP of the LC3 concrete is higher when its strength is higher, but the final parameter that captures the result of the volume reduction thanks to the higher compressive strength is the carbon footprint emitted for the entire building. Although C70 concrete might seem excessive for a building where the columns are designed to be of strength class C30/37, it is interesting to have the comparative analysis of a wider range of strengths. In case optimization is required for reasons such as cost efficiency, the solution between the two extremes values might be considered.

Finally, the scatter plot of all 46 solutions shows non-negligible differences between the total GWP impact of concrete solutions that belong to the same concrete category (e.g. concretes with limestone). These results demonstrate that simply classifying a mix under a category of concretes with fly ash or with limestone is indeed insufficient to predict its true environmental impact. This variance depends entirely on the precise SCM replacement percentage and the structural volume adjustments, among other factors such as water to binder ratio. The following table reports the detailed concrete mix recipes for the five best performing solutions, as well as the baseline concrete, to support the discussion made in this section.

Table 42: Concrete mix recipes of the five best performing concrete mixes.

Compositions of the 5 best performing concrete mixes							
Concrete mix	Unit	1. Composite CEM V/B (S-V)	2. Blast furnace slag CEM III/B	3. Composite cement, CEM VI (S-V-L)	4. Composite cement, CEM VI (S-L)	5. LC3, C70	Baseline concrete
Clinker - CEM I 52.5 R	kg	90	117	90	90	175	370
Clinker - CEM I 42.5 R	kg	-	-	-	-	-	-
GGBS	kg	60	274	60	60	-	-
Fly Ash (EN 450)	kg	250	-	125	-	-	-
Calcined clay	kg	-	-	-	-	105	-
Limestone (powder 1)	kg	-	-	145	289	53	-
Gypsum	kg	-	-	-	-	18	-
Water	kg	143	156	142	142	130	175
Superplasticizer	kg	2.4	3.9	3.3	4.5	3.8	0.0
River sand 0-2mm	kg	523	738	524	524	855	780
River gravel 4-8mm	kg	434	447	434	434	420	420
River gravel 8-16mm	kg	823	671	823	823	631	630
w/c (water-to-binder ratio)	-	0.36	0.40	0.34	0.32	0.37	0.48
Binder	kg	400	391	420	439	350	370
Aggregates	kg	1780	1856	1781	1781	1906	1830
Additives	kg	2.4	3.9	3.3	4.5	3.8	0.0
Water	kg	143	156	142	142	130	175
w/c (water-to-binder ratio)	-	0.36	0.40	0.34	0.32	0.37	0.48

Table 43: Results of the analysis of A1 GWP impacts for top 15 most sustainable concrete solutions vs. the baseline case.

Ranking	Concrete mix	Total GWP of the pillars (t CO ₂ e)	Total concrete pillars volume (m ³)	28d compressive strength (N/mm ²)	ECO _c efficiency of the mix (t CO ₂ e/MPa)
1	Concrete with composite cement, CEM V/B (S-V)	125.85	1033.2	50.9	2.5
2	Blast furnace slag concrete, CEM III/B	133.89	973.9	54.0	2.5
3	Concrete with composite cement, CEM VI (S-V-L)	137.71	1158.3	45.4	3.0
4	Concrete with composite cement, CEM VI (S-L)	150.09	1288.9	40.8	3.7
5	Low-binder concrete LC3, C70	152.69	755.6	69.6	2.2
6	Low-binder concrete LC3, C60	171.10	885.3	59.4	2.9
7	Blast furnace slag concrete, CEM III/B	172.16	1314.7	40.0	4.3
8	Low-binder concrete LC3, C50	175.73	1058.1	49.7	3.5
9	Concrete with pozzolanic cement, CEM IV/B (V)	186.06	757.8	69.4	2.7
10	Blast furnace slag concrete, CEM III/B	193.98	939.1	56.0	3.5
Baseline	Concrete with Portland CEM I, C30	776.68	1753.0	30.0	24.9

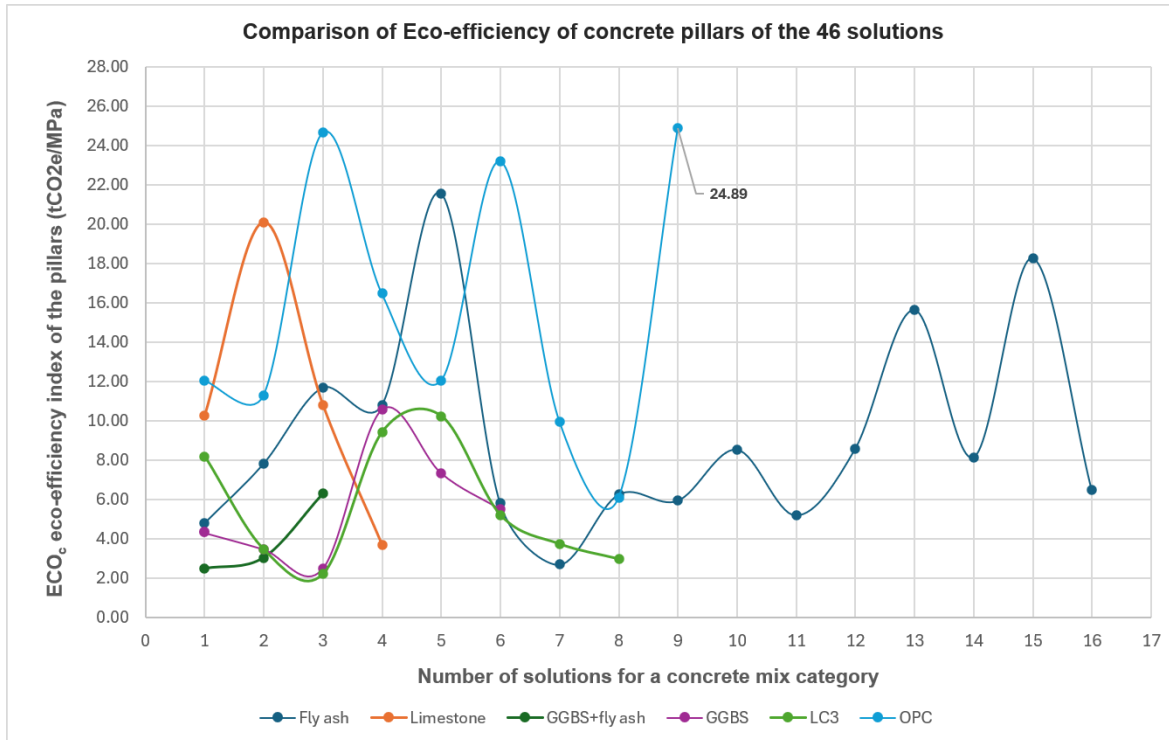


Figure 47: Comparison of Eco-efficiency index of concrete pillars of all the 46 solutions.

Analyzing the eco-efficiency scatter plot of the 46 solutions, it is visible that the same trend applies as with the case of comparing the total GWP impact of the mixes, meaning that putting two concrete solutions together into the same category because they contain the same SCM does not mean their eco-performance is going to be nearly the same. Here the purpose was to show the importance of compressive strength that leads to decreasing the total impact, as the index ECO_c is measured in tons of CO_2 equivalent expressed per unit of strength (or tCO_2e/MPa). However, the solution that shows the overall lowest impact (CEM V/B (S-V)) in fact has a slightly higher ECO_c index than the fifth solution which is LC3 C70, because also its compressive strength is almost 20 MPa lower. We see the same trend among the LC3 solutions, that the lower the strength is, the higher the eco-efficiency index becomes.

The lowest index tells us that indeed for the compressive strength available, that concrete solution yields the lowest impact. While it is a useful measure of concrete sustainability, still the best solution is measured by the total impact of the concrete pillars. The results therefore highlight that the most sustainable mix is the product of an optimized compromise which lays between a low-clinker binder combined with a lower water-to-binder ratio to achieve a higher mechanical performance.

5.1.1.3. Geographic and market context

Having a better understanding of major drivers and SCMs that yield more sustainable concretes, it is also important to understand the geographic context of the availability of these SCMs and the presence of certain solutions in the Italian market. While mixes containing siliceous fly ash show the best results in the environmental rankings in this study, it is important to have a realistic look at the applicability of these laboratory configurations into the Italian construction market. Siliceous fly ash (V) is an artificial pozzolan produced as a byproduct from the flue gases of coal-fired power stations. As stated in the report from 2020 of the Mineral Products Association [40], the reduction of coal-fired electricity production due to European decarbonization policies represents a significant constraint on the supply side. The domestic availability of industrial fly ash is therefore becoming increasingly scarce and consequently, relying on binders with high volume fly ash for large-scale logistics would become unfeasible. This represents a conflict between short-term GWP mitigation with fly ash and long-term accessibility.

However, there are alternatives to maintain the low GWP impact of the best performing solutions. Instead of using the industrial fly ash, the industrial focus can shift toward naturally occurring alternatives local to the Italian peninsula, such as natural pozzolana (or volcanic ash – P) or limestone. According to Calderoni et al. (2024) [68], the use of natural pozzolans and calcined limestones besides having a great potential in reducing the CO₂ footprint of cement production also yields similar mechanical performance to Portland cement CEM I, and their work explores integration of natural pozzolans within CEM IV and CEM V. The availability of volcanic ash is a significant advantage since thousands of tons of ash erupt from each Strombolian event from the Etna volcano [68]. The authors argue that removing huge amounts of this material from urbanised areas after eruption events is a valuable resource that can be utilized in cement mixes instead of disposing of it as waste.

Another set of SCMs that have a great regional potential are limestone and calcined clay. National mineral data from ISTAT reported in the figure below, highlights that Italy has a strong and established extraction industry of these raw materials. As the data reports, the country extracts 68.8 million tons of limestone-based minerals and 4.4 million tons of industrial ceramic minerals annually. Both of these minerals are used in the Limestone Calcined Clay Concrete (LC3) technology. The low-grade clays such as kaolinitic clays used in LC3 concrete can be utilized in its production rather than treated as quarry waste of ceramic minerals. Although such concrete does not represent a traditional concrete production process in Italy, the natural availability of these minerals presents a potential for securing long-term SCM availability for producing eco-sustainable concretes.



FIGURA 2. ESTRAZIONI DI RISORSE MINERALI DA CAVE E MINIERE ^(a) PER AGGREGATO A LIVELLO NAZIONALE. Anno 2018, valori assoluti in milioni di tonnellate, variazioni percentuali rispetto al 2017 (scala destra)

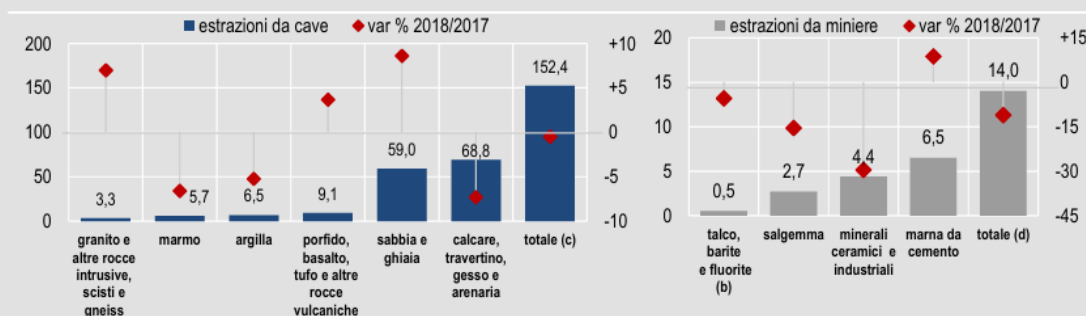


Figure 48: Extractions of mineral resources from quarries and mines by aggregate at national level, Italy. Source: ISTAT, Italy, 2020.

To understand the availability of cements that are currently actively produced in Italy, a comparative analysis was carried out between eight different cement producers in Italy. Collection of the EPDs was performed through the EPD Italy and the International EPD database. For each of the eight producers, cements that are produced were identified and their EPDs collected. The study reveals that on the Italian market currently the following cement types are available: CEM I, CEM II, CEM III and CEM IV. For other cement types that are available and produced such as composite CEM V, there were no available EPDs hence it was excluded from the analysis.

The results of the data collection reveal that among cement categories there can be significant differences of the carbon footprints. Analyzing their EPDs, it can be understood that differences could come from various factors, such as percentage of SCMs used, pre-consumer recycled content, but also importantly, thermal energy for production of clinker or Thermal Substitution Rate (TSR)⁵. This is why we observe mixes such as CEM I which show even lower impact than some CEM II or CEM IV solutions, which unlike CEM I contain a certain percentage of supplementary cementitious materials.

⁵ Thermal Substitution Rate (TSR) in cement production is the percentage of total kiln thermal energy that is derived from alternative fuels rather than traditional fossil fuels. Higher percentage of TSR during cement production implies lower environmental footprint of the clinker production.

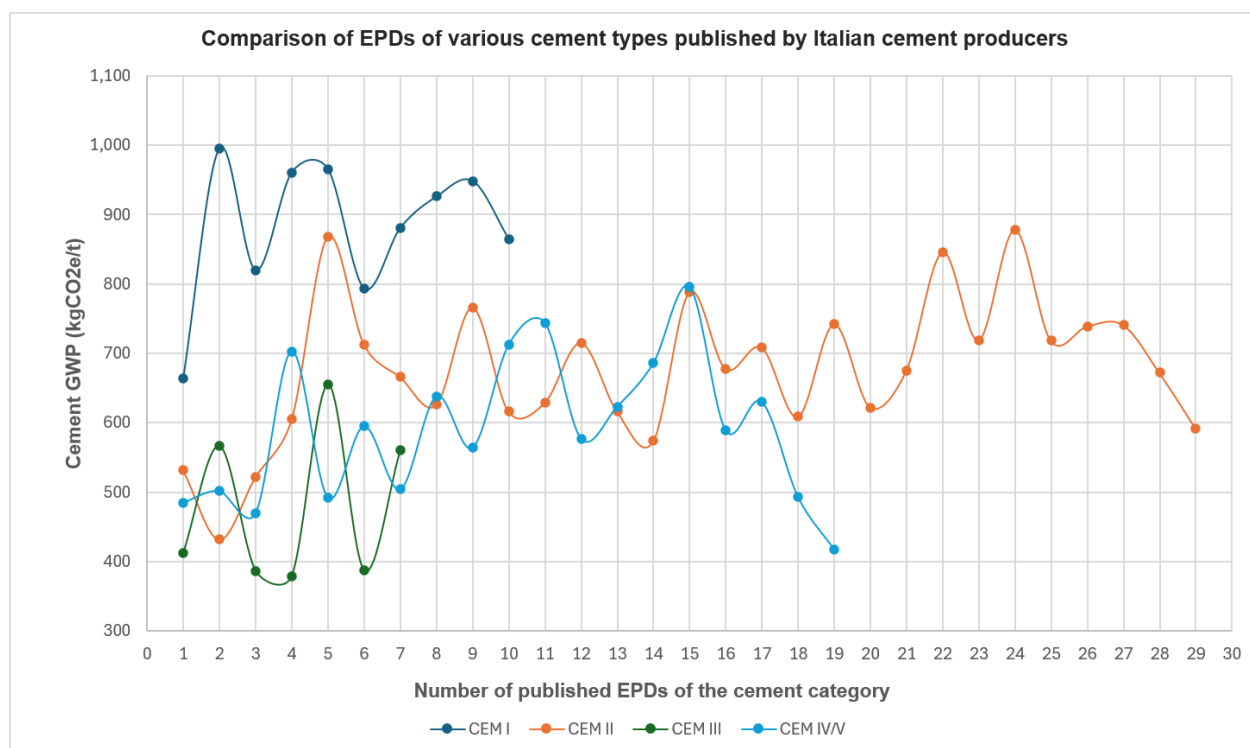


Figure 49: Comparative analysis of EPDs of various cement types published by eight Italian cement producers.

Producer 1 consistently shows the lowest GWP values of their cement mixes among the cement categories: CEM I, CEM II and CEM IV and CEM V. For CEM III however, no available EPDs were found from this producer. The major driver of the consistently best results is the TSR used in the kiln during clinker production, which is significantly higher compared to other producers (that being 80.8% compared to 43.7% as the second highest TSR of another producer). Interestingly enough, CEM III/B mix containing 70% of ground granulated blast furnace slag shows overall the lowest reported GWP expressed per ton of cement sample, coming from Producer 4. Other competitive cements are mixes of CEM V/A, CEM IV/A (V) and CEM II/B-LL, becoming more frequently used in Italian building construction in concrete.

Table 44: Top 3 least impacting cements of each cement category evaluated, expressed per 1 ton of sample, A1-A3 stage.

Producer	GWP (kgCO ₂ e / t), A1-A3	GWP improvement % compared to the worst performing product of the cement type
CEM I		
Producer 1 - CEM I	664	33.3
Producer 5 - CEM I	794	20.2
Producer 3 - CEM I	820	17.6
CEM II		
Producer 1 - CEM II/B-LL	432	56.6
Producer 1 - CEM II/B-LL	522	47.5
Producer 4 - CEM II/C-M (S-LL)	574	42.4

CEM III		
Producer 4 - CEM III/B	386	61.2
Producer 7 - CEM III/B	387	61.1
Producer 3 - CEM III/B	412	58.6
CEM IV/V		
Producer 1 - CEM V/A(Q-S)	417	58.1
Producer 1 - CEM IV/A(V)	469	52.8
Producer 1 - CEM IV/A (V)	485	51.3

Connecting the results of the data analysis of the local market and the results obtained from laboratory tests of eco-sustainable concrete types, it can be concluded that pozzolanic cements such as CEM V have great potential of improvement, since they are already actively produced and backed by localized EPDs by major Italian suppliers. Furthermore, literature supports this shift, as recent research of Calderoni et al. [68] confirms that regional waste materials such as Etna volcanic ash can serve as highly effective SCMs. Utilizing the currently established CEM V mix while transitioning to local volcanic pozzolana could ensure significant carbon reductions that are aligned with the comparative analysis carried out, while at the same time remaining aligned with the geographic realities of Italian supply chains.

5.1.1.4. Precast pillars embodied carbon optimization

Having justified for the production stage of the LCA the most sustainable concrete mix assessed within the scope of this analysis (that being concrete mix with CEM V/B (S-V)), now it is necessary to move from the impacts of separate ingredients and complete the analysis by evaluating the total impact of the pillars through Cradle-to-Grave. After the A1 stage comes the stage of the transportation of these materials to the manufacturing plant of concrete, followed by mixing the ingredients to obtain a precast pillar. Finally, the End-of-life stages C1-C4 are modelled to complete the analysis. Therefore, these paragraphs present the final Steps 3 and 4, reported in Figure 45 in the chapter 5.1.1.2.

With regards to concrete, to model A2 and A3 stages of its production, a reference is made to typical Italian concrete EPDs compliant with EN 15804:2012+A2:2019, such as EPDs released by the major Italian concrete supplier representative of the industry standard⁶. The transport of the materials (A2) assuming the geographical limit to be within borders of Italy⁷ contributes to approximately 6% of the total A1-A3 GWP impacts, while the manufacturing stage (A3) consisting of batching plant energy demands contributes less than 1% of the total cradle-to-gate (A1–A3)

⁶ Colabeton S.p.A. is a major Italian concrete supplier, its EPD referenced here as a representative market baseline since they frequently supply concrete for large-scale logistics and warehouse developments across Italy. Reference is made to the registration number of one of the company's EPDs within the International EPD database. The serial number of the reference EPD is *S-P-09881*.

⁷ Transport of the raw materials to the production plant modelled at the distance less than 160km.

GWP, which means that raw material chemistry (A1) is indeed the primary environmental driver, as in the A3 stage there is no heavy material chemical processing such as the pyroprocessing stage of clinker production in A1 stage.⁸

With regards to steel, EPD of a prominent Italian supplier was used, showing a very high percentage of recycled steel content with an energy-efficient production path, that is further detailed and justified in the following chapters.

After the precast pillar is produced, it is durable through the entire building's service life, considered as 50 years. At the end of the building's service life, the physical handling of a concrete pillar is independent of the concrete mix's internal molecular design. According to a published EPD⁹ compliant with EN 15804:2012+A2:2019 of a local supplier of precast reinforced concrete pillars, the end-of-life stage is handled in the following way:

- C1: The handling of mechanical energy required for building deconstruction and demolition. The model accounts for the use of diesel-powered machinery;
- C2: The transport of heavy concrete rubble to a processing facility, average transport distance of 20km;
- C3: The electricity and machinery required for crushing and sorting of steel and secondary aggregates with the purpose of recovery of construction and demolition waste;
- C4: The final disposal of residues in a landfill.

To be methodologically consistent, impacts of the C1-C4 stages are referenced based on the available EPD, keeping the same consistent impacts for all the solutions. The baseline impact is reported in Table 43, composed of Portland CEM I concrete and rebars with recycled content of 75%. Total volume of the pillars in the building is 1,711.5 m³. Having calculated and ranked the impacts of A1 stage for various concrete mixes and having considered the impacts of reference industry standards for other stages until the pillar's end-of-life, the following table is a summary of the comparison of the five best performing solutions, compared to the baseline:

⁸ It must be noted that the precise GWP allocation percentages for Module A2 (transportation) and Module A3 (plant operations) vary in reality between individual batching facilities depending on specific quarry distances and plant efficiencies. Therefore, the values presented here should be interpreted as representative industrial average rather than absolute. For the scope of this comparative analysis, these percentages were kept uniform across all concrete mix variations as a controlled variable to ensure strict methodological consistency.

⁹ MANINI Prefabbricati S.p.A. is an Italian company in the industrial precast concrete sector, specializing in the engineering and production of advanced structural systems for logistics, commercial, and industrial buildings. Reference is made to the registration number of one the company's EPDs within the International EPD database. The serial number of the reference EPD is *EPDITALY0647*.

Table 45: Comparison of Cradle-to-Grave LCA results of precast pillars with five most sustainable concrete solutions and improvement from the baseline.

	Precast reinforced concrete pillars	GWP (kgCO ₂ e), A1-A3	GWP (kgCO ₂ e/m ³), A1-A3	GWP (kgCO ₂ e), A4-A5	GWP (kgCO ₂ e), C1-C4	Total GWP (kgCO ₂ e)	Total GWP (kgCO ₂ e/m ³)
Solution 01	Concrete with composite cement, CEM V/B (S-V)	177,200.0					
	Steel rebars, 99% recycled	21,088.9	115.9	15,960	62,773.5	277,022.5	161.9
	Precast pillar	198,289.0					
Solution 02	Blast furnace slag concrete, CEM III/B	185,245.4					
	Steel rebars, 99% recycled	21,088.9	120.6	15,960	62,773.5	285,067.9	166.6
	Precast pillar, option 02	206,334.4					
Solution 03	Concrete with composite cement, CEM VI (S-V-L)	189,060.1					
	Steel rebars, 99% recycled	21,088.9	122.8	15,960	62,773.5	288,882.6	168.8
	Precast pillar	210,149.1					
Solution 04	Concrete with composite cement, CEM VI (S-L)	201,444.1					
	Steel rebars, 99% recycled	21,088.9	130.0	15,960	62,773.5	301,266.5	176.0
	Precast pillar	222,533.0					
Solution 05	Low-binder concrete LC3, C70	204,038.6					
	Steel rebars, 99% recycled	21,088.9	131.5	15,960	62,773.5	303,861.1	177.5
	Precast pillar	225,127.6					
Baseline	OPC CEM I, C30	828,026.2					
	Steel rebars, 75% recycled	46,145.4	510.8	15,960	62,773.5	952,905.1	556.8
	OPC CEM I precast pillar	874,171.6					

In combination with concrete composed of composite cement CEM V/B (S-V) containing blast furnace slag and fly ash, and highly-recycled steel reinforcement rebars, it is possible to achieve the improvement of 71.3% in the embodied impact of the precast reinforced concrete pillars through the Cradle-to-Grave life cycle, reaching around 277 tCO₂e or 161.9 kgCO₂e/m³ compared to the baseline that reports 952 tCO₂e or 556.8 kgCO₂e/m³.

5.1.2. Steel reinforcement embodied carbon optimization

The life cycle assessment of steel reinforcement is performed as a comparative analysis between available EPDs of Italian suppliers of steel reinforcement in accordance with the EN 15804+A2 and ISO 14025 standard. Data collection and analysis is made based on available environmental

product declarations of six local producers. The objective is to find an alternative, more sustainable solution for all the reinforcing steel rebars of the building used during the on-site casting of reinforced concrete.

Considering the particular nature of steel with its high recyclability and its scrap handling, the picture is wider than comparing GWP values solely based on the recycled content. It is necessary to understand various other factors such as allocation of steel scrap and electricity mix used for production. In order to give a more complete picture before presenting the data collected, the following chapters will be briefly discussed: steel production routes, electricity modeling in LCA, scrap logistics and types, and standard recycling approaches.

5.1.2.1. Introduction to steel production

To understand the significance and possibilities of reduction of the carbon emissions during the A1-A3 product stage for steel-making, it is important to understand the routes of steel-making, key raw materials and their amounts. It is estimated based on 2021 studies of Worldsteel Association that "the global steel industry used about 2.3 billion tonnes of iron ore, 1.1 billion tonnes of metallurgical coal and 680 million tonnes (Mt) of recycled steel to produce 1.95 billion tonnes of crude steel" [69]. Therefore, it is crucial to use more environmentally sustainable routes and exploit the possibility of using recycled content to reduce the raw material extraction. Two main routes for steel production are:

- Basic oxygen furnace (BOF) route – accounts for around 70% of global steel production;
- Electric arc furnace (EAF) route – accounts for around 30% of global steel production,
 - DRI-EAF route – route using scrap and Direct Reduced Iron (DRI), driven by electricity;
 - Scrap-based EAF route – almost entirely scrap-based.

The difference in the requirement of hot metal for the steel-making process between the BOF route and DRI-EAF route is huge, equal to 1.24 billion tonnes less in the DRI-EAF process, while DRI-EAF includes 210 million tonnes more of the scrap content. For the crude steel output, both of these routes are using the key raw materials: the iron ore, metallurgical coal to produce coke, limestone and recycled steel.

On the other hand, the scrap-based EAF route uses almost entirely the scrap content, with minimum additions of DRI, lime, dolomite and alloys. This is, in fact, the strongly dominant route for steel production in Italy [70]. The main inputs and their respective amounts to produce 1000 kg of crude steel are illustrated in the following figure, showing the average global values.



Figure 50: Three main routes of steel production and their related inputs, global average.

EAF route steel production therefore relies on:

- Electricity, and
- Recycled metals.

This route is substantially less energy intensive when compared with BOF steel production in terms of both resource use and CO₂ emissions, since the main energy-intensive process in BOF route is the blast furnace (BF) where the iron ore is reduced [71]. According to the Annual report of 2022 by the Steel Manufacturers Association (SMA) [72], 650 million tonnes of steel are recycled globally every year, which is possible due to its inherent 100% recyclability. The same source reports that EAF route contributes to 75% fewer CO₂ emissions compared to the traditional BOF steel-making route and requires 44.4% fewer working hours to produce steel compared to BOF.

When it comes to the EAF process itself, electrical currents are used in order to melt the scrap steel and additional input recycled material. The process is schematically illustrated in the figure below. Firstly, the collection of scrap steel and necessary amount of DRI virgin material is performed. Then melting of the scrap is done using high-power electric arcs. The melting process in the electric arc furnace is the most energy-intensive step. The next step is transferring the EAF steel in liquid form then followed by continuous casting, which consists of solidifying the liquid steel, where the form depends on the final product. In case of steel rebars, solid, rectangular steel pieces are formed from which ribber rebars are formed in the rolling mill. This is the conclusion of the production stage. Ultimately, a building reaches its end-of-life, where at this stage rebars and magnetically separated from the crushed concrete, corresponding to the demolition C1-C3 stage. Finally, the recovered rebars reaching their EoL are going to be the recycled scrap used in the life cycle of a future product. Consideration of the environmental burdens in relation to the life cycle of a product using recycled content is discussed in the following chapters.

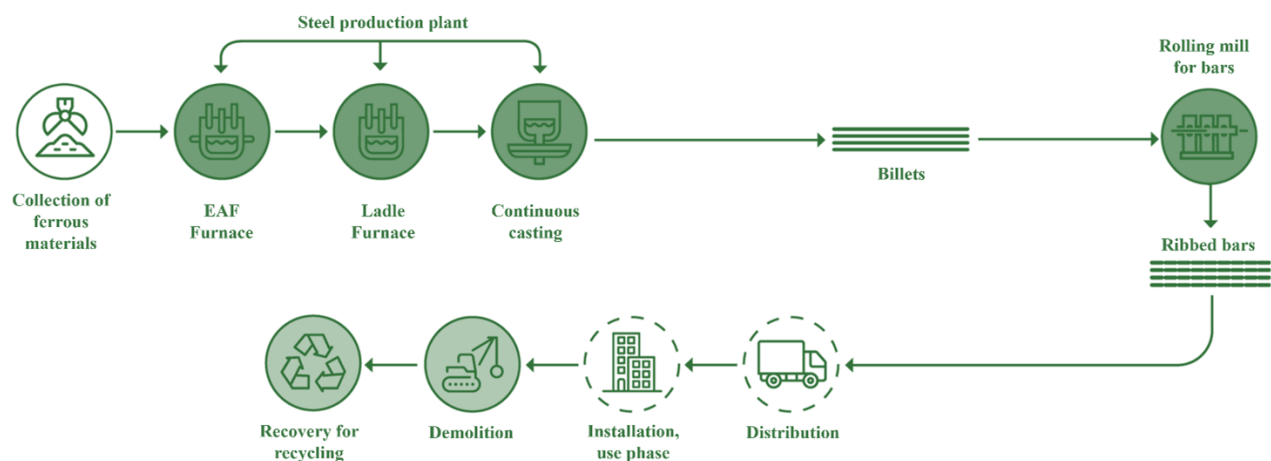


Figure 51: Schematic illustration of a rebar life cycle produced through the EAF route.

5.1.2.2. Electrical energy mixes used for steel production

Carbon emissions coming from the production of steel are highly dependent on the origin of electricity used in the process. Among the analyzed EPDs of Italian suppliers of steel reinforcement, two types of electricity mix used for steel production are distinguished:

1. The residual mix,
2. The residual mix combined with Guarantees of Origin (GOs),

The meanings are the following:

1. The Residual mix represents the remaining portion of the electricity mix after accounting for purchased green electricity, such as electricity that is backed by Guarantees of Origin (GOs). A GO is a certificate that demonstrates to the end-user that a particular share of

energy was in fact produced from renewable sources. Therefore, the residual mix is essentially what is left in the grid for the end-users that do not purchase certified green electrical energy. As a consequence, residual mix often contains a higher share of sources that are fossil-based which are carbon-intensive and increase the emissions.

2. On the other hand, the Residual mix when combined with GO becomes a market-based mix that reflects a producer's specific energy procurement strategy. Residual mix + GO is a result of the producer's contractual choice for electricity. The resulting mix therefore depends directly on the amount of purchased renewable electricity that has zero direct CO₂ emissions. In alignment with the Market-based approach of the GHG Protocol [73], this procurement decision achieves the reduction of environmental impact by promoting the share of renewables with the energy mix.

5.1.2.3. Scrap logistics and types

Understanding recycled material flow with regards to the life cycle of steel production and end of life is essential for interpreting the data of recycled content reported inside the EPDs of steel reinforcement products, as steel is a highly recyclable material. Recycled steel content, further referred as scrap content varies in terms of its origin. Scrap input to the steelmaking process is therefore divided into three different types of according to ISO 14021:2016:

- Internal scrap – this is the steel scrap from the BOF or EAF process of steel production up to the casting process, that is then put back into the EAF or BOF process. Internal scrap is immediately returned into the same process and it never leaves the steel production loop, therefore it is not evaluated as a new material input.
- Pre-consumer scrap – compared to the internal scrap that is produced up to casting, this scrap is generated after casting and before a steel product reaches the end-user. There are two types of pre-consumer scrap:
 - Home scrap – this is the scrap that after BOF or EAF casting that is put back into the steelmaking process. Scrap such as rolling mill cutoffs, trims from hot rolling or deficient billets that cracked during the process, are collected and reintroduced within the boundary of the steelmaking facility;
 - Fabrication or manufacturing scrap from outside the boundary of a steelmaking mill – this is the scrap generated and collected from facilities such as rebar cutting facilities or fabrication shops, but as well never reach the consumer.
- Post-consumer scrap – material that has been actively in use, produced by households or commercial, manufacturing and institutional facilities, but can no longer be used as they reached the end of life. Post-consumer scrap comes from building demolition, machinery, end-of-life vehicles, etc. The materials then go through the process of collection, sorting, shredding and cleaning, pre-treatment (such as removal of existing coatings) and finally the transport to a steelmaking plant.

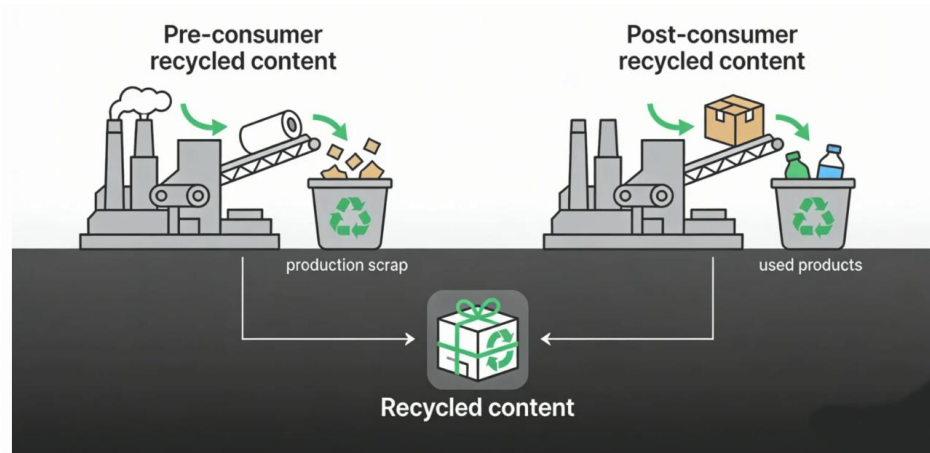


Figure 52: Pre-consumer vs. post-consumer recycled content, illustration.

5.1.2.4. Understanding of standard recycling approaches

Steel is a material with an inherent recyclability without the consequence of its downgrading in terms of quality due to the process of recycling. As the quality of the material does not degrade and the original purpose of the product (e.g. rebar) remains the same in the next life cycle, it is considered a closed loop recycling process. Discussions in relation to the best approach for consideration of recycling of steel in LCA are still on-going; however, two main approaches are highlighted, as reported in the Life cycle inventory methodology report for steel products published by the World Steel Association (2017) [74]:

- Cut-off approach (100-0) – this approach is also called „recycled content method“ because the benefits of recycling are only recognized for the input side hence their contribution is evident in the reduction in production emissions due to the reduction of the need for original virgin content. No burdens are considered for the recycled material in the production stage A1-A3 except for the scrap remelting as shown in the figure below, because melting of the content is an essential step in steelmaking that is performed regardless of the amount of the input recycled content. Besides the fact that remelting is accounted as a burden as it is a part of the process to produce a new product, it is also important to distinguish how pre- and post-consumer scrap are considered.

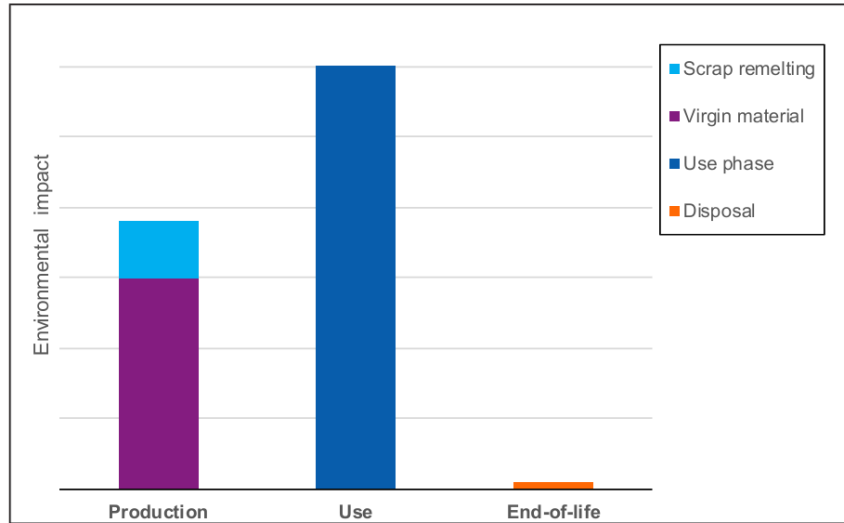


Figure 53: Qualitative bar chart explaining the cut-off approach for a product that uses both virgin content and recycled steel inputs.

For the cut-off approach, allocation of environmental burdens of pre- and post-consumer scrap are defined according to the EN 15804+A2 standard. When scrap material is produced during the manufacturing process, the EPD must allocate part of the manufacture emissions to this material. Since pre-consumer material is essentially a part of the upstream process, it must also carry upstream burdens.

On the other hand, post-consumer scrap enters the system with no upstream burdens. Therefore, the higher the content of post-consumer scrap that goes into the production of a steel element, the more positive is the contribution to the reduction of environmental impact of a new steel material.

- End-of-life approach (0-100) – on the other hand, this method differs significantly in terms of production stage and end-of-life stage compared to the cut-off approach. The emissions of the incoming recycled content are considered as a burden in the production stage of the new steel, but consequently, the system is credited with avoided impacts in the end-of-life. Therefore this approach particularly rewards the product in the D module. This avoided burden shown in the figure below is based on the reduction of necessity for the production of virgin material for the next life cycle. Following this approach, the recyclability of the material after its end of life is awarded. Benefits of the scrap essentially belong to the product that creates it, rather than belonging to the next life cycle of another product, that in the cut-off approach reaps the benefits of recycled content from a previous life cycle. Essentially, the cut-off approach rewards the new rebar for significantly reducing the impacts in the A1-A3 stage based on post-consumer content of the previous rebar that is now recycled, while the end-of-life approach rewards the rebar that reached its EoL by crediting its D module and rewarding its high recyclability. More precisely, in the D module,

the credit is given for the net scrap. At the end-of-life, the net scrap is evaluated in the following way:

$$\text{Net scrap} = \text{Amount of steel recycled at the EoL} - \text{Scrap input}$$

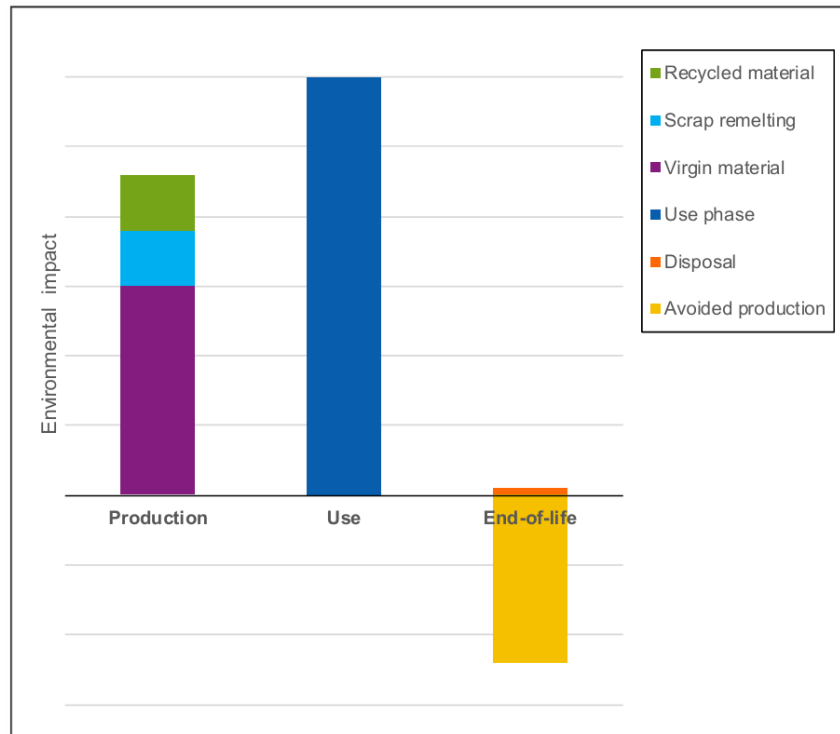


Figure 54: Qualitative bar chart explaining the end-of-life approach for a product that uses both virgin content and recycled steel inputs.

5.1.2.5. LCA of steel reinforcement

The following table presents a summary of how the presented concepts are applied to the analyzed EPDs of local producers, as well as their GWP impact expressed per ton of steel reinforcement, related to the A1-A3 production stage:

Table 46: Environmental impact per ton of steel reinforcement for A1-A3 stage from EPDs of six Italian producers.

Producer 1	GWP (kgCO₂e/t), A1-A3	353
	El. factor (kgCO ₂ e/kWh)	0.118
	El. source description	Supplier-specific mix with GO
	Pre-consumer content (%)	14.7%
	Post-consumer content (%)	84.6%
	Total recycled content (%)	98.9%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach
Producer 2	GWP (kgCO₂e/t), A1-A3	506
	El. factor (kgCO ₂ e/kWh)	0.457
	El. source description	Residual mix + GO
	Pre-consumer content (%)	14.7%
	Post-consumer content (%)	84.1%
	Total recycled content (%)	98.8%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach
Producer 3	GWP (kgCO₂e/t), A1-A3	660
	El. factor (kgCO ₂ e/kWh)	0.457
	El. source description	Residual mix + GO
	Pre-consumer content (%)	35.6%
	Post-consumer content (%)	63.4%
	Total recycled content (%)	99.0%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach
Producer 4	GWP (kgCO₂e/t), A1-A3	775
	El. factor (kgCO ₂ e/kWh)	0.656
	El. source description	Residual mix
	Pre-consumer content (%)	0%
	Post-consumer content (%)	76.4%
	Total recycled content (%)	76.4%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach

Producer 5	GWP (kgCO₂e/t), A1-A3	776
	El. factor (kgCO ₂ e/kWh)	0.656
	El. source description	Residual mix
	Pre-consumer content (%)	0
	Post-consumer content (%)	87.5%
	Total recycled content (%)	87.5%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach
Producer 6	GWP (kgCO₂e/t), A1-A3	677
	El. factor (kgCO ₂ e/kWh)	0.522
	El. source description	Residual mix + GO
	Pre-consumer content (%)	12.2%
	Post-consumer content (%)	83.5%
	Total recycled content (%)	95.7%
	Steel-making route	Electric Arc Furnace (EAF)
	Allocation method for scrap	Cut-off approach

According to the available EPDs of the local steel reinforcement producers, the cut-off approach is, in fact, a default method for performing a life cycle assessment in accordance to the EN 15804+A2 standard, therefore this is the approach followed in the analyzed EPDs. All of the pre- and post-consumer recycled content that these EPD report apply the rules of cut-off method for distribution of environmental burdens within the general life cycle scheme. Furthermore, all of the producers follow the Electric Arc Furnace (EAF) route, utilizing recycled ferrous materials (scrap) to produce steel billets, followed by hot rolling. Besides Producers 4 and 5, all the rest of the producers use the percentage of recycled content higher than 95%, while Producer 4 uses 76.4% which is the lowest percentage of recycled content reported among the EPDs.

In terms of the emission factor for electricity, the process of EAF is particularly electricity-sensitive hence the emission factor significantly influences the GWP results. Producer 1 shows the lowest total GWP of the A1-A3 production stage, which can be attributed to its very low emission factor, attributed to the use of a supplier-specific mix that is backed by 100% GOs. This supplier has a specific contract ensuring all their power is matched with renewable certificates, which allows them to bypass the residual mix entirely for their operational footprint calculation.

Finally, comparative analysis was performed between the six suppliers and the baseline. To establish a representative benchmark the "Rebar, generic, 70% recycled (One Click LCA)" reinforcing rebar was chosen from the OneClickLCA database. This generic dataset provides a transparent, independent threshold against which the supplier-specific EPDs are compared. Producer 1 shows the highest percentage of improvement compared to the baseline. Therefore, it will be considered as the optimized solution of the reinforcing steel rebars used in the building. The summary table of the Cradle-to-Grave impacts are reported in the following table:

Table 47: Cradle-to-Grave GWP impacts comparative analysis of 6 Italian steel rebars suppliers vs. the baseline.

Steel producer/supplier	GWP (kgCO ₂ e), A1-A3	GWP (kgCO ₂ e), C1-C4	GWP (kgCO ₂ e), Cradle-to-Grave	GWP reduction % compared to Baseline	Recycled, Recovered, By-product - total %
Producer 1	164,448.0	33,998.3	198,446.3	67.2%	98.9
Producer 2	235,724.3	46,331.9	282,056.2	53.4%	98.8
Producer 3	275,788.1	33,998.3	309,786.4	48.9%	99.0
Producer 4	361,040.2	13,547.2	374,587.3	38.2%	76.4
Producer 5	361,506.0	13,570.5	375,076.5	38.1%	87.5
Producer 6	315,386.0	15,976.6	331,362.7	45.3%	95.7
Baseline	586,981.4	18,900.1	605,881.4	-	70

5.2. Building envelope embodied carbon optimization

5.2.1. Construction and sustainability of the envelope system

The building envelope is separated into two distinct parts: warehouse envelope and office blocks envelope. This analysis deals exclusively with warehouse envelope area, as there will be no variations proposed for the office blocks area to maintain the baseline operational energy needs. The total surface area of the warehouse covered with the vertical envelope in the precast concrete panels is 13,874.00 m². Excluding the openings and loading bays, the area equals to 12,050.32 m². This area is significant and the baseline life-cycle model shows that the envelope covered in precast concrete panels is in top 5 highest contributors to GWP through the life cycle among all the materials of the building, with 4.33% of contribution. Therefore, consideration is given to alternative solutions and variations of the vertical envelope to understand if and in which way it is possible to reduce the GWP coming from the building facade.

According to the traditional construction practice for warehouse buildings in Italy, there two most prominent envelope systems:

- Precast concrete panels with thermal break, covering the vertical envelope completely
- Metal sandwich panels with polyisocyanurate (PIR) foam.

The following paragraphs will describe both the construction and End-of-Life treatment of these two envelope systems.

Both solutions are modular and prefabricated out of site, transported and then assembled on site. This well-established construction technology is not an arbitrary choice for constructing envelopes of industrial buildings in Italy, as the big surface area to be covered requires optimization of time, cost and socio-environmental impact. In fact, as a modular construction it aligns with principles of circular design strategies.



Figure 55: Material flow according to the circular design principle.

After mining and extracting the raw materials, the panels are then produced in factory under controlled conditions, to be then transported directly to the site. The dry assembly and mechanical connections of the modular panels carried by cranes and cladded to the building structure is a design-for-disassembly (DfD) strategy. According to Joensuu et al. (2022) [75] DfD is a method to break the linear chain of „take-use-dispose“ building materials and enables their greater reuse and recycling at the building's end of life. Roberts et al. (2023) [76] argues that beyond the process of assembly-disassembly on site, modularity and prefabrication as well are all important and interconnected parts of the DfD strategy.

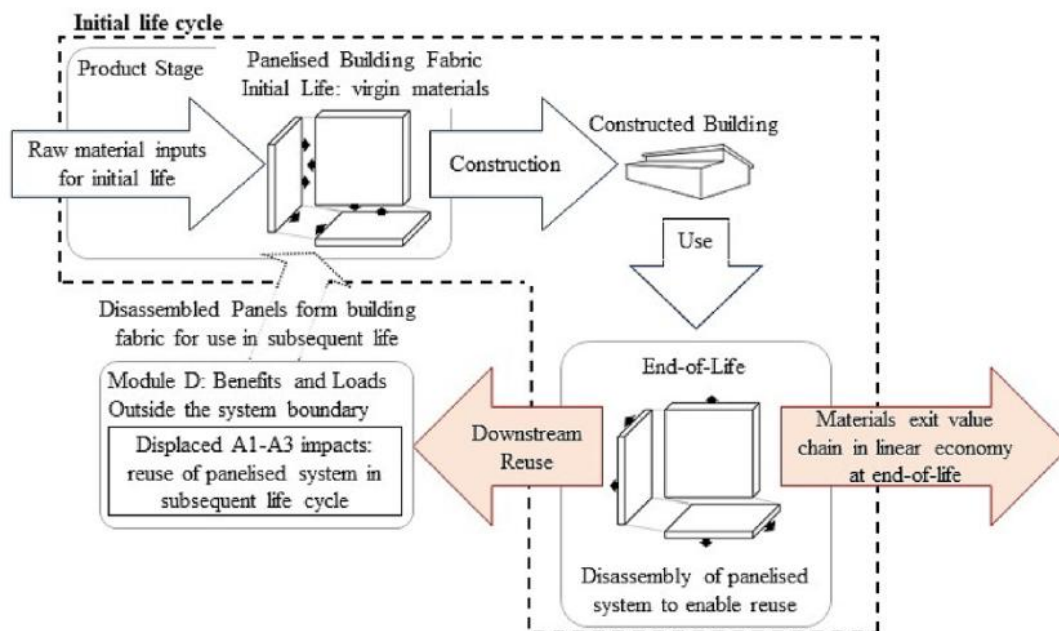


Figure 56: Life cycle for panelised system designed for downstream reuse.

Prefabricated concrete and metal panels are by definition modular, as modular construction is „a building method where individual components, or modules, are prefabricated in a factory-controlled environment and then transported to the construction site. These modules are typically designed to fit together seamlessly to form a complete structure.“ [77] The following table is a summary of advantages and disadvantages of modular building envelope from both economic and socio-environmental point of view, as reported by Shooshtarian et al. (2025) [78].

Table 48: Advantages and disadvantages of prefabrication in building construction from economic and socio-environmental point of view.

	Advantages	Description	Disadvantages	Description
Economic point of view	Faster construction	Simultaneous off-site fabrication and on-site foundation work	Transportation	Shipping large modules to the site can be expensive
	Cost-effective (affordable)	Modules produced in a controlled environment, reducing labor and material costs	Limited customization	Design has limitations in terms of architectural creativity and flexibility
	Improved construction quality	Factory-controlled construction ensures higher quality control	Dependency on factory production	Delays in the factory can lead to project delays
Socio-environmental point of view	Less disturbance to the site's residents	Minimizing on-site noise and dust pollution and project completion time	Size limitations	Restrictions on the max. dimensions of a prefabricated structure for transportation
	Reduced material waste	Precise manufacturing processes minimize waste that would otherwise end up in a landfill	Potential for damage	Modules can be susceptible to damage during transportation and installation
	Safer working conditions	On-site workers exposed to fewer hazards as much of the construction is done off-site	Requires skilled labor	Specialized skills needed for module fabrication and on-site assembly

The following isometries and reference images illustrate the stratigraphy of layers that the two types of modular panels are composed of.

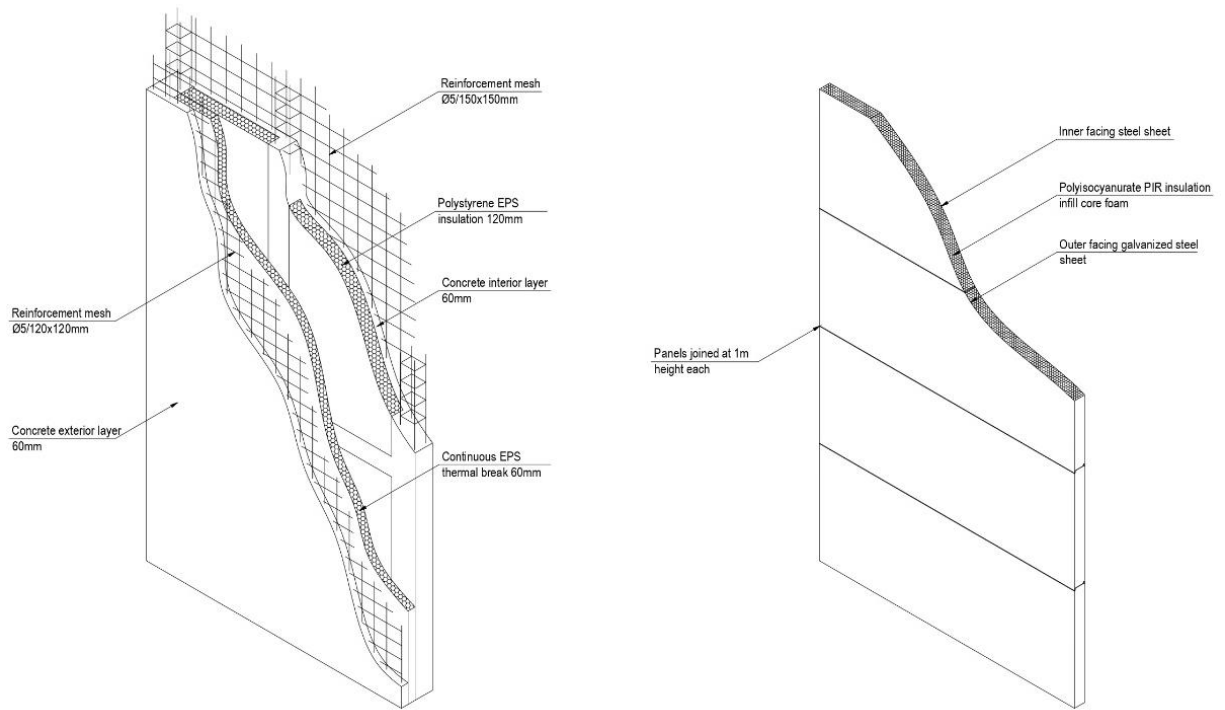


Figure 57: Isometries illustrating the layers of precast concrete and metal PIR panels.



Figure 58: Real project execution of precast concrete panels (left) and metal PIR panels (right).

Table 49: Stratigraphy of the precast concrete thermal break panel and the end-of-life treatment.

Precast concrete thermal break panel, 2.5m x 12.5m size of one module				
Layer no.	Stratigraphy	Amount per panel	Unit	End-of-Life treatment, as per EPD
1	Exterior concrete layer	1.8	m ³	5.63% recycled aggregates and 1.09% recovered for reuse
2	Steel reinforcement	72.6	kg	Steel recycling up to 99%
3	EPS Polystyrene insulation, 180mm	30.0	m ²	15% recycled, rest sent to landfill
4	Steel reinforcement	108.8	kg	Steel recycling up to 99%
5	Interior concrete layer	1.8	m ³	5.63% recycled aggregates and 1.09% recovered for reuse

Table 50: Stratigraphy of the metal PIR sandwich panel and the end-of-life treatment.

Metal PIR sandwich panel, 9m x 1m size of one module				
Layer no.	Stratigraphy	Amount per panel	Unit	End-of-Life treatment, as per EPD
1	Galvanized steel sheet, 0.7mm	9.0	m ²	Steel recycling, up to 90%
2	Polyisocyanurate PIR foam, 100mm	9.0	m ²	Disposal in a landfill
3	Steel sheet, 0.5mm	9.0	m ²	Steel recycling, up to 90%

The two types of panels can be combined in different ways to form an envelope. Since the clear interior height of the warehouse is 11 meters, accounting for additional 1m deep perimeter beam and 1m of parapet wall of the roof, the total height that the envelope must achieve is 13 meters. Two construction systems that will be evaluated for LCA in this project regarding precast concrete and metal panels are the following:

- Precast concrete panels: fully covering the entire height of the building envelope with vertical panels 2.5 meters wide and 13 meters high. These panels transfer the loads to the continuous, perimetral foundation strip.
- Metal PIR panels: covering only the top 8 meters of the envelope. The bottom 5 meters are covered with precast thermal break panels, on top of which a secondary steel frame is anchored consisting of vertical mullions spaced each 4.5 meters. The steel frame serves as structural support for metal panels. Therefore, the sandwich panels transfer the loads to the steel frame, which then transfers the loads to the precast concrete panels, supported by strip foundation.

Construction systems are illustrated in the following isometries:

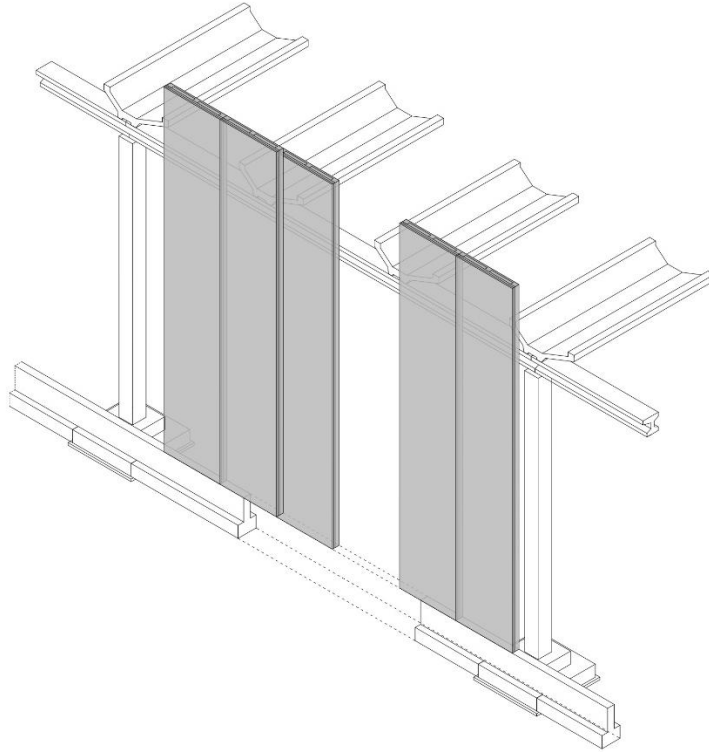


Figure 59: Precast concrete thermal break panels construction system isometry.

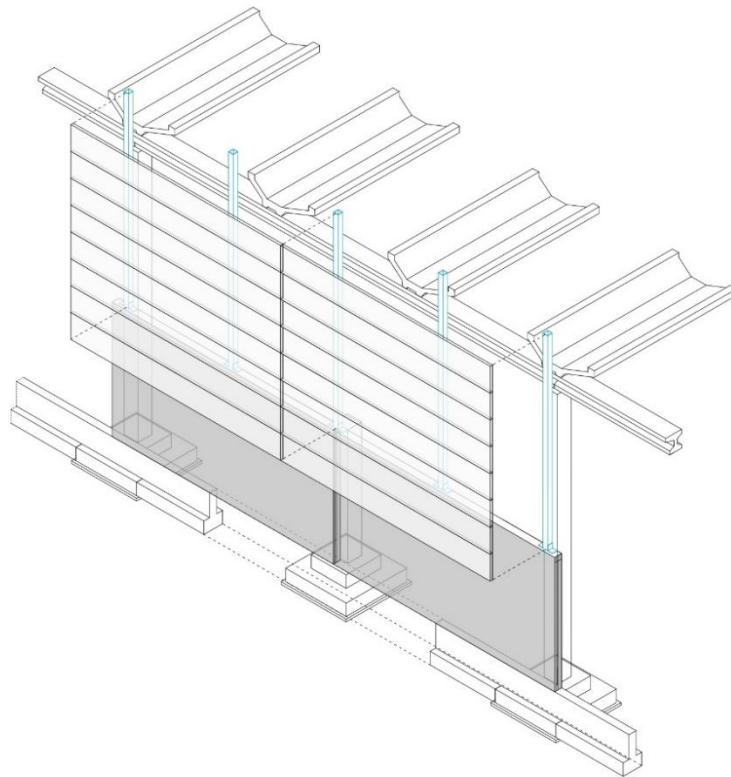


Figure 60: Metal PIR sandwich panels construction system isometry.

To conclude the introduction to these two envelope system, it is important to understand how they are treated at the end of life. As reported in the EPDs of Italian producers of precast concrete thermal break panels and metal sandwich panels, the EoL is treated in the following way:

- C1) Deconstruction and demolition for precast panels includes the "disassembly" of the product using diesel-powered mechanical means, meaning that the panels get demolished. For metal panels, energy consumption for removal is considered.
- C2) Transport: Transport to waste treatment and disposal: an average distance of 20 km from the treatment center is assumed.
- C3) Waste treatment of precast panels includes the recovery of construction and demolition waste essentially consisting of reinforcing steel, mineral aggregates, and polystyrene. The concrete fraction is processed Recycled Concrete Aggregates (RCA). In terms of metal panels, every process (collection, crushing process, etc.) suitable for the recycling of 90% of the sandwich panel's sheet metal is considered.
- C4) Final waste disposal of the scraps resulting from the recycling of previous processes for precast panels are sent to a landfill. The landfill disposal consists of steel scrap and inert waste. For metal panels the processes considered are for the landfill disposal of the remaining 10% of the steel and all the insulation material.

5.2.2. Thermal performance of the envelope systems

The surface area that is covered in these two envelope systems is non-negligible and carries and consists of a significant number of panels. All of these panels must be joined and sealed on site, which means that there is a substantial number of joints that change the heat flow along the length of the building envelope. This brings into question the impact of the thermal bridges that they might have on the comfort condition of the warehouse space. Although the warehouse is not a conditioned space, it was decided to do a verification of the thermal bridges related to various nodes and run the energy simulation with the corrected values of the envelope thermal transmittances (U-values). The decision to focus only on the comfort condition of the warehouse in relation to thermal bridges and not the heating and cooling loads change in the office blocks, is because the office blocks represent only 2.1% of the entire building volume. The nodes evaluated are the following:

Solution with fully concrete thermal break panels:

- Detail 1.0. – Precast panel full horizontal section
- Detail 1.1. – Precast panel wall-to-window horizontal section
- Detail 1.2. – Precast panel wall-to-internal floor vertical section
- Detail 1.3. – Precast panel wall-to-roof vertical section
- Detail 1.4. – Precast panel wall-to-ground vertical section
- Detail 1.5. – Precast panel wall-to-wall horizontal joint section

Solution with metal sandwich panels with precast concrete panel base:

- Detail 2.0. – Sandwich panel full horizontal section

- Detail 2.1. – Sandwich panel wall-to-window horizontal section
- Detail 2.2. – Sandwich panel wall-to-internal floor vertical section
- Detail 2.3. – Sandwich panel wall-to-roof vertical section
- Detail 2.4. – Precast panel wall-to-ground vertical section
- Detail 2.5. – Sandwich panel wall-to-wall horizontal wall section

Details 1.0 and 2.0 are evaluated to understand the thermal transmittance value of a single panel, that will be the base U-value without considering additional thermal bridges. Details 1.4. and 2.4. are identical, because in both cases the precast concrete thermal break panels are in contact with the ground, therefore the construction detail remains the same.

In order to evaluate the thermal transmittances and heat transfer through the identified sections, THERM software is utilized. THERM LBNL is a FEM-based computer program developed at Lawrence Berkeley National Laboratory (LBNL) to model the two-dimensional heat-transfer effects in building components. In order to run the calculation in THERM, it is important to define the boundary conditions of the chosen section according to the standard ISO 10077-2:2017 [60], as reported in the following table:

Table 51: Definition of boundary conditions according to ISO 10077-2:2018.

Boundary conditions	Surface resistance [m²K/W]	Surface heat transfer coefficient [W/m²K]	Temperature [°C]
Adiabatic	-	-	-
Exterior	0.04	25	20
Interior	0.13	7.7	20

Purpose of running the thermal simulations will be to find a linear thermal transmittance value for each detail (thermal bridge node) identified and assessed, apply it to the total length of the thermal bridge and correct the base thermal transmittance of the envelope. Having the corrected U-value, building energy simulation will be performed to obtain interior air temperature of the warehouse.

To assess the potential for condensation in the envelope system, THERM infrared temperature distribution display option is used to show thermal performance and obtain the interior surface temperatures of the curtain wall components. By comparing these surface temperatures to the dew point temperature derived from the psychrometric chart, we can evaluate whether condensation will occur. If the simulated surface temperature is lower than the dew point temperature, it indicates a high risk of condensation formation, necessitating design adjustments to mitigate moisture-related issues.

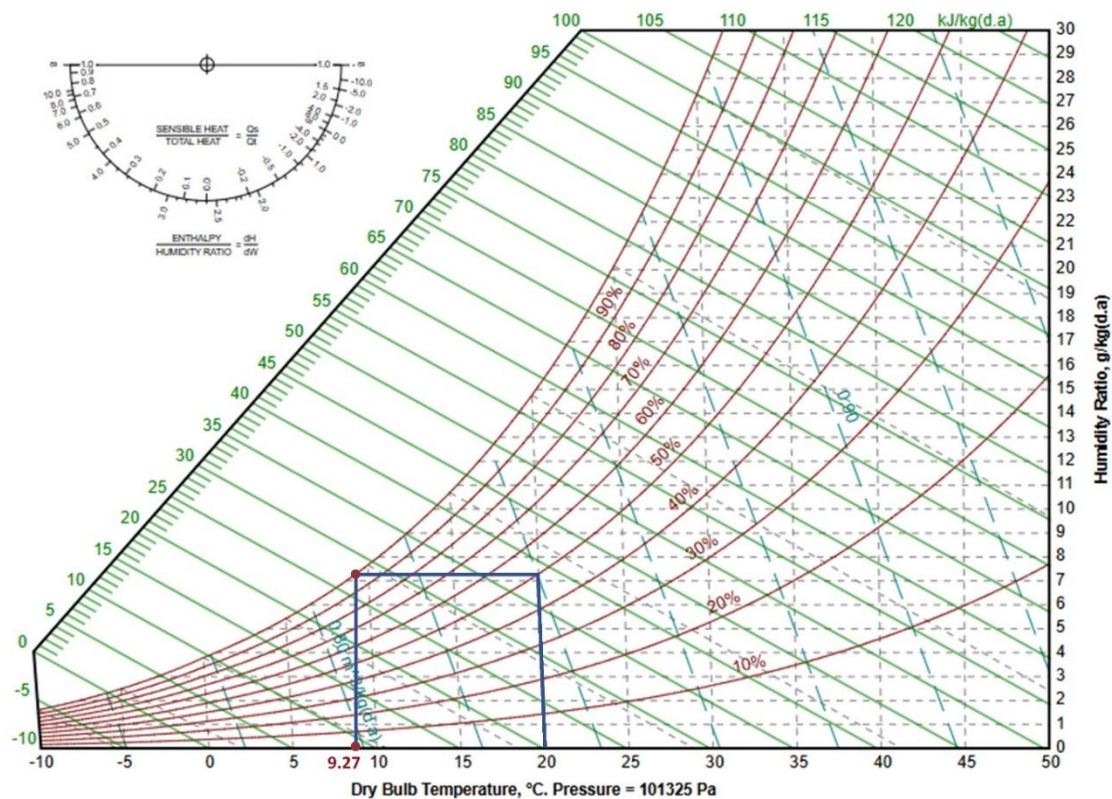


Figure 61: Psychrometric chart according to ASHRAE Standard 41.1.

The dew-point temperature has been identified according to the psychrometric chart. Taking the relative humidity of 50%, the indoor dry-bulb temperature of 20°C and outdoor -5°C, therefore the temperature difference of 25°C, the dew-point temperature in this condition is 9.27°C. This means that at no point of the interior surface the temperature shall not be lower than 9.27 °C, otherwise condensation will occur. Condensation verification has been assessed detail by detail.

5.2.2.1. Concrete thermal break panels thermal analysis

Thermal transmittance of a single precast thermal break panel results in 0.338 W/m²K and is found as the function of the total heat flow through the section, panel length and the temperature difference between the interior and the exterior surface:

Table 52: Thermal transmittance of a precast concrete thermal break panel.

Detail 1.0. – Panel's thermal transmittance			
Φ	Heat flow	21.12	W/m of depth
L_{PT}	Projection depth	1.00	m

L	Length	2.50	m
ΔT	Temperature difference	25.00	K
U_{eff}	Effective U-value	0.338	W/m²K

$$U_{eff} = \frac{\Phi}{L \cdot \Delta T} = 0.338 \frac{W}{m^2 K}$$

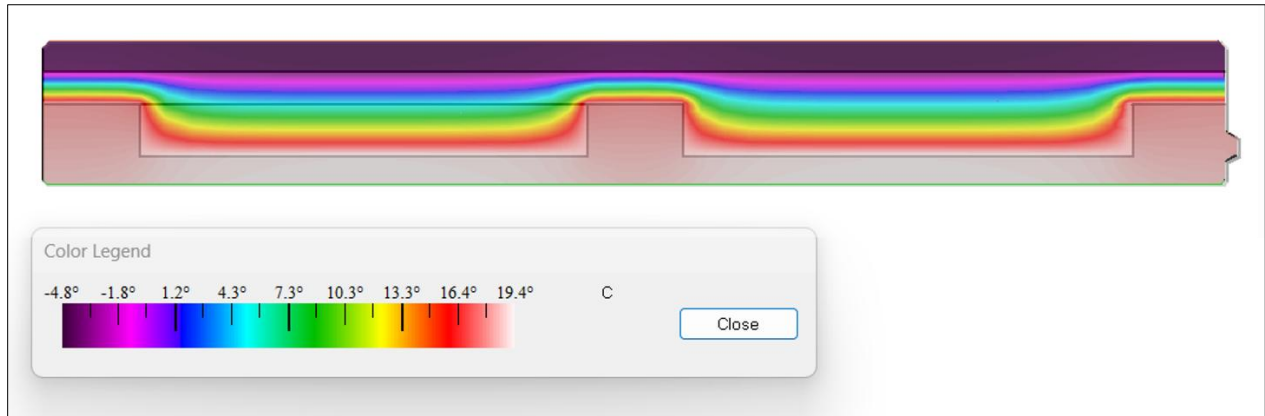


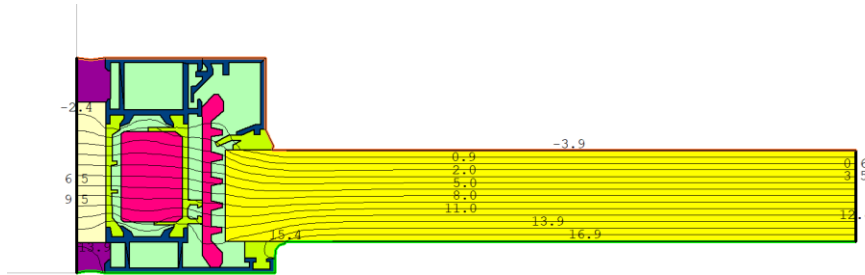
Figure 62: Detail 1.0.

The following detail is a junction between the concrete thermal break panel and the double-glazed window with a thermally broken aluminum frame. To properly obtain the linear thermal transmittance of the node, we must find the U-value of the frame itself, according to the standard EN ISO 10077-2:2017 [60]. Thermal transmittance of the frame is therefore the following:

$$U_f = \frac{L_f^{2D} - U_p b_p}{b_f}$$

Table 53: Thermal transmittance (U-value) of the window frame simulated in THERM.

Thermal transmittance of the window frame			
Φ	Heat flow	7.19	W/m of depth
ΔT	Temperature difference	25.00	K
L^{2D}	Linear thermal coupling coefficient	0.287	W/mK
U_p	U-value of the insulating panel	0.927	W/m²K
b_p	Length of the insulating panel	0.2	m
b_f	Length of the frame	0.059	m
U_f	U-value of the frame	1.748	W/m²K



The following sequence reports the thermal analysis of the important details listed in the introduction of the chapter.

In fact, looking at this detail, it is easily understood that there is a possible risk of condensation on the interior surface area of the wall close to the joint with the window frame. Since the window is cladded directly to the concrete column, the heat escapes easier in this junction. In case the life cycle assessment shows that the precast concrete thermal break panels show the least environmental impact, this detail must be reviewed and condensation risk solved, possibly by attaching the window frame in line with the continuous thermal break in EPS.



Figure 65: Detail 1.2.

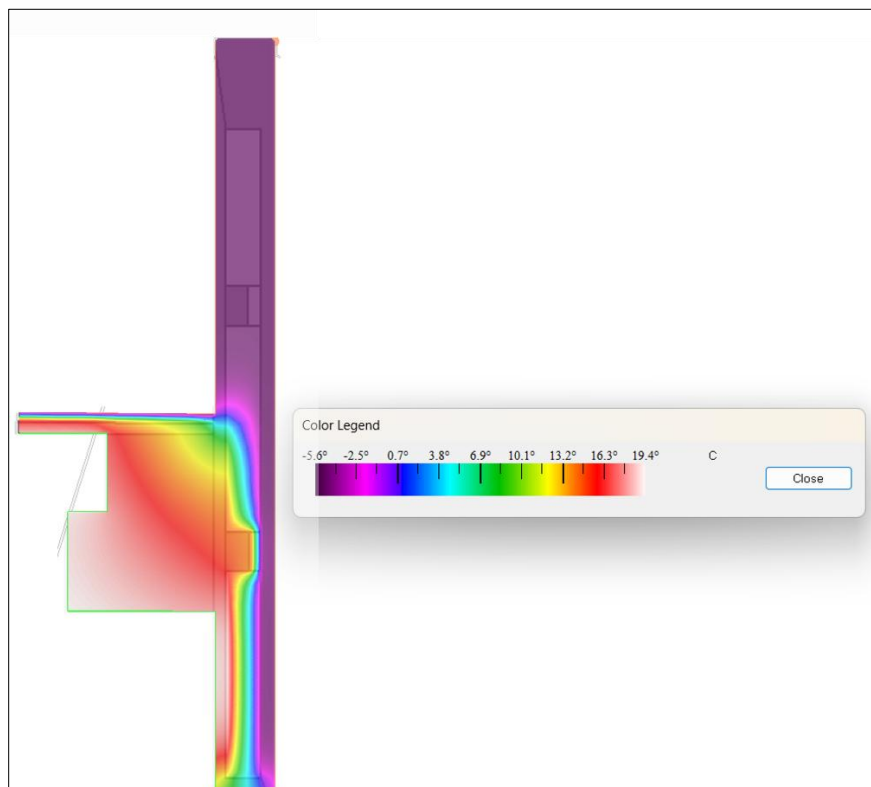


Figure 66: Detail 1.3.

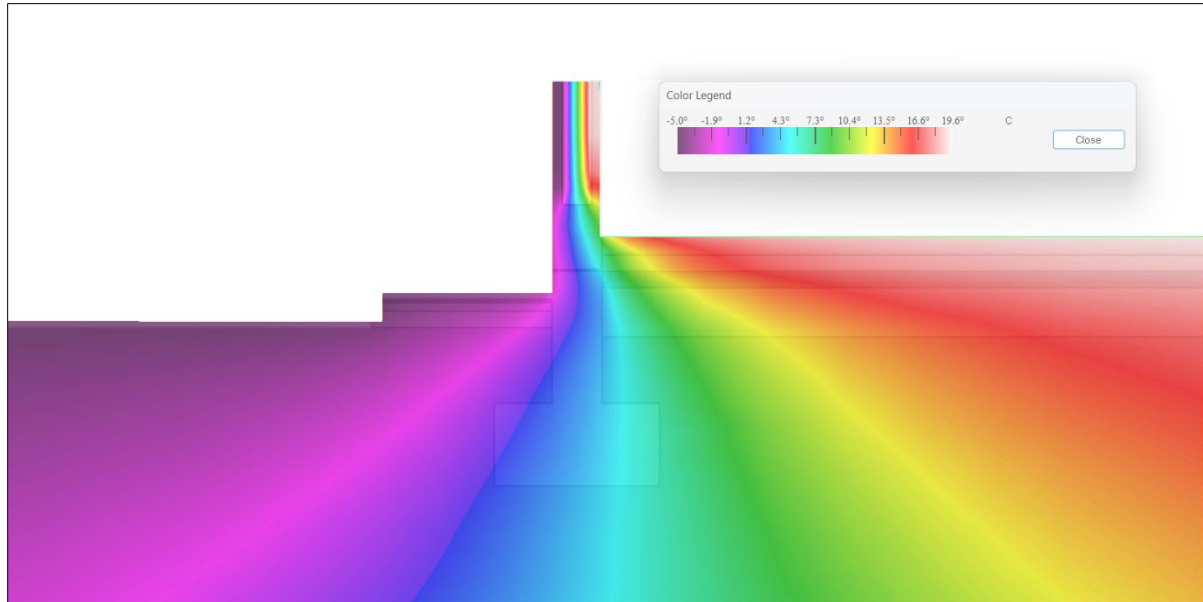


Figure 67: Detail 1.4.

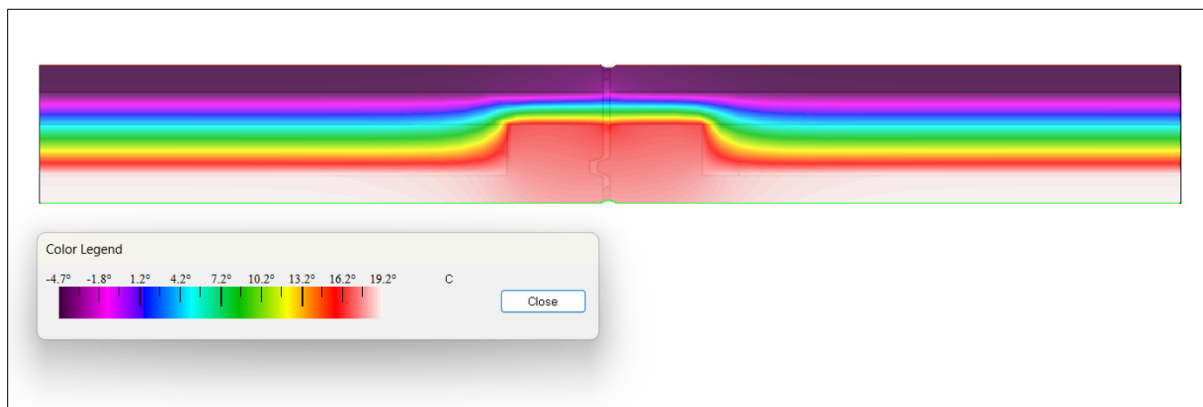


Figure 68: Detail 1.5.

The following tables report the corrected thermal transmittance values for all four façade orientations, taking into account the calculated linear thermal transmittances for analyzed sections and applied to the respective lengths of thermal bridges. The corrected U-values are indicated with “ U_{corr} ”, which takes into account the thermal conductance of thermal bridges reported in “ Hc_{tb} ”, that is a function of linear thermal transmittance and thermal bridge length.

Table 54: Corrected thermal transmittance of the north façade covered in precast thermal break panels.

NORTH FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.338	1.1. (horizontal section)	0.337	281.6	95.0	0.511
	1.1. (vertical section)	0.337	316.8	106.9	
	1.2.	0.010	294.2	3.0	
	1.3.	0.166	294.2	49.0	
	1.4.	0.402	294.2	118.3	
	1.5.	0.037	1411.9	52.8	

Table 55: Corrected thermal transmittance of the south façade covered in precast thermal break panels.

SOUTH FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.338	1.1. (horizontal section)	0.337	345.6	116.6	0.548
	1.1. (vertical section)	0.337	388.8	131.2	
	1.2.	0.010	354.4	3.6	
	1.3.	0.166	354.4	59.0	
	1.4.	0.402	354.4	142.5	
	1.5.	0.037	1700.9	63.7	

Table 56: Corrected thermal transmittance of the east and west façade covered in precast thermal break panels.

EAST AND WEST FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.338	1.1. (horizontal section)	0.337	70.4	23.8	0.398
	1.1. (vertical section)	0.337	79.2	26.7	
	1.2.	0.010	0.0	0.0	
	1.3.	0.166	144.6	24.1	
	1.4.	0.402	144.6	58.2	
	1.5.	0.037	694.3	26.0	

We observe that the difference between the base effective and the final corrected thermal transmittance value is non-negligible, in the worst case (on the south façade) rising from 0.338 W/m²K to 0.548 W/m²K. The highest linear thermal transmittances are reported for the joint between the panels and the ground and between the panels and the windows.

5.2.2.2. Metal sandwich panels thermal analysis

Thermal transmittance of a single metal sandwich panel results in 0.212 W/m²K and is found as the function of the total heat flow through the section, panel length and the temperature difference between the interior and the exterior surface:

Table 57: Thermal transmittance of a metal sandwich panel.

Detail 1.0. – Panel's thermal transmittance			
Φ	Heat flow	5.31	W/m of depth
L_{PT}	Projection depth	1.00	m
L	Length	1.00	m
ΔT	Temperature difference	25.00	K
U_{eff}	Effective U-value	0.212	W/m²K

$$U_{eff} = \frac{\Phi}{L \cdot \Delta T} = 0.212 \frac{W}{m^2 K}$$

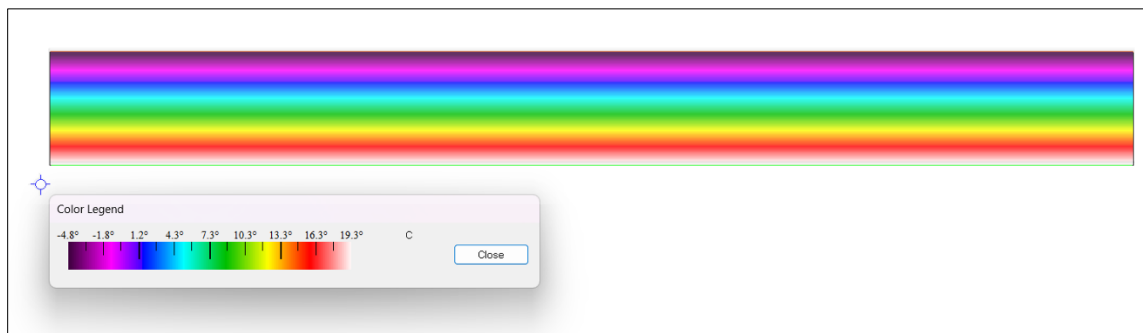


Figure 69: Detail 2.0.

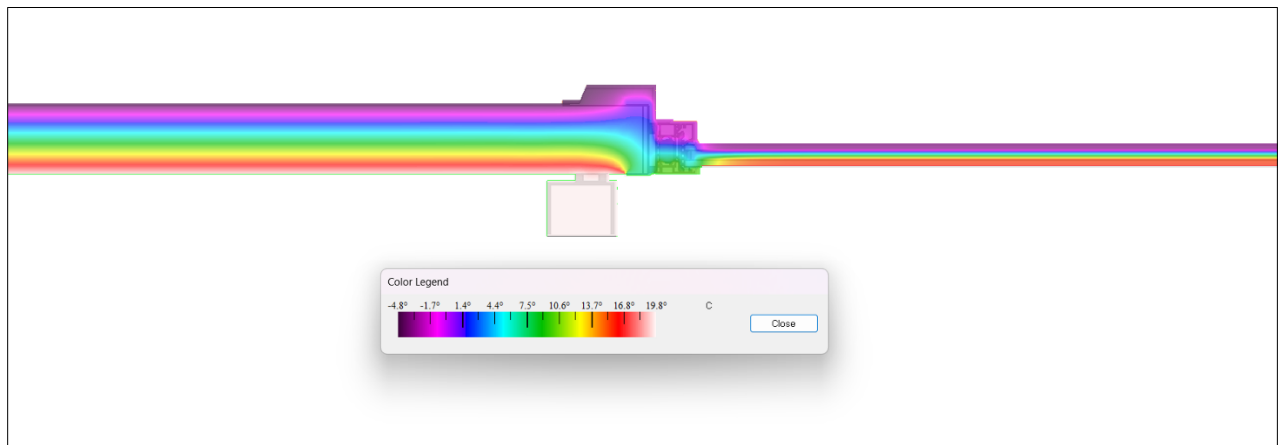


Figure 70: Detail 2.1.



Figure 71: Detail 2.2.

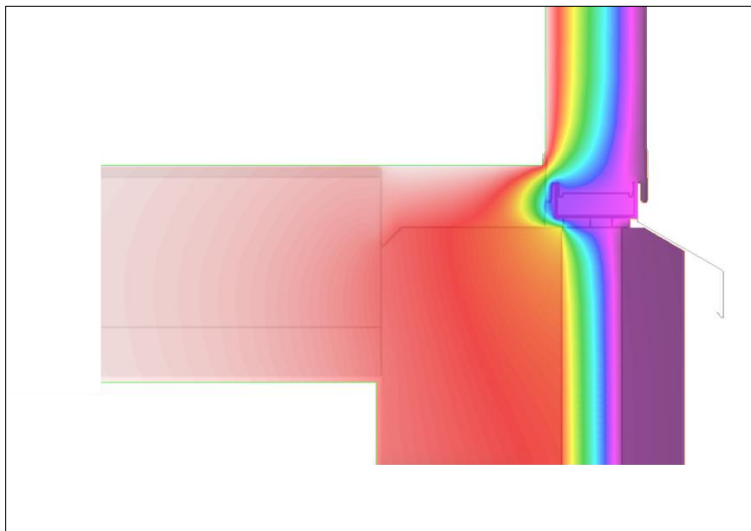


Figure 72: Detail 2.2. – close-up.

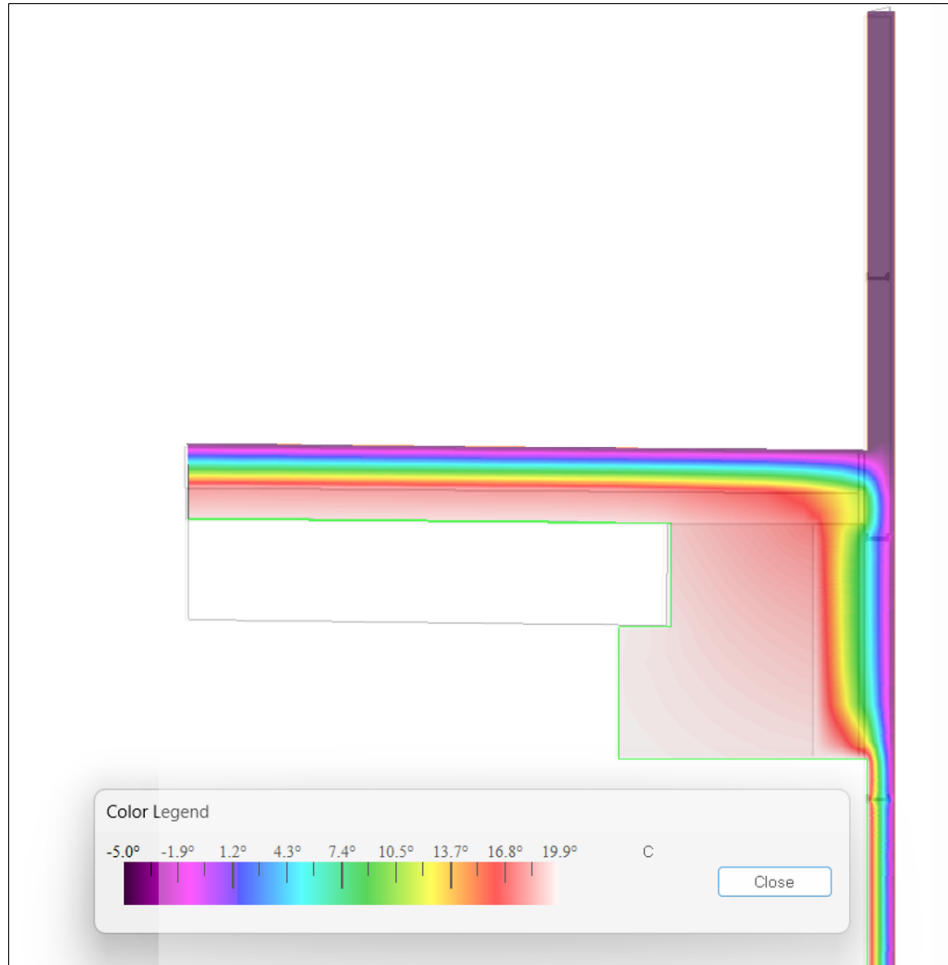


Figure 73: Detail 2.3.

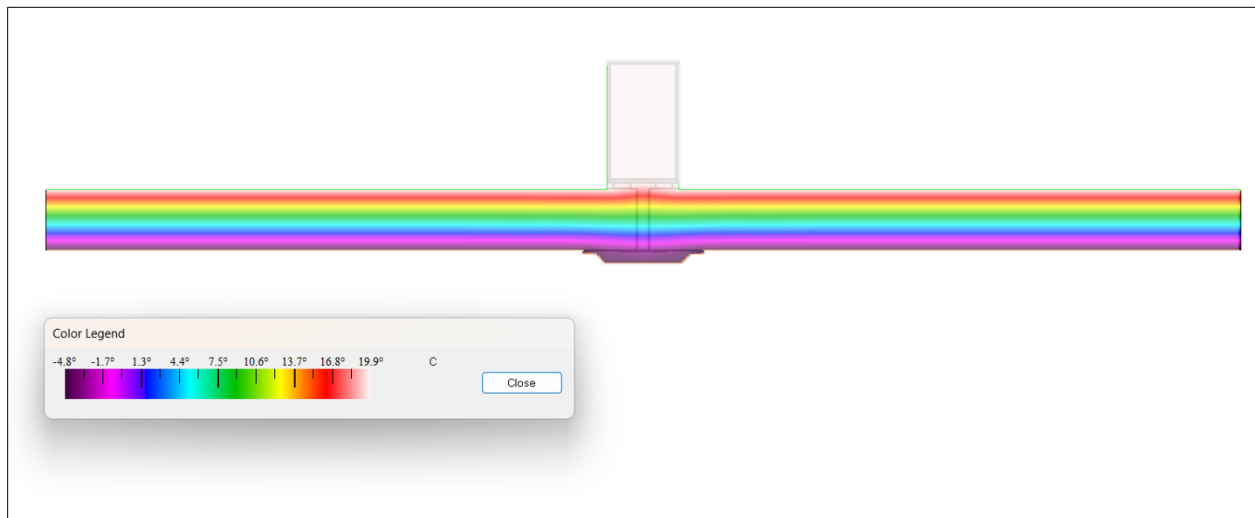


Figure 74: Detail 2.5.

The following tables report the corrected thermal transmittance values for all four façade orientations:

Table 58: Corrected thermal transmittance of the north façade covered in sandwich panels with precast thermal break panels base.

NORTH FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.212	2.1. (horizontal section)	0.025	281.6	6.9	0.267
	2.1. (vertical section)	0.025	316.8	7.8	
	2.2.	0.083	294.2	24.6	
	2.3.	0.022	294.2	6.4	
	2.4.	0.402	294.2	118.3	
	2.5.	0.032	220.6	7.1	

Table 59: Corrected thermal transmittance of the south façade covered in sandwich panels with precast thermal break panels base.

SOUTH FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.212	2.1. (horizontal section)	0.025	345.6	8.5	0.279
	2.1. (vertical section)	0.025	388.8	9.6	
	2.2.	0.083	354.4	29.6	
	2.3.	0.022	354.4	7.7	
	2.4.	0.402	354.4	142.5	
	2.5.	0.032	265.8	8.6	

Table 60: Corrected thermal transmittance of the east and west façade covered in sandwich panels with precast thermal break panels base.

EAST AND WEST FACADE					
U_eff [W/m²K]	Thermal bridge detail	ψ [W/mK]	Length [m]	Hc_tb [W/K]	U_corr [W/m²K]
0.212	2.1. (horizontal section)	0.025	70.4	1.7	0.231
	2.1. (vertical section)	0.025	79.2	2.0	
	2.2.	0.083	0.0	0.0	
	2.3.	0.022	144.6	3.1	
	2.4.	0.402	144.6	58.2	
	2.5.	0.032	108.5	3.5	

Compared to the solution with fully precast concrete panels, sandwich panels show significantly lower linear thermal transmittance values in the junction between the panel and the window. This

significantly also reduces the difference between the base effective U-value and the final corrected one. In case of the concrete panels, the increase in the U-value was around 38%, while in case of sandwich panels with the concrete base, the increase is about 23%, rising from 0.212 W/m²K to 0.279 W/m²K. Significant portion of thermal bridge contribution here, however, is still due to the contact with the ground where precast concrete panels are in contact with the ground. In terms of connections with the openings, the solution with sandwich panels performs significantly better than precast concrete panels.

These results made it possible to run the energy simulation and find the average air temperature of the warehouse portion of the building after correcting the thermal transmittances.

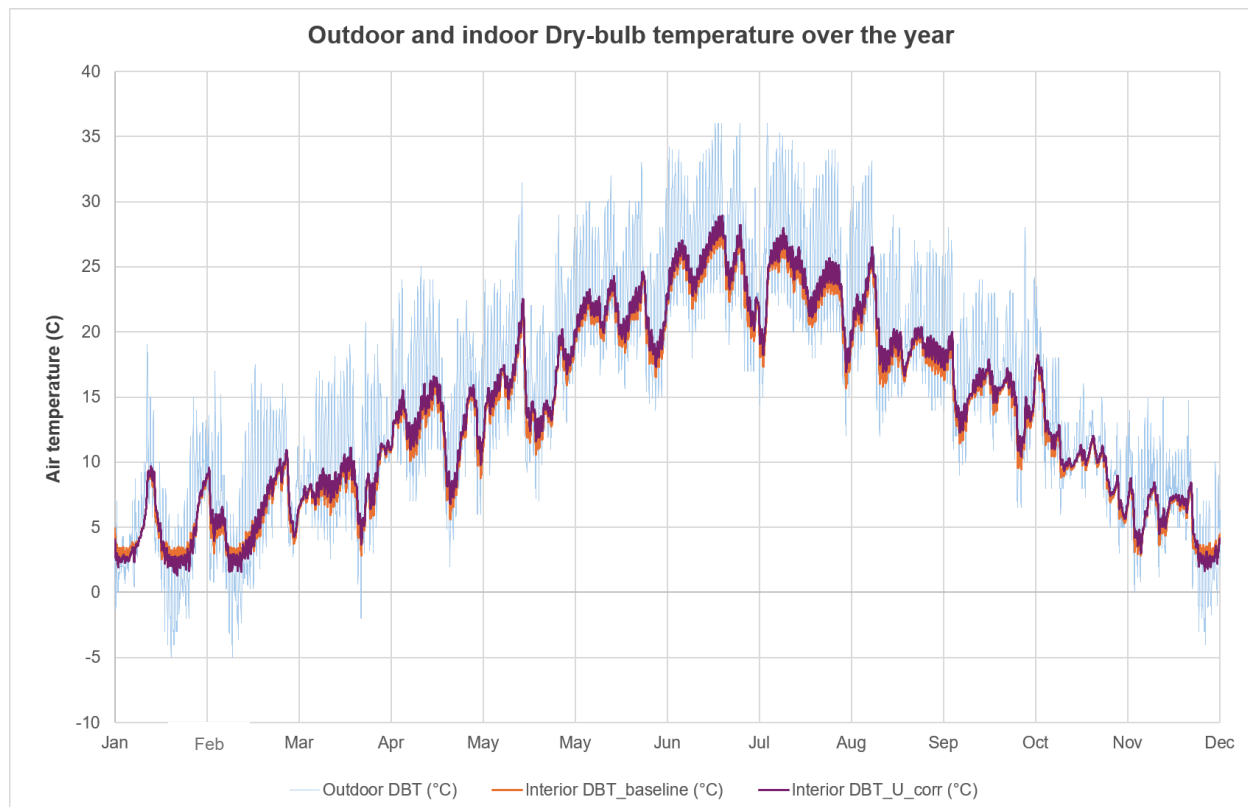


Figure 75: Outdoor and indoor Dry-bulb temperature over the year, for baseline and corrected envelope U-values.

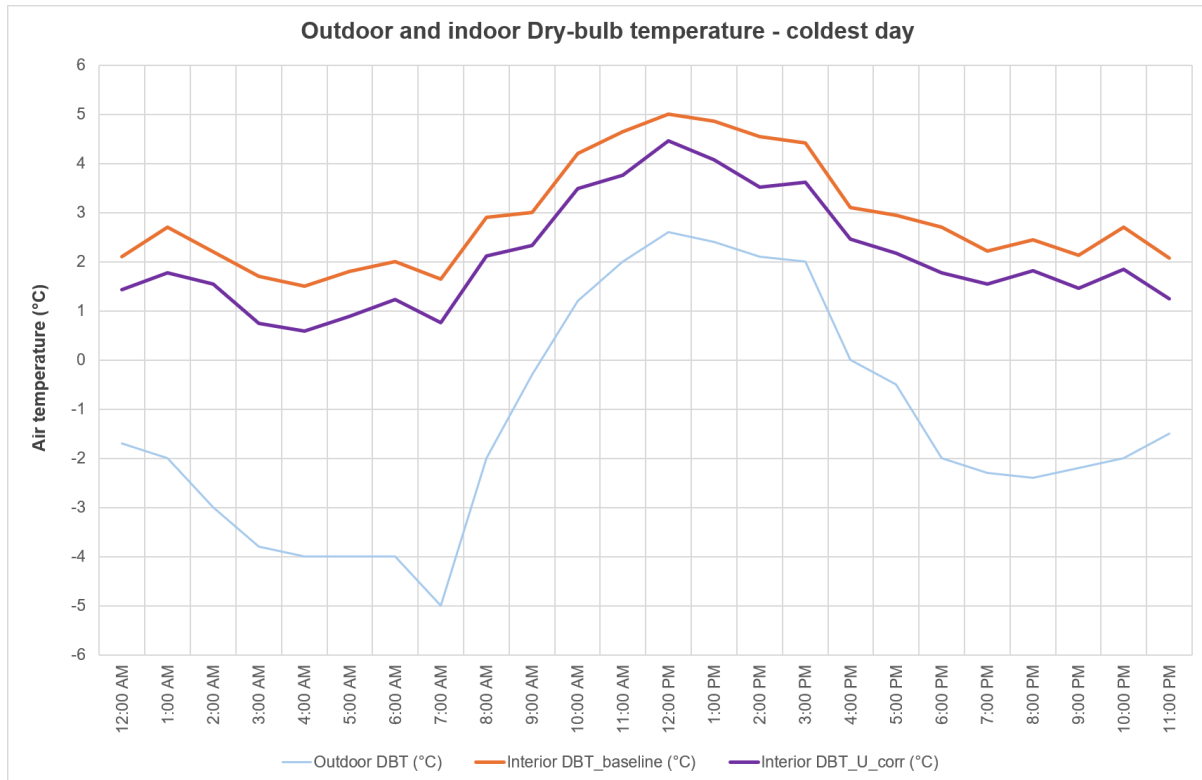


Figure 76: Outdoor and indoor DBT for baseline and corrected U-values on the coldest day (January 19th).

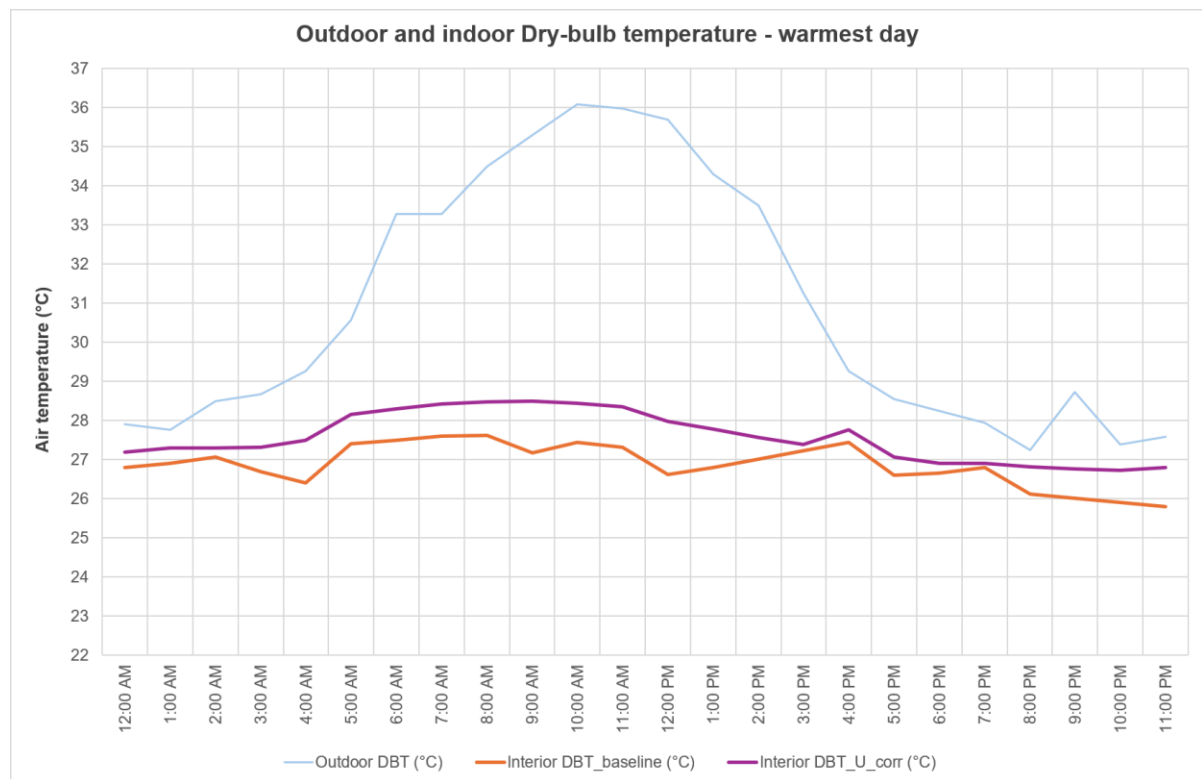


Figure 77: Outdoor and indoor DBT for baseline and corrected U-values on the warmest day (July 15th).

Running the energy simulation with the updated thermal transmittances, the average dry bulb temperature of the warehouse does not change significantly. Besides looking at the annual distribution of the DBT, a closer look was taken also for the average coldest and warmest day, those being January 19th and July 15th, respectively. We can see that the interior temperature follows the trend of the outdoor temperature, because it is free-floating and there is no conditioning system inside except for the continuous ventilation provided by the AHU.

Comparing the absolute air temperature difference between the baseline and the scenario with corrected U-values, for both the coldest and the warmest day this difference does not exceed 0.96°C, although the difference in U-value for precast concrete panels in the worst-case equals to 0.21 W/m²K, for the south façade. Since the warehouse is not a conditioned space, thermal transmittance will be excluded as the constraint to propose an alternative envelope solution, and thermal bridge analysis will not be performed for this solution.

5.2.3. Proposal of the timber frame envelope module

As it has been explained the concrete panels are downcycled rather than reused in its original form, as the concrete is crushed and recovered into the RCA. EPS is partially recycled but mostly around 15% (depending on the EPD) and the rest is sent to landfill. On the other hand the metal panels are in great majority disposed on the landfill, with only slightly higher than 3% of PIR being recycled. Steel rebars from the concrete panels and metal sheets from PIR panels are indeed the only parts that are undergo high-value recycling, meaning that they can be used in their original form in the life cycle of the future product.

Although the method of controlled production, fast on-site assembly and disassembly at the end of life for both of these types of panels are all principles aligned with DfD, there is still a high need for virgin material to be extracted so the new panels can be produced, with the exception of steel. This means a new production of clinker and EPS for concrete panels and polyisocyanurate for metal panels, as in the previous life they were either downcycled or disposed in a landfill with only small percentage recovered or recycled.

For this reason, it is proposed to replace the metal PIR panels with timber frame panels. The decision is based on the fact that this substitution would not only represent a possible reduction in GWP, but the carbon would be actively stored within the timber frame panels for the duration of the building's life. Timber is a material that absorbs CO₂ from the atmosphere as it grows, storing the carbon inside of its biomass, therefore characterized by its biogenic carbon storage capacity.

Furthermore, load-bearing elements inside of the timber frame panel are timber joists while infill of insulation contributes to the panel's thermal properties, whereas for PIR panels the insulation has both thermal and structural performance. It must be bonded to the metal sheets and during End-of-Life this presents a challenge to easily separate the insulation. In the case of timber frame, the members are mechanically connected and the panel's composition inherently aligns with DfD strategy. Since insulation is non-structural, this gives a possibility to choose a wider range of

insulations, including bio-based ones. Advantages and possible risks of installing such a system over PIR sandwich panels are presented in the following table.

Table 61: Advantages and disadvantages of installing timber frame panels vs. metal sandwich PIR panels.

	Advantages	Disadvantages
Timber frame panels	Biogenic carbon storage capacity	Durability of the materials
	Mechanical connection between all the members	Greater thickness needed to reach the same thermal performance
	Higher potential for reuse of timber	Complexity of the module is higher than PIR panels
	Wider range of insulation infill choice	Capacity to reach higher spans is lower
	Higher potential for insulation recycling	Non-traditional system for industrial halls
Metal sandwich PIR panels	Durable when installed correctly	Energy-intensive production process
	Great thermal performance with lower thickness	Chemical adhesives used for panel construction
	Modules are lightweight and easy to assemble	More difficult to reuse and recycle
	Modules have the capacity to reach higher spans	Low range of insulation choice
	Traditional and well-known system for industrial halls	Delamination could occur if not installed properly on-site

Regardless of the risks that should not be ignored, following chapters will be dedicated to the structural analysis of the timber panels to assess the possibility of its installation and LCA analysis in comparison with the other two envelope systems. To do so, a preliminary stratigraphy is proposed:

Table 62: Preliminary stratigraphy of a timber frame panel and the end-of-life treatment.

Timber frame panel, size of one module to be determined (TBD)				
Layer no.	Stratigraphy	Thickness per one panel	Unit	End-of-Life treatment, as per EPD
1	Oriented strand board OSB	19	mm	58% recycled, 25% incinerated and sent for energy recovery, 17% to landfill
2	Vapor barrier membrane	0.2	mm	Material incineration
3	Horizontal spruce timber joists	TBD	mm	Incinerated, used 100% for energy recovery
4	Vertical spruce timber joists	TBD	mm	Incinerated, used 100% for energy recovery
5	Thermal insulation infill	TBD	mm	TBD
6	Cement fiber panel FERMACELL	12.5	mm	80% of the material is downcycled, 20% sent to landfill

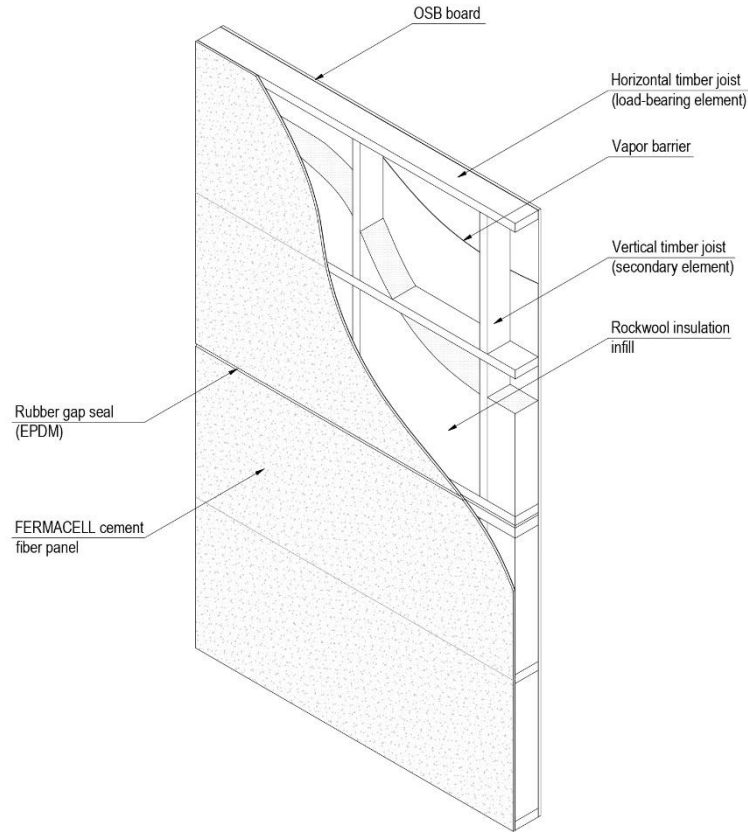


Figure 78: Isometry illustrating the layers of a timber frame panel.

5.2.4. Timber frame envelope structural analysis

To size the timber frame the structural analysis is performed taking into consideration dead load of the panel and self-weight of the timber members as well as wind loads. After calculating the loads, load bearing timber joists are evaluated for bending resistance and deflection. Considering the panels are supported by a secondary steel frame as explained in previous chapters, vertical steel mullions are evaluated for bending, buckling resistance and deflection. Therefore, the analysis is divided into four parts: dead load calculations, wind load calculations, timber frame structural analysis and steel mullions structural analysis.

5.2.4.1. Dead load calculations

As it is reported in Table 62, the panel consists of an OSB board on the interior side, vapor barrier membrane, horizontal and vertical timber joists between which an insulation fill is placed, and as finishing a water-resistant cement fiber board is placed. Initial assumption for sizing of timber joists is to have the width of 60mm and depth of 160mm. Since in the solution with metal panels the distance between centres of two vertical mullions was 4500mm, the same distance is kept for

the first iteration in order to keep the amount of steel the same. The stratigraphy is therefore the following:

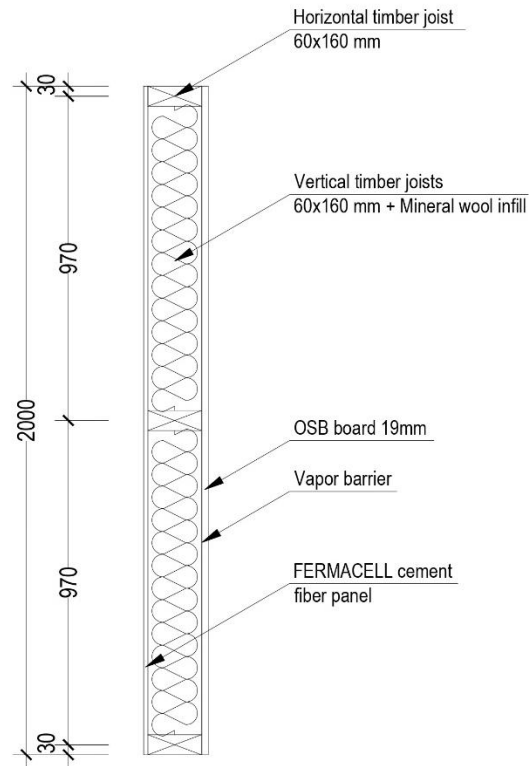


Figure 79: Timber frame panel stratigraphy of the first iteration.

Therefore, the dead load of the entire panel and self-weight of a horizontal timber joist (load-bearing joist) represented per square area are reported in the following tables:

Table 63: Permanent non-structural (dead) loads of the timber frame panel.

Timber panel stratigraphy						
Permanent non-structural G2 loads						
Layer no.	Material	Thickness [mm]	Thickness [m]	Density ρ [kg/m ³]	Density δ [kN/m ³]	Distributed Load [kN/m ²]
1	OSB panel	19	0.019	620	6.08	0.12
2	Vapor barrier	0.4	0.0004	950	9.32	0.00
3	Rock wool insulation	160	0.16	30	0.29	0.05
4	Cement fiber panel	12.5	0.0125	1150	11.28	0.14
5	Timber joists	-	-	550	5.40	0.08
SUM		191.9	0.19	-	-	0.40

Table 64: Self-weight included for the horizontal joist (load-bearing member).

Horizontal joist self-weight		
Width	0.08	m
Depth	0.20	m
Section area	0.02	m ²
Density δ	5.40	kN/m ³
Linear load	0.09	kN/m
Influence length	1.00	m
Distributed load	0.09	kN/m²

5.2.4.2. Wind load calculations

Wind loads are evaluated according to the official national technical standard Norme Tecniche per le Costruzioni 2018 (NTC 2018). Analyzing the wind velocities based on the “epw” file of the location, it is understood that 99% of wind velocities fall within the range of up to 8m/s for all orientations. The four main orientations experience this wind velocity. In terms of the total share of wind hours, the SSW orientation experiences 22% of wind hours, while West (W) and WSW receive 12% and 11%, respectively.

Therefore, it is possible to conclude that the orientations most affected by the wind are the South and the West. Taking into account the surface area affected by the wind, the South orientation is the most affected one. Regardless, the envelope system is consistent throughout the entirety of the building, therefore the worst case of wind speed is affecting the building whose envelope does not change by orientation.

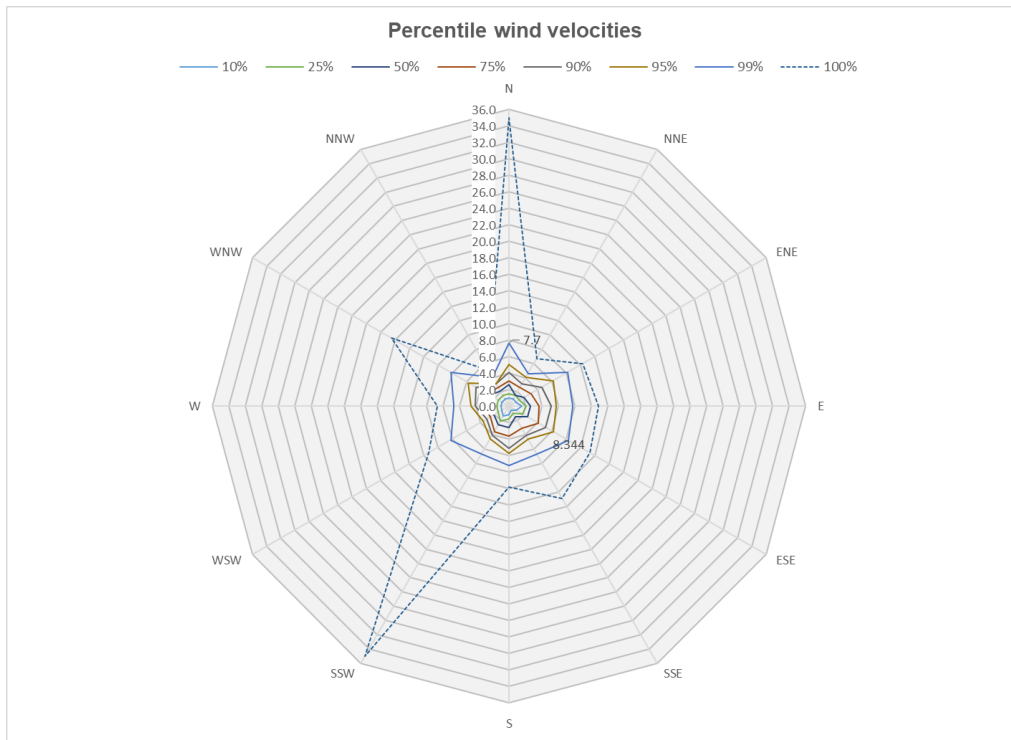


Figure 80: Percentiles of wind velocities on a wind rose diagram.

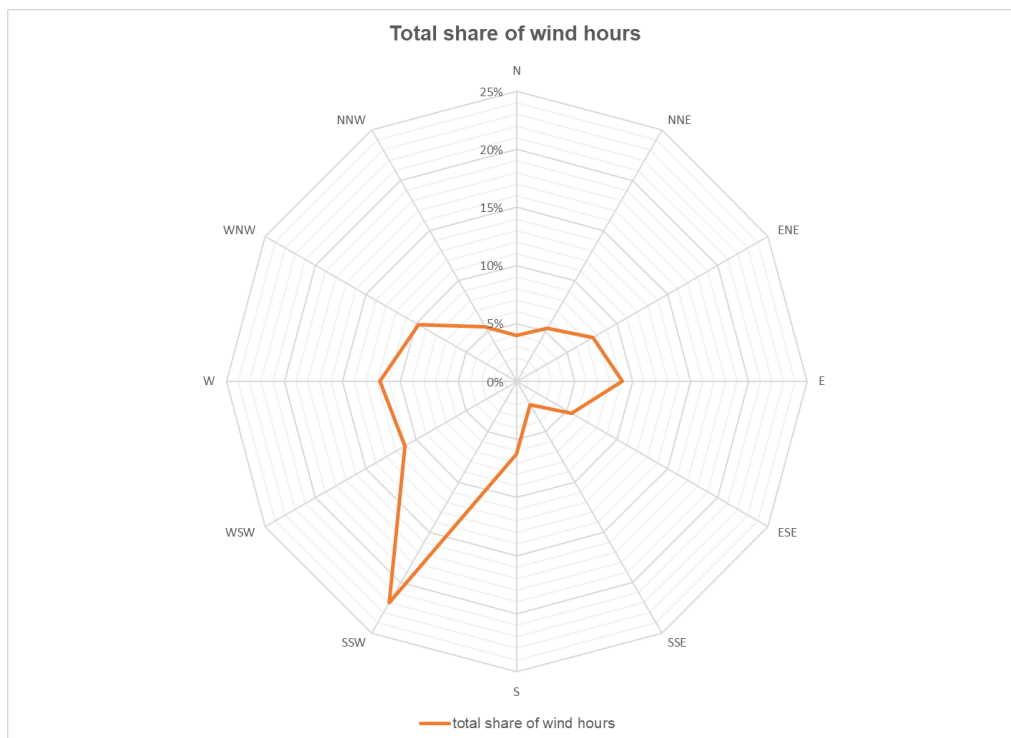


Figure 81: Total share of wind hours on a wind rose diagram.

The wind load on the building is calculated starting from the wind pressure acting on the façade, that is defined by the following formula:

$$p = q_r \cdot C_e \cdot C_d \cdot (C_{pe} - C_{pi})$$

where:

- q_r is the reference kinetic pressure;
- C_e is the exposure coefficient;
- C_d is the dynamic coefficient;
- C_{pe} is the external pressure coefficient;
- C_{pi} is the internal pressure coefficient.

Regarding to NTC 2018, chapter 3.3.1, the kinetic pressure was calculated according to the following equation:

$$q_r = \frac{1}{2} \rho v_b^2 = \frac{1}{2} \cdot 1,25 \frac{kg}{m^3} \cdot \left(2 \frac{m}{s}\right)^2 = 390.63 \frac{N}{m^2} = 0.39 \frac{kN}{m^2}$$

where:

- the air density ρ is assumed as a constant equal to 1,25 kg/m³;
- the base reference velocity v_b is the mean value over 10 minutes, at a height of 10 m above the ground on a flat, homogeneous terrain of exposure category III, referring to a return period TR = 50 years.

In the absence of specific and adequate statistical investigations, v_b is given by the expression:

$$v_b = v_{b,0} \cdot c_a = 25 \frac{m}{s}$$

where:

- $v_{b,0}$ is the reference base velocity at sea level, assigned in Table 65 according to the region in which the building stands (in this case, Emilia Romagna);
- c_a is the altitude coefficient provided by the relation:

$$\begin{aligned} c_a &= 1 && \text{per } a_s \leq a_0 \\ c_a &= 1 + k_s \left(\frac{a_s}{a_0} - 1 \right) && \text{per } a_0 < a_s \leq 1500 \text{ m} \end{aligned} \quad [3.3.1.b]$$

Table 65: Values for reference base velocity according to NTC.

Tab. 3.3.I - Valori dei parametri $v_{b,0}$, a_0 , k_s

Zona	Descrizione	$v_{b,0}$ [m/s]	a_0 [m]	k_s
1	Valle d'Aosta, Piemonte, Lombardia, Trentino Alto Adige, Veneto, Friuli Venezia Giulia (con l'eccezione della provincia di Trieste)	25	1000	0,40
2	Emilia Romagna	25	750	0,45
3	Toscana, Marche, Umbria, Lazio, Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria (esclusa la provincia di Reggio Calabria)	27	500	0,37
4	Sicilia e provincia di Reggio Calabria	28	500	0,36
5	Sardegna (zona a oriente della retta congiungente Capo Teulada con l'Isola di Maddalena)	28	750	0,40
6	Sardegna (zona a occidente della retta congiungente Capo Teulada con l'Isola di Maddalena)	28	500	0,36
7	Liguria	28	1000	0,54
8	Provincia di Trieste	30	1500	0,50
9	Isole (con l'eccezione di Sicilia e Sardegna) e mare aperto	31	500	0,32

The exposure coefficient is given in function of the height of the considered point with respect to the ground level and of the topography of the construction site. The coefficient is calculated according to the following formulas:

$$\begin{aligned}
 c_e(z) &= k_t^2 c_t \ln(z/z_0) [7 + c_t \ln(z/z_0)] & \text{per } z \geq z_{\min} \\
 c_e(z) &= c_e(z_{\min}) & \text{per } z < z_{\min}
 \end{aligned}
 \quad [3.3.7]$$

where:

- k_r , z_0 , $z_{\min}$ are assigned according to the exposure category of the construction site;
- c_t is the topography coefficient, defined equal to 1.

Table 66: Roughness classes of the soil.

Tab. 3.3.III - Classi di rugosità del terreno

Classe di rugosità del terreno	Descrizione
A	Aree urbane in cui almeno il 15% della superficie sia coperto da edifici la cui altezza media superi i 15 m
B	Aree urbane (non di classe A), suburbane, industriali e boschive
C	Aree con ostacoli diffusi (alberi, case, muri, recinzioni,...); aree con rugosità non riconducibile alle classi A, B, D
D	a) Mare e relativa fascia costiera (entro 2 km dalla costa); b) Lago (con larghezza massima pari ad almeno 1 km) e relativa fascia costiera (entro 1 km dalla costa) c) Aree prive di ostacoli o con al più rari ostacoli isolati (aperta campagna, aeroporti, aree agricole, pascoli, zone paludose o sabbiose, superfici innevate o ghiacciate, ...)

The selected area is ranked in the roughness category B and being further than 30 km distance from seaside and under 500 m over sea-level, category IV of exposure is assigned.

Table 67: Assignment of the exposure class according to the site location.

ZONE 1,2,3,4,5						
A	--	IV	IV	V	V	V
B	--	III	III	IV	IV	IV
C	--	*	III	III	IV	IV
D	I	II	II	II	III	**
* Categoria II in zona 1,2,3,4 Categoria III in zona 5						
** Categoria III in zona 2,3,4,5 Categoria IV in zona 1						

Using the following table, the parameters for defining the exposure coefficient can be defined.

Table 68: Parameters for defining the exposure coefficient according to the exposure class.

Tab. 3.3.II - Parametri per la definizione del coefficiente di esposizione

Categoria di esposizione del sito	K_r	z_0 [m]	z_{min} [m]
I	0,17	0,01	2
II	0,19	0,05	4
III	0,20	0,10	5
IV	0,22	0,30	8
V	0,23	0,70	12

The exposure coefficient was taken as the one corresponding to the highest level of the building, as it represents the most unfavourable case.

$$C_e(z) = K_r^2 c_t \ln(z/z_0) [7 + c_t \ln(z/z_0)]$$

$$C_e(13) = 0.22^2 \cdot 1 \cdot \ln\left(\frac{13}{0.3}\right) \cdot [7 + 1 \cdot \ln\left(\frac{13}{0.3}\right)] = 1.96$$

Now the pressure coefficients must be defined. To define their values, Appendix G - Global Aerodynamic Coefficients, CNR DT 207 2008 [79] was followed. The pressure coefficient C_p is calculated based on the external and internal pressure coefficients C_{pe} and C_{pi} .

The external pressure coefficient depends on the orientation of the building with respect to the wind direction and on the ratio between the height and width dimensions of the structure. Knowing that $h/d = 0.11$ the short side (east and west) and $h/d = 0.06$ for the long side of the building (north and south), we can get the external pressure coefficient as in the following table:

Table 69: External pressure coefficient calculation for windward, lateral and leeward elements.

Tabella G.I – Edifici a pianta rettangolare: c_{pe} per facce sopravento, sottovento e laterali.

Faccia sopravento	Facce laterali	Faccia sottovento
$h/d \leq 1$: $c_{pe} = 0,7 + 0,1 \cdot h/d$	$h/d \leq 0,5$: $c_{pe} = -0,5 - 0,8 \cdot h/d$	$h/d \leq 1$: $c_{pe} = -0,3 - 0,2 \cdot h/d$
$h/d > 1$: $c_{pe} = 0,8$	$h/d > 0,5$: $c_{pe} = -0,9$	$1 < h/d \leq 5$: $c_{pe} = -0,5 - 0,05 \cdot (h/d - 1)$

For the internal pressure coefficient, on the other hand, the values +0.2 and -0.3 were used.

Once all the necessary parameters were determined, the design wind pressures could be calculated using the following formula:

$$p = q_r \cdot C_e \cdot C_d \cdot (C_{pe} - C_{pi})$$

The calculation of the wind pressure resulted in six pressure values for each direction, with two values assigned to each face. These results are summarized in the tables below. For each face, the worst-case values were selected accordingly.

Table 70: Wind pressure results in Direction X, for windward, lateral and leeward elements.

DIRECTION X	WINDWARD ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	0.71	0.20	0.51
	13	0.391	1.96	1	0.71	-0.30	0.77
	LATERAL ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	-0.54	0.20	-0.74
	13	0.391	1.96	1	-0.54	-0.30	-0.24
	LEEWARD ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	-0.32	0.20	-0.52
	13	0.391	1.96	1	-0.32	-0.30	-0.02

Table 71: Wind pressure results in Direction Y, for windward, lateral and leeward elements.

DIRECTION Y	WINDWARD ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	0.70	0.20	0.50
	13	0.391	1.96	1	0.70	-0.30	0.77
	LATERAL ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	-0.54	0.20	-1.10
	13	0.391	1.96	1	-0.54	-0.30	-0.60
	LEEWARD ELEMENTS						
	z [m]	q _r [kN/m ²]	C _e	C _d	C _{pe}	C _{pi}	p [kN/m ²]
	13	0.391	1.96	1	-0.31	0.20	-0.51
	13	0.391	1.96	1	-0.31	-0.30	-0.01

Based on the results, the highest absolute value of wind pressure will be considered for structural verification, which is 0.77 kN/m², reported for suction on windward elements in both X- and Y-direction.

The structural design must be verified against two main types of load combinations in accordance with the NTC 2018 code: Ultimate Limit State (SLU) combinations and Serviceability Limit State (SLE) combinations.

ULS combination will be used to evaluate the structure under the most critical and severe loading scenario the façade can realistically face. These combinations ensure that the structure maintains overall stability and avoids collapse under extreme conditions. The loads assessed include permanent (dead) loads and wind loads, which are combined with partial safety factors to simulate worst-case scenarios.

Conversely, SLS combinations focus on the structure's behavior under normal service conditions. These checks aim to control deformations, vibrations, and crack widths in structural elements.

According to NTC 2018, both ULS and SLS combinations are explicitly defined with prescribed partial safety factors and combination coefficients for each load type. The combinations checked for the envelope structural analysis are the fundamental SLU combination and the characteristic SLS combination:

$$ULS (SLU) \text{ Combination: } \gamma_{G1} \cdot G_1 + \gamma_{Qw} \cdot \Psi_{02} \cdot Q_{K2}$$

$$SLS (SLE) \text{ Combination: } G_1 + \Psi_{2j} \cdot Q_{K2}$$

where:

- γ is the partial safety factor coefficient based on Table 72;
- Ψ are the combination coefficient based on Table 73.

Table 72: Partial safety coefficients for permanent structural loads and variable (wind) loads.

Partial safety factor coefficients γ			
Permanent load - structural G1	Favorable	γ_{G1}	1
	Unfavorable		1.3
Variable loads (wind)	Favorable	γ_{Gw}	0
	Unfavorable		1.5

Table 73: Values of combination coefficients for a warehouse building.

Tab. 2.5.I – Valori dei coefficienti di combinazione

Categoria/Azione variabile	Ψ_{0j}	Ψ_{1j}	Ψ_{2j}
Categoria A - Ambienti ad uso residenziale	0,7	0,5	0,3
Categoria B - Uffici	0,7	0,5	0,3
Categoria C - Ambienti suscettibili di affollamento	0,7	0,7	0,6
Categoria D - Ambienti ad uso commerciale	0,7	0,7	0,6
Categoria E – Aree per immagazzinamento, uso commerciale e uso industriale Biblioteche, archivi, magazzini e ambienti ad uso industriale	1,0	0,9	0,8
Categoria F - Rimesse , parcheggi ed aree per il traffico di veicoli (per autoveicoli di peso ≤ 30 kN)	0,7	0,7	0,6

5.2.4.3. Bending moment and deformation of the timber frame

Timber frame is composed of horizontal joists and vertical posts. Horizontal joists are load-bearing members that are subjected to biaxial bending, resisting both the vertical gravity loads of the cladding and the lateral pressures from wind action. The vertical posts provide global stability to the module, ensuring the frame maintains its geometric integrity and stiffness.

The horizontal joists are acting as simply supported beams. One end is configured as a pinned connection, restraining both vertical and horizontal translation. The opposite end is configured as a sliding (roller) connection, which restrains vertical displacement while allowing longitudinal horizontal translation. This degree of freedom is allowed at one end to accommodate thermal expansion and possible moisture-caused movement within timber, preventing that internal stresses damage the façade fixings. The following figure illustrates the static scheme, showing the bending moment induced around y- and z-axis caused by wind and dead load, respectively.

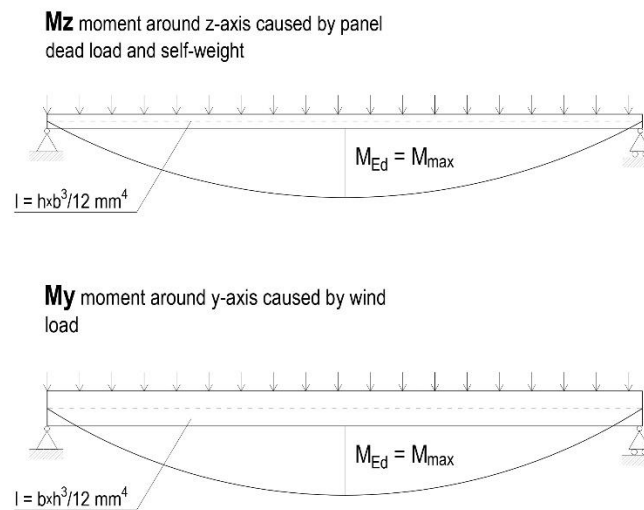


Figure 82: Bending moment diagram around z- and y-axis of the horizontal timber joist.

As it has been introduced in the stratigraphy, one single panel of 2-meter height is supported by three horizontal joists, one on the top, one on the bottom and one in the middle. The influence length of a joist is therefore considered as 1 meter. The initial length of a panel is 4.5 meters, the same one as of the existing structure adapted to metal sandwich panels. The figure below illustrates the distribution of influence areas of the joists, indicating the length as “TBD” (to be determined), which must be verified. Therefore, the influence area is:

$$A_{influence} = L_{influence} \cdot L_{joist} = 1m \cdot 4.5m = 4.5m^2$$

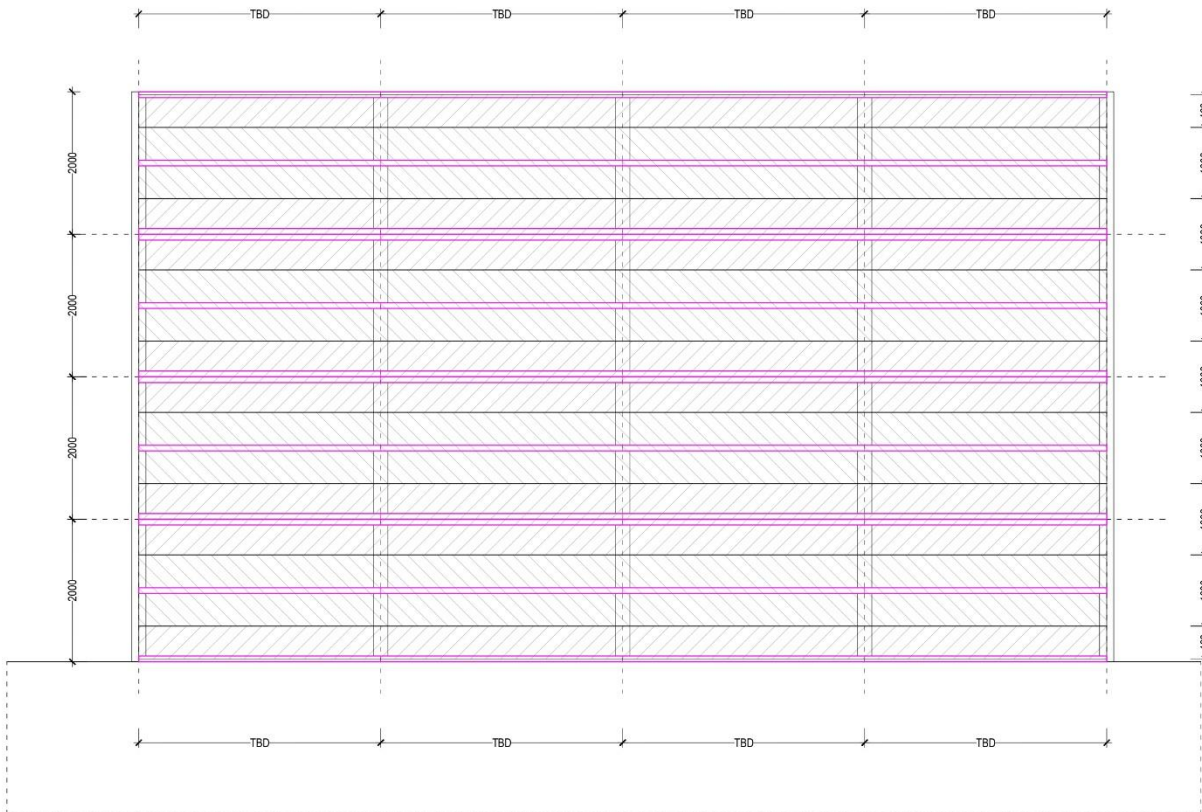


Figure 83: Distribution of influence areas of timber joists along the height.

The initial iteration will be made with a 60mm wide, 160mm deep and 4500mm long joist, as reported in the following table:

Table 74: First iteration of horizontal timber joists geometry.

	Joist geometry	Value	Unit	Value	Unit
B	Joist width	60	mm	0.06	m
H	Joist depth	160	mm	0.16	m
L	Joist length	4500	mm	4.5	m

The strength of a timber joist is defined by the material strength, that depends on the wood grade considered in the analysis. The NTC standard defines the strength of a structural member made of timber in the following way:

$$f_{m,d} = \frac{k_{mod} \cdot f_{m,k}}{\gamma_M}$$

Where:

f_{mk} – characteristic strength of a material based on the grade of wood;

γ_M – safety partial coefficient relative to the material;

k_{mod} – corrective coefficient taking into account effect on the material due to creep over time and the humidity of the structure.

In terms of characteristic strength, the C24 grade wood is considered, and according to the EN 338:2016 – Structural timber – strength classes [80], the characteristic material strength of this wood grade is:

$$f_{m,k} = 24 \frac{N}{mm^2} = 24 MPa$$

The following tables report the corrective coefficient and the safety partial coefficient for solid timber. The corrective coefficient depends on the duration of the load, where dead load is considered as permanent class of load duration ($k_{mod} = 0.60$), while wind load is an instantaneous load ($k_{mod} = 1.10$).

Table 75: Values of k_{mod} corrective coefficient for solid timber.

Tab. 4.4.IV - Valori di k_{mod} per legno e prodotti strutturali a base di legno

Materiale	Riferimento	Classe di durata del carico				
		Permanente	Lunga	Media	Breve	Istantanea
Legno massiccio	UNI EN 14081-1	0,60	0,70	0,80	0,90	1,10
Legno lamellare incollato (*)	UNI EN 14080	0,60	0,70	0,80	0,90	1,10
LVL	UNI EN 14374, UNI EN 14279	0,50	0,55	0,65	0,70	0,90
Compensato	UNI EN 636:2015	0,60	0,70	0,80	0,90	1,10
		0,60	0,70	0,80	0,90	1,10
		0,50	0,55	0,65	0,70	0,90
Pannello di scaglie orientate (OSB)	UNI EN 300:2006	OSB/2	0,30	0,45	0,65	0,85
		OSB/3	0,40	0,50	0,70	0,90
		OSB/4	0,30	0,40	0,55	0,70
Pannello di particelle (truciolare)	UNI EN 312 :2010	Parti 4, 5	0,30	0,45	0,65	0,85
		Parte 5	0,20	0,30	0,45	0,60
		Parti 6, 7	0,40	0,50	0,70	0,90
		Parte 7	0,30	0,40	0,55	0,70
Pannello di fibre, pannelli duri	UNI EN 622-2:2005	HB.LA,	0,30	0,45	0,65	0,85
		HB.HLA 1 o 2	0,20	0,30	0,45	0,60
		HB.HLA 1 o 2	0,20	0,30	0,45	0,60
Pannello di fibre, pannelli semiduri	UNI EN 622-3:2005	MBH.LA1 o 2	0,20	0,40	0,60	0,80
		MBH.HLS1 o 2	0,20	0,40	0,60	0,80
		-	-	-	0,45	0,80
Pannello di fibra di legno, ottenuto per via secca (MDF)	UNI EN 622-5:2010	MDF.LA,	0,20	0,40	0,60	0,80
		MDF.HLS	-	-	-	0,45
		MDF.HLS	-	-	-	0,45

Per i materiali non compresi nella Tabella si potrà fare riferimento ai pertinenti vti nei riferimenti tecnici di comprovata validità indicati nel Capitolo 12, nel rispetto dei livelli di sicurezza delle presenti norme.

(*) I valori indicati si possono adottare anche per i pannelli di tavole incollate a strati ilimitatamente alle classi di servizio 1 e 2.

Table 76: Safety partial coefficient value for solid timber.

Tab. 4.4.III - Coefficienti parziali γ_M per le proprietà dei materiali

Stati limite ultimi	Colonna A γ_M	Colonna B γ_M
combinazioni fondamentali		
legno massiccio	1,50	1,45
legno lamellare incollato	1,45	1,35
pannelli di tavole incollate a strati incrociati	1,45	1,35
pannelli di particelle o di fibre	1,50	1,40
LVL, compensato, pannelli di scaglie orientate	1,40	1,30
unioni	1,50	1,40
combinazioni eccezionali	1,00	1,00
Per i materiali non compresi nella Tabella si potrà fare riferimento ai pertinenti valori riportati nei riferimenti tecnici di comprovata validità indicati nel Capitolo 12, nel rispetto dei livelli di sicurezza delle presenti norme.		

The design strength against wind loads is:

$$f_{m,d} = \frac{1,10 \cdot 24 \text{ MPa}}{1,50} = 17,6 \text{ MPa}$$

While the design strength against dead loads is:

$$f_{m,d} = \frac{0.60 \cdot 24 \text{ MPa}}{1.50} = 9.6 \text{ MPa}$$

The design bending stress of a horizontal joist must be verified with respect to the material strength. The design bending stress is a function of the design bending moment, distance from the neutral axis and the moment of inertia of the section. The expression can be further simplified by expressing the bending stress as a function of design bending moment and the elastic section modulus.

$$\sigma_{m,d} \leq f_{m,d}$$

$$\sigma_{m,d} = \frac{M_{Ed} \cdot y}{I} = \frac{M_{Ed}}{W_{el}}$$

M_{Ed} – design bending moment;

y – for a rectangular section of the joist, the maximum distance from the neutral axis is the half of its depth parallel to the direction of the load received, $y = \frac{h}{2}$;

I – moment of inertia;

W_{el} – elastic section modulus.

Considering a simply supported beam, the design bending moment is calculated as a function of the load multiplied with SLU safety coefficient and the length of the beam. Bending moment will be verified for action of both the dead load and the wind loads separately, since the façade panel is exposed to biaxial bending.

The bending moment of a simply supported beam subjected to wind loads is as follows:

$$M_{Ed} = \frac{q_{wind,lin} \cdot \gamma_{Qw} \cdot L_{joist}^2}{8}$$

Wind load as force over a linear meter is obtained by multiplying the distributed wind pressure in [kN/m²] with the length of influence of a timber joist, therefore:

$$q_{wind,lin} = q_{wind,lin} \cdot L_{lin} = 0.77 \frac{kN}{m^2} \cdot 1m = 0.77 \frac{kN}{m}$$

$$M_{Ed} = \frac{0.77 \frac{kN}{m} \cdot 1.5 \cdot (4.5m)^2}{8} = 2.94 \text{ kNm}$$

Elastic section modulus is then calculated based on the section geometry:

$$W_{el} = \frac{B \cdot H^2}{6} = \frac{60mm \cdot (160mm)^2}{6} = 256,000 \text{ mm}^3$$

Therefore the design bending stress of the joist is the following:

$$\sigma_{m,d} = \frac{M_{Ed} \cdot y}{I} = \frac{M_{Ed}}{W_{el}} = 11.48 \text{ MPa}$$

$$f_{m,d} = 17.6 \text{ MPa}$$

$$\sigma_{m,d} < f_{m,d} \rightarrow \textbf{Verified}$$

Now we must verify if the joist is able to resist the bending stress imposed by the dead load of the panel:

$$M_{Ed} = \frac{q_{dead,lin} \cdot \gamma_{Q1} \cdot L_{joist}^2}{8} = \frac{0.40 \frac{kN}{m} \cdot 1.3 \cdot (4.5m)^2}{8} = 1.59 \text{ kNm}$$

Considering that dead load and wind load are acting perpendicular with respect to each other, the elastic section moduli differ. The elastic section modulus considering the direction of the dead load is calculated:

$$W_{el} = \frac{H \cdot B^2}{6} = \frac{160mm \cdot (60mm)^2}{6} = 96,000 \text{ mm}^2$$

The design bending stress of the joist subjected to the panel dead loads is the following:

$$\sigma_{m,d} = \frac{M_{Ed} \cdot y}{I} = \frac{M_{Ed}}{W_{el}} = 16.51 \text{ MPa}$$

$$f_{m,d} = 9.6 \text{ MPa}$$

$$\sigma_{m,d} < f_{m,d} \rightarrow \textbf{Not Verified}$$

With the initial geometry, the bending stress is not verified. Further iterations of the panel geometry are therefore necessary to verify the resistance of the joists to bending stress. Regardless, the following calculations will show the procedure of calculating deflection of the first iteration. As introduced, besides the bending moment, deflection must be calculated as well, following the SLU combination. Firstly, the limit is defined, which according to Paragraph 4.4.7. of NTC 2018 is defined according to the type of load. The deflection limits for timber structures are the following:

$$\text{Wind loads: } \delta_{inst,max} = \frac{L}{300}$$

$$\text{Dead loads: } \delta_{dead,max} = \frac{L}{200}$$

This means that for the first iteration the deflection limits are:

$$\text{Wind loads: } \delta_{inst,max} = \frac{L}{300} = \frac{4500mm}{300} = 15.0mm$$

$$\text{Dead loads: } \delta_{dead,max} = \frac{L}{200} = \frac{4500mm}{200} = 22.5mm$$

For a simply supported beam, the design deflection can be calculated as a function of the load, beam length, its geometry (moment of inertia) and the material (elastic modulus) using the following equation:

$$\delta = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I}$$

For deflection the SLS combination is considered, meaning that for deflection induced by wind load the safety partial coefficient considered is 0.8, while for deflection due to dead loads it is 1.0. Additionally, according to NTC 2018 the long-term deformation k_{def} of timber members must be accounted for, depending on the class of use. The coefficient accounts for the increase in deformability over time caused by the combined effect of creep (viscosity), material moisture and its variations.

As it is indicated in the following table, long-term deformation considered refers to Service class 2, defined by conditions where the moisture content of the wood corresponds to a temperature of 20°C and a relative humidity of the surrounding air exceeding 85% only for a few weeks per year. Class service 1 is wood protected in interior environment, while Class 3 is wooden element completely exposed to the exterior environment.

Table 77: Values of k_{def} corrective coefficient for permanent deflection of a timber element.

Tab. 4.4.V -Valori di k_{def} per legno e prodotti strutturali a base di legno

Materiale	Riferimento	Classe di servizio		
		1	2	3
Legno massiccio	UNI EN 14081-1	0,60	0,80	2,00
Legno lamellare incollato *	UNI EN 14080	0,60	0,80	2,00
LVL	UNI EN 14374, UNI EN 14279	0,60	0,80	2,00
Compensato	UNI EN 636:2015	0,80	-	-
		0,80	1,00	-
		0,80	1,00	2,50
Pannelli di scaglie orientate (OSB)	UNI EN 300:2006	OSB/2	2,25	-
		OSB/3 OSB/4	1,50	2,25
Pannello di particelle (truciolare)	UNI EN 312:2010	Parte 4	2,25	-
		Parte 5	2,25	3,00
		Parte 6	1,50	-
		Parte 7	1,50	2,25
Pannello di fibre, pannelli duri	UNI EN 622-2:2005	HB.LA	2,25	-
		HB.HLA1, HB.HLA2	2,25	3,00
Pannello di fibre, pannelli semiduri	UNI EN 622-3:2005	MBH.LA1, MBH.LA2	3,00	-
		MBH.HLS1, MBH.HLS2	3,00	4,00
Pannello di fibra di legno, ottenuto per via secca (MDF)	UNI EN 622-5:2010	MDF.LA	2,25	-
		MDF.HLS	2,25	3,00

Per materiale posto in opera con umidità prossima al punto di saturazione delle fibre, e che possa essere soggetto a essiccazione sotto carico, il valore di k_{def} dovrà, in assenza di idonei provvedimenti, essere aumentato a seguito di opportune valutazioni, sommando ai termini della tabella un valore comunque non inferiore a 2,0.

Per i materiali non compresi nella Tabella si potrà fare riferimento ai pertinenti valori riportati nei riferimenti tecnici di comprovata validità indicati nel Capitolo 12, nel rispetto dei livelli di sicurezza delle presenti norme.

* I valori indicati si possono adottare anche per i pannelli di tavole incollate a strati incrociati, ma limitatamente alle classi di servizio 1 e 2.

Therefore:

$$\delta_{wind} = \frac{5 \cdot q \cdot \gamma_{Qi} \cdot L^4}{384 \cdot E \cdot I} = 14.68mm$$

$$\delta_{dead} = \frac{5 \cdot q \cdot \gamma_{Qi} \cdot L^4}{384 \cdot E \cdot I} \cdot (1 + k_{def}) = 146.17mm$$

$$\delta_{wind} < \delta_{inst,max} \rightarrow \textbf{Verified}$$

$$\delta_{dead} < \delta_{dead,max} \rightarrow \textbf{Not Verified}$$

A sequence of iterations has therefore been performed with different joist geometry and length in order to arrive to a solution that complies with both the bending moment and deflection. Iteration 5 is compliant, as presented in the table below. Based on this joist span, verification of vertical steel studs is performed, i.e. with the distance centers of studs' axes being 3200mm.

Table 78: Iterations with varying joist geometry to verify the resistance to bending stress and non-exceedance of deflection limit.

Iteration	Joist geometry			Bending moment	Deflection
Iteration 1	Joist width	60	mm	Not verified	Not verified
	Joist depth	160	mm		
	Joist length	4500	mm		
Iteration 2	Joist width	60	mm	Not verified	Not verified
	Joist depth	160	mm		
	Joist length	4000	mm		
Iteration 3	Joist width	80	mm	Verified	Not verified
	Joist depth	200	mm		
	Joist length	4000	mm		
Iteration 4	Joist width	80	mm	Verified	Not verified
	Joist depth	200	mm		
	Joist length	3500	mm		
Iteration 5	Joist width	80	mm	Verified	Verified
	Joist depth	200	mm		
	Joist length	3200	mm		

The iteration that yielded the result compliant with both the bending moment and deflection was Iteration 5 as reported in the table above. Bending stress must be verified for both dead loads and wind loads:

Dead loads:

$$\sigma_{m,d} = \frac{M_{Ed} \cdot y}{I} = \frac{M_{Ed}}{W_{el}} = 3.76 \text{ MPa}$$

$$f_{m,d} = 9.6 \text{ MPa}$$

$$\sigma_{m,d} < f_{m,d} \rightarrow \textbf{Verified}$$

Wind loads:

$$\sigma_{m,d} = \frac{M_{Ed} \cdot y}{I} = \frac{M_{Ed}}{W_{el}} = 2.79 \text{ MPa}$$

$$f_{m,d} = 17.6 \text{ MPa}$$

$$\sigma_{m,d} < f_{m,d} \rightarrow \textbf{Verified}$$

However, the final check must be performed for combined biaxial bending, where the sum of the ratios between the calculated bending moment and the resisting bending moment for dead load and wind load, must be less or equal to one:

$$\frac{M_{Ed,wind}}{M_{Rd,wind}} + \frac{M_{Ed,dead}}{M_{Rd,dead}} \leq 1$$

Resisting bending moment is a function of material strength and its elastic section modulus, reduced by a partial coefficient, therefore:

$$M_{Rd,wind} = \frac{W_{el,y} \cdot f_{m,k}}{\gamma_M} = 8.53 \text{ kNm}$$

$$M_{Rd,wind} = \frac{W_{el,z} \cdot f_{m,k}}{\gamma_M} = 3.41 \text{ kNm}$$

$$\frac{M_{Ed,wind}}{M_{Rd,wind}} + \frac{M_{Ed,dead}}{M_{Rd,dead}} = 0.41 \rightarrow \textbf{Verified}$$

5.2.4.4. Bending moment and deformation of the steel frame

Following the structural analysis of the timber frame itself, its main support is the steel structural frame consisting of vertical mullions that is supported on the base to the precast concrete panels with a pinned support, while on the top, the support is a roller attached to the primary perimetral precast beam of the warehouse. Since the timber panels attached at the top also act as a roof parapet, the steel mullions actually extend beyond the roller support, creating a cantilever. Therefore, the first 6.5 meters from the base to the roller support are acting as pin-roller, while the ultimate 1.5 meter act as a cantilever, that being the total height of 8 meters of vertical steel mullions. The following figure illustrates the distribution of influences areas of the mullions:

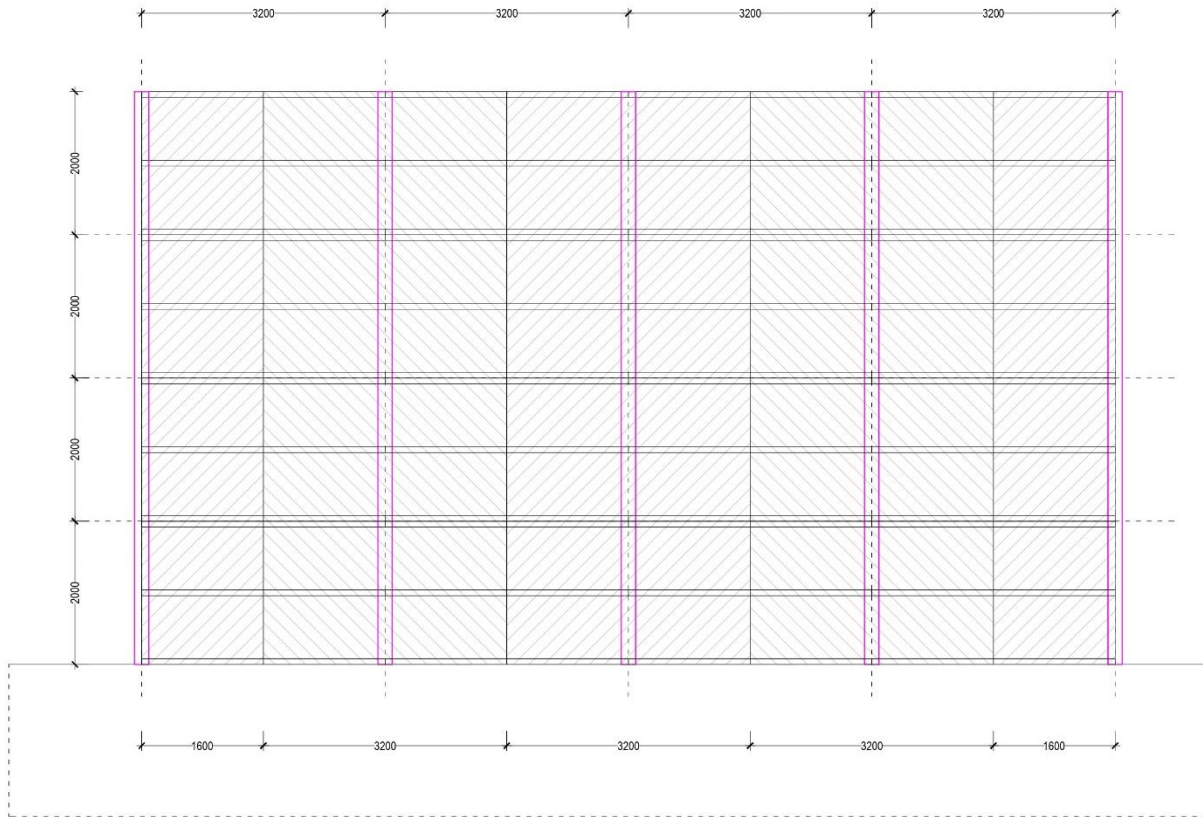


Figure 84: Distribution of influence areas of vertical mullions along the façade perimeter.

For the steel frame, bending moment and axial load must be verified. Bending moment is caused primarily by wind action; however, since the timber frame panels are attached eccentrically to the mullions, we must take into account the eccentric load imposed by the panels onto the mullion. Besides the panels contribution to eccentric bending moment onto the frame, they contribute to axial load that must be verified through the mullions' buckling resistance. Finally, the following check must be verified:

$$\frac{N_{Ed}}{N_{b,Rd}} + \frac{M_{Ed}}{M_{Rd}} \leq 1$$

The static scheme is illustrated in the following figure:

M_y moment around y-axis caused by wind load

M_{ecc} eccentricity moment around y-axis caused by eccentric gravity load

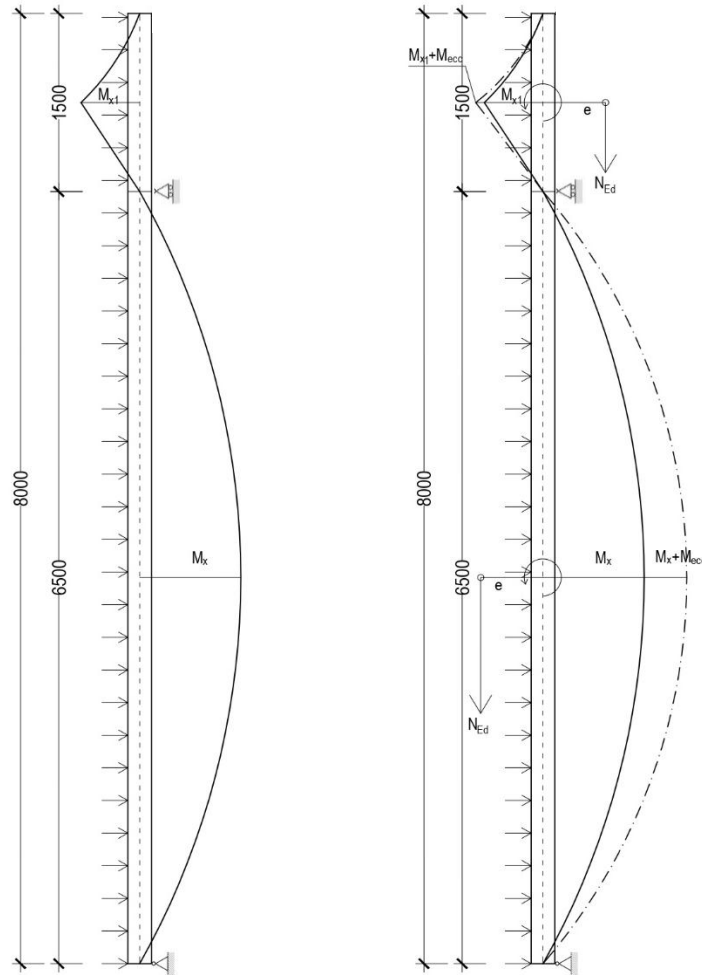


Figure 85: Bending moment diagram of the vertical steel mullion – moment around y-axis and moment due to eccentric load of the façade panels.

Bending moment will differ between the supports and for the cantilever part of the beam. Bending moment between supports is calculated in the following way:

$$M_x = \frac{q_{wind,lin} \cdot \gamma_{Qw} \cdot x}{2 \cdot L} \cdot (L^2 - a^2 - x \cdot L)$$

$$M_x = M_{Ed} = 12.78 \text{ kNm}$$

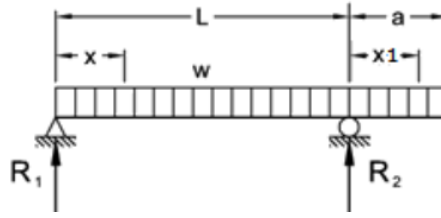


Figure 86: Scheme used for notation of the parameters defining the bending moment equation.

Besides the bending moment induced by the wind, the beam also experiences a bending moment due the weight of the panels that are at an eccentric distance of 20cm offset from the mullion axis, so their vertical load does not act through the centroid of the steel section. This bending moment is calculated as the axial force multiplied by the eccentric distance:

$$M_{ecc} = N_{Ed} \cdot d$$

$$N_{Ed} = N \cdot \gamma_{Qi} = q_{facade} \cdot L_{infl} \cdot L_{height} \cdot n_{panels}$$

$$N_{Ed} = 52.64 \text{ kN}$$

$$M_{ecc} = N_{Ed} \cdot d = 10.53 \text{ kNm}$$

This is a non-negligible bending moment. The final bending moment results in:

$$M_{Ed,fin} = 23.31 \text{ kNm}$$

Bending moment of the overhang:

$$M_{overhang} = M_{x1} + M_{ecc}' = \frac{q_{wind,lin} \cdot \gamma_{Qw}}{2} \cdot (a - x_1)^2 + M_{ecc}'$$

$$M_{overhang} = 3.42 \text{ kNm}$$

This means that the highest bending moment is actually in the middle of the span between the supports. To understand if the frame can resist buckling, the buckling resistance load must be calculated. It is a function of the material strength, mullion section area and the resistance reduction factor, reduced by a partial coefficient:

$$N_{b,Rd} = \frac{f_{m,k} \cdot A_{section} \cdot X}{\gamma_M}$$

The resistance reduction factor X is furthermore a function of the coefficient of reduction Φ considered as 1.26 and non-dimensional slenderness:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}} \leq 1.0$$

$$\bar{\lambda} = \sqrt{\frac{A_{section} \cdot f_{m,k}}{N_{cr}}}$$

Which is the non-dimensional slenderness for steel section classes 1, 2 and 3. Finally, we must find the critical buckling load or the Euler critical load, which itself is a function of the critical length of the stud (considered as fully 8 meters), steel Young's modulus and the section moment of inertia:

$$N_{cr} = \frac{\pi^2 EI}{L_{cr}^2} = 727.47 \text{ kN}$$

Therefore:

$$\bar{\lambda} = \sqrt{\frac{A_{section} \cdot f_{m,k}}{N_{cr}}} = 1.27 \text{ and } X = 0.77$$

Considering the section profile of 180mm x 180mm, the buckling resistance load is calculated:

$$N_{b,Rd} = \frac{f_{m,k} \cdot A_{section} \cdot X}{\gamma_M} = 850.64 \text{ kN}$$

Compliance is therefore verified for the combined action of wind and gravity load of the panels:

$$\frac{N_{Ed}}{N_{b,Rd}} + \frac{M_{Ed}}{M_{Rd}} \leq 1$$

$$\frac{N_{Ed}}{N_{b,Rd}} + \frac{M_{Ed}}{M_{Rd}} = \frac{52.64 \text{ kN}}{850.64 \text{ kN}} + \frac{23.31 \text{ kNm}}{74.15 \text{ kNm}} = 0.38 \rightarrow \textbf{Verified}$$

Finally, the last check to perform is the deflection of the mullions, that is verified in the following way:

$$\delta_{supports} = \frac{qx}{24EIL} \cdot (L^4 - 2L^2x^2 + Lx^3 - 2a^2L^2 + 2a^2x^2)$$

$$\delta_{overhang} = \frac{qx_1}{24EIL} \cdot (4a^2L - L^3 + 6a^2x_1 - 4ax_1^2 + x_1^3)$$

The highest deflection will happen in the middle between the supports:

$$\delta_{supports} = 3.40 \text{ mm}$$

$$\text{Wind loads: } \delta_{inst,max} = \frac{L}{300} = \frac{8000\text{mm}}{300} = 26.67 \text{ mm}$$

$$\delta_{supports} < \delta_{inst,max} \rightarrow \text{Verified}$$

This means that with the following geometrical input, the timber frame envelope system is verified in terms of both bending moment and deflection:

Table 79: Timber frame system geometry.

System	Joist geometry			Bending moment	Deflection
Timber frame	Joist width	80	mm	Verified	Verified
	Joist depth	200	mm		
	Joist length	3200	mm		
Vertical support	Mullions height	8000	mm	Verified	Verified
	Mullions length	180	mm		
	Mullions width	180	mm		
	Distance between axes	3200	mm		

Table 80: Final stratigraphy of a timber frame module after structural analysis.

Timber frame panel, size of one module 3200mm (length) x 2000mm (height)					
Layer no.	Stratigraphy	Thickness per one panel	Unit	End-of-Life treatment, as per EPD	
1	Oriented strand board OSB	19	mm	58% recycled, 25% incinerated and sent for energy recovery, 17% to landfill	
2	Vapor barrier membrane	0.2	mm	Material incineration	
3	Horizontal spruce timber joists	200	mm	Incinerated, used 100% for energy recovery	
4	Vertical spruce timber joists	200	mm	Incinerated, used 100% for energy recovery	
5	Thermal insulation infill	200	mm	TBD	
6	Cement fiber panel FERMACELL	12.5	mm	80% of the material is downcycled, 20% sent to landfill	

Following figures illustrate in the isometric view the positioning of the metal sandwich panels vs. timber frame panels and their attachment onto vertical steel mullions, pinned to the precast concrete panels base.

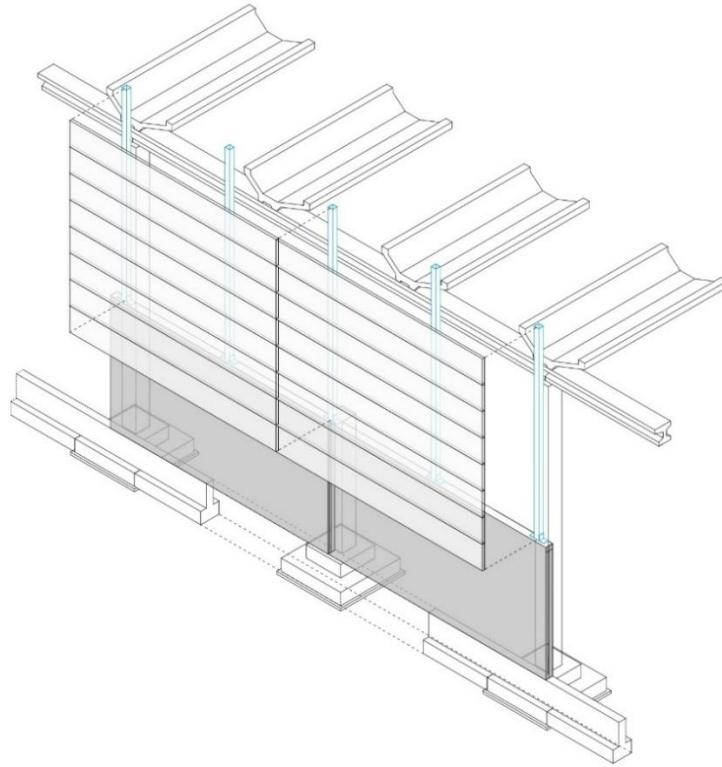


Figure 87: Metal PIR sandwich panels construction system isometry.

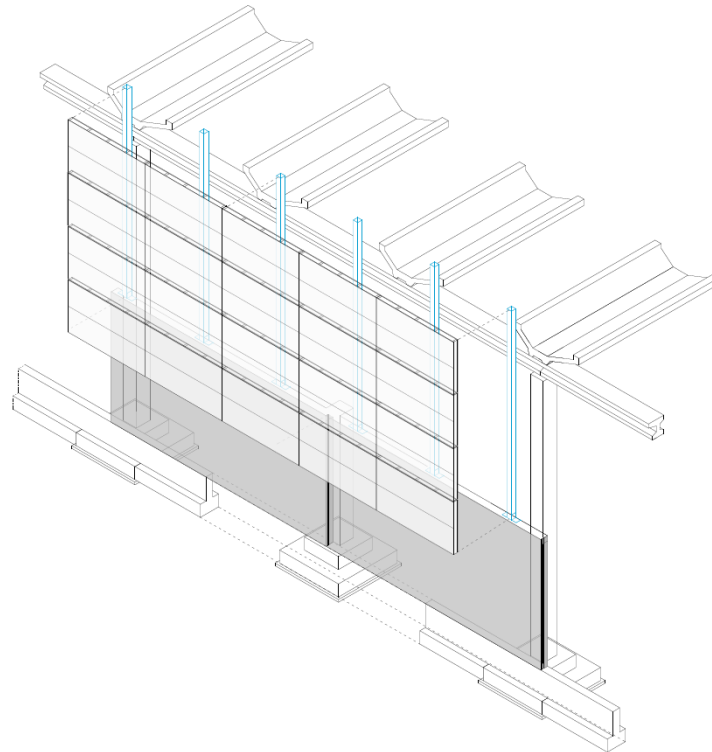


Figure 88: Timber frame panels construction system isometry.

5.2.5. LCA of the envelope solutions

5.2.5.1. Variables of the optimization analysis

Having introduced the envelope types that will be assessed in this analysis, the following paragraphs will show a single-objective optimization of the envelope based on changing properties of certain materials as input variables with the goal of minimizing the GWP. The variables are the following:

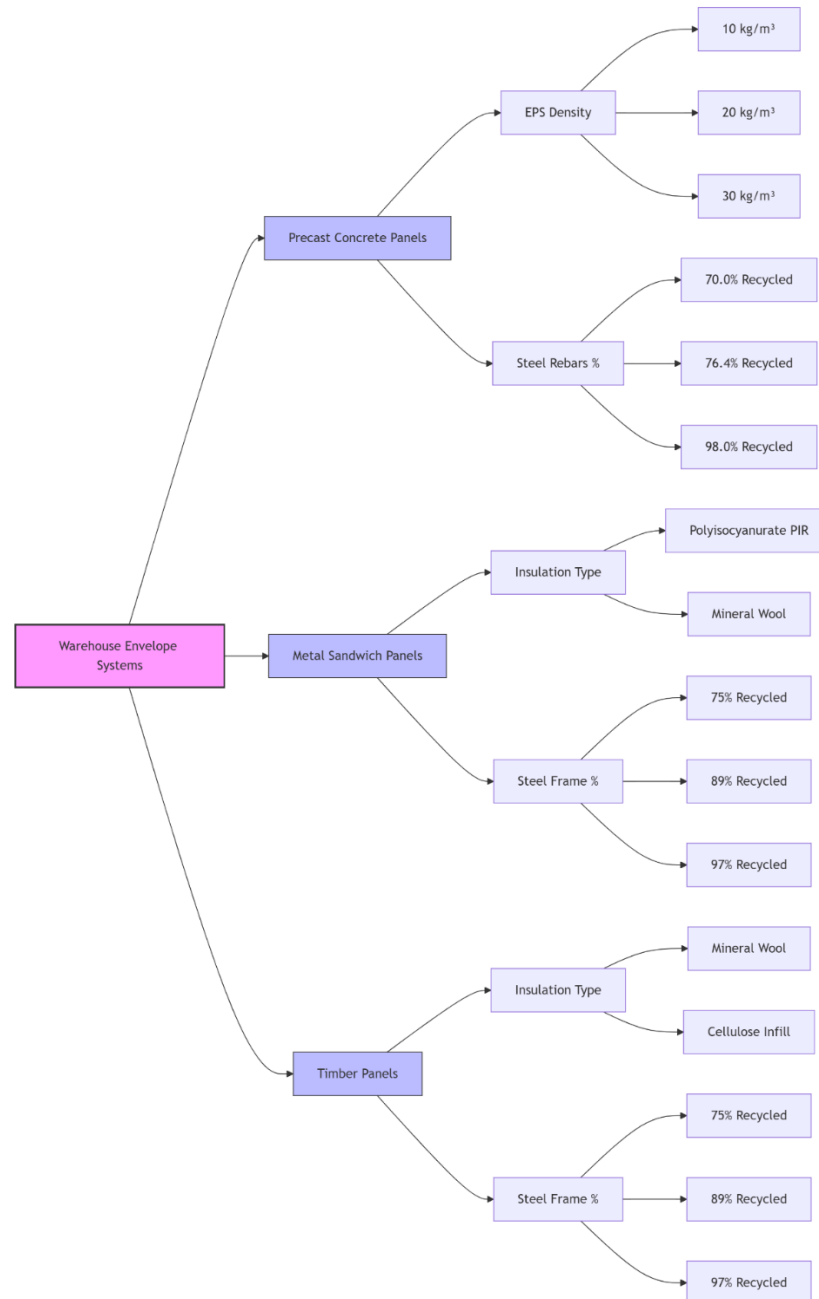


Figure 89: Input variables for optimization of the three envelope solutions.

The selection of the three expanded polystyrene (EPS) products with varying densities (10, 20 and 30 kg/m³) is derived from empirical supplier data utilized in previous projects where precast concrete panels were used. This range allows to evaluate trade-off between structural weight and environmental impact. All three solutions are utilized to lighten the weight of the entire panel and provide a continuous thermal break as well. While these three products are used and verified in practice, it is important to be aware of their advantages and potential risks, as outlined in the following table. The analysis of the results regarding GWP of envelope solutions will have to take into account these inputs.

Table 81: Three variations of EPS applied to precast concrete panels for optimization analysis.

	EPS variation 1	EPS variation 2	EPS variation 3
Density (kg/m³)	10 (Lower)	20 (Medium)	30 (Higher)
Virgin content (%)	100	100	85
Recycled content (%)	0	0	15 (post-consumer)
Primary advantage	Lowest total weight	Standard market balance	Highest compressive strength
Primary risk	Higher fragility	Higher carbon footprint compared to light foam	Higher carbon footprint compared to light foam
Thermal conductivity (W/mK)	0.042	0.043	0.033
End-of-Life (EoL)	Landfill/Incineration	Landfill/Incineration	Recycling/Incineration for energy recovery

The other variable is steel with different percentage of recycled content. As it has already been introduced in the Chapter 5.1.2., the GWP of different steel rebars depends on the recycled content but also on the electricity source, mix and electricity factor used. Evaluation is separated between steel rebars used in the precast concrete panels and steel secondary frame used to support metal panels and timber frame panels.

For steel rebars the following percentages of recycled content are considered: 70.0%, 76.4%, 98%. For the steel secondary frame the percentages are: 75.0%, 89.0%, 97.0%. All of the steel products in the analysis are produced by Electric Arc Furnace (EAF) process.

The EPDs showing 98% and 99% of recycled content of rebars and the frame, respectively, are chosen based on empirical supplier data used in previous projects of logistics halls. The other EPDs showing lower recycled content are chosen from the available OneClickLCA database, in order to provide a range within the analysis, starting from 70%.

Finally, variable for the timber frame panels is the insulation infill. Ultimately two types of infill are evaluated: mineral wool (rockwool) and cellulose infill. The decision was made after assessing different insulation types through their whole life cycle to understand which type of assessed insulation materials shows the lowest impact keeping the same infill thickness of 200mm, which corresponds to the depth of horizontal and vertical joists of the timber frame panel.

Table 82: Thermal conductivity and End-of-Life treatment of different insulation materials.

Insulation material	Thermal conductivity (W/mK)	Density (kg/m ³)	EoL treatment, as per EPD
Mineral (rock) wool	0.035	30	Disposal in a landfill
Glass wool	0.032	30	Inert waste landfill
Natural cork	0.052	165	Disposal in a landfill
Wood fiber	0.038	50	Incineration with energy recovery
Hemp fiber	0.038	75	Take-back system for recycling
Cellulose infill	0.038	30	Incineration with energy recovery

Among the insulation types chosen for the analysis, mineral (rock) wool and glass wool are inorganic-based materials, while natural cork, wood fiber, hemp fiber and cellulose are bio-based (organic-based) materials, derived from renewable biological resources. Since the baseline insulation infill material for the timber frame is mineral wool as shown in the panel stratigraphy, the point of this analysis is to provide an alternative organic-based solution. Structural performance and compression strength is not a constraint as the bearing elements have been verified in the previous chapters, and insulation only serves as infill for non-structural purposes. However, a lighter material is more beneficial indeed because it is able to reduce the overall weight of the timber frame panel. In fact, out of all the six insulation types assessed, natural cork with density of 165 kg/m³ and hemp fiber with 75 kg/m³ would cause the timber joist to have excessive deflection that exceeds the limit that is reported in the chapter of structural verification 5.2.4.3. Regardless, their GWP impact will be shown.

The following diagrams show the LCA of 1m² of the insulation of 160mm thickness in terms of production stage (A1-A3), EoL stage (C1-C4) and net benefits beyond the system boundary (D stage). The transport and construction stage (A4 and A5) and use (B stage) are neglected because the scope of the assessment is to understand environmental impacts of the material itself. These stages are also not reported in the EPDs taken as reference for the insulation types considered.

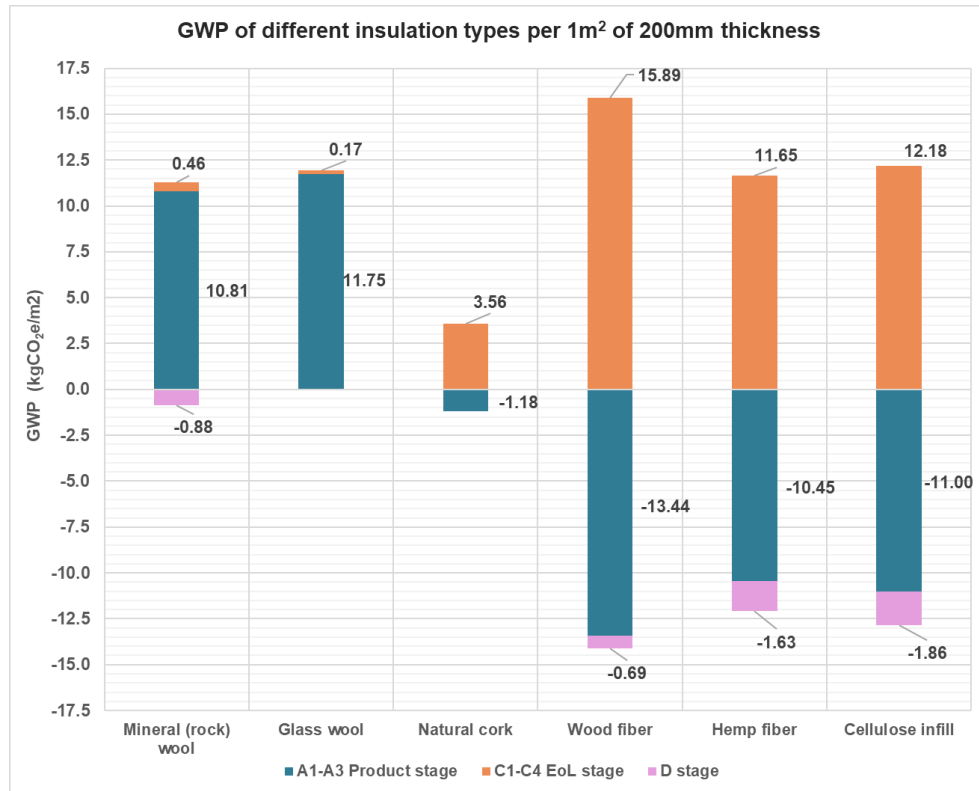


Figure 90: GWP by stages of different insulation types for timber frame panels per 1m² of 200mm thick insulation.

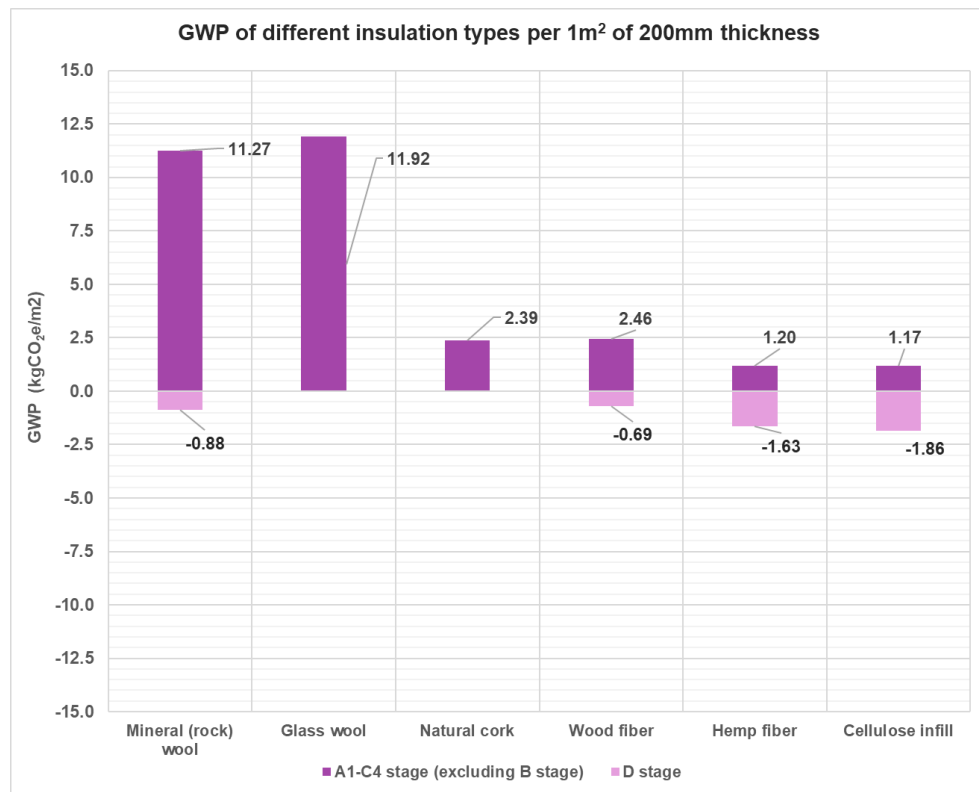


Figure 91: Net GWP of different insulation types for timber frame panels per 1m² of 200mm thick insulation.

The LCA data shows a significant difference between inorganic-based insulations (mineral and glass wool) and bio-based insulations. In the production stage the difference is driven by biogenic carbon sequestration, reflected in the negative values of GWP for bio-based insulations because these materials enter the factory gate with an already negative carbon footprint. Mineral wool and glass wool show positive GWP values in this stage because their manufacturing is energy intensive in order to melt rock and glass. Comparing the four bio-based materials among each other, natural cork differs the most with only -1.18 kgCO₂e in A1-A3 stage compared to wood fiber, hemp fiber and cellulose that show -13.44, -10.45 and -11.00 kgCO₂e of GWP impact, respectively. Natural cork although harvested from the outer bark, requires a production process that involves energy-intensive expansion of cork granules so the process offsets its initial carbon sequestration, which results in a net A1-A3 balance closer to zero compared to the other three insulation types that are mechanically processed, hence the difference is due to the production process.

However, the EoL stage of bio-based insulations is critical for the final balance. For Wood Fiber and Cellulose, the negative GWP in A1-A3 stage is largely neutralized in the C1-C4 stage (15.89 kg and 12.18 kgCO₂e respectively) because incineration for energy recovery releases the stored biogenic carbon back into the atmosphere. Hemp fiber EoL impact is slightly lower, but still non-negligible regardless its EoL treatment which is take-back system¹⁰ for recycling. The carbon previously sequestered within the product is leaving the product system and the carbon balance for the overall life cycle is respected according to EN 15804.

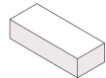
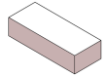
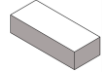
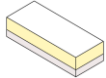
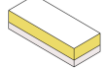
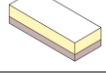
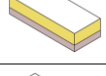
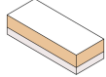
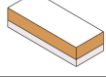
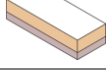
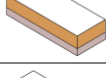
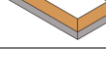
The benefits of insulation materials treatment in its EoL are captured in the D module. Wood fiber shows the lowest benefit, while hemp fiber and cellulose have almost equal benefits. For wood fiber and cellulose, the net benefit out of the system boundary is due to energy recovery after the products' incineration, while hemp fiber is recycled therefore the future product of the next life cycle uses less virgin content. Overall, cellulose shows the best results, both in net sum through Cradle-to-Gate, as well as in the D module. This result aligns with the research of Cascione et al. (2025) [81] who show in their research covering all of the assessed insulations here, that cellulose shows the lowest GWP impact. Therefore, it was decided that for the timber envelope, for one solution an inorganic mineral wool insulation will be considered, and for the other solution the best-performing bio-based cellulose infill insulation.

5.2.5.2. Results of the LCA

Having introduced all the variables within the three main envelope systems, their combinations have been created. As introduced, the solutions that include metal panels and timber frame panels are designed in combination with precast concrete panels. Finally, a combinatorial analysis was used to generate 117 distinct permutations. The solutions assessed are the following:

¹⁰ Take-back system for recycling is a circular economy strategy where the manufacturer or supplier assumes responsibility for a product at the end of its life, physically collecting it separately from other construction waste to recycle or repurpose it.

Table 83: List of envelope solutions and number of permutations analyzed.

Envelope type	Notation	Solution	Symbol
Fully precast concrete envelope	Precast panel 1	Fully precast facade with higher density EPS, 3 variations of recycled rebars	
	Precast panel 2	Fully precast facade with medium density EPS, 3 variations of recycled rebars	
	Precast panel 3	Fully precast facade with lower density EPS, 3 variations of recycled rebars	
	Number of combinations: 9		
Metal sandwich panels combined with precast concrete panels	Metal panel 1, Precast panel 1	Metal panels with PIR foam, 3 variations of recycled steel frame + Precast panels with lower density EPS, 3 variations of recycled rebars	
	Metal panel 2, Precast panel 1	Metal panels with PIR foam, 3 variations of recycled steel frame + Precast panels with medium density EPS, 3 variations of recycled rebars	
	Metal panel 1, Precast panel 2	Metal panels with PIR foam, 3 variations of recycled steel frame + Precast panels with higher density EPS, 3 variations of recycled rebars	
	Metal panel 2, Precast panel 2	Metal panels with mineral wool, 3 variations of recycled steel frame + Precast panels with lower density EPS, 3 variations of recycled rebars	
	Metal panel 1, Precast panel 3	Metal panels with mineral wool, 3 variations of recycled steel frame + Precast panels with medium density EPS, 3 variations of recycled rebars	
	Metal panel 2, Precast panel 3	Metal panels with mineral wool, 3 variations of recycled steel frame + Precast panels with higher density EPS, 3 variations of recycled rebars	
	Number of combinations: 54		
Timber frame panels combined with precast concrete panels	Timber panel 1, Precast panel 1	Timber panels with mineral wool, 3 variations of recycled steel frame + Precast panels with lower density EPS, 3 variations of recycled rebars	
	Timber panel 2, Precast panel 1	Timber panels with mineral wool, 3 variations of recycled steel frame + Precast panels with medium density EPS, 3 variations of recycled rebars	
	Timber panel 1, Precast panel 2	Timber panels with mineral wool, 3 variations of recycled steel frame + Precast panels with higher density EPS, 3 variations of recycled rebars	
	Timber panel 2, Precast panel 2	Timber panels with cellulose infill, 3 variations of recycled steel frame + Precast panels with lower density EPS, 3 variations of recycled rebars	
	Timber panel 1, Precast panel 3	Timber panels with cellulose infill, 3 variations of recycled steel frame + Precast panels with medium density EPS, 3 variations of recycled rebars	
	Timber panel 2, Precast panel 3	Timber panels with cellulose infill, 3 variations of recycled steel frame + Precast panels with higher density EPS, 3 variations of recycled rebars	
	Number of combinations: 54		
Total no. of combinations: 117			

The output of the analysis is a comparison front showing the total GWP impacts taking into account all stages from A1 to C4 (Cradle-to-Grave approach) on the x-axis and the total GWP impacts including the D stage showing additional benefits outside of the system boundary (Cradle-to-Cradle approach) on the y-axis. Therefore:

- x-axis: Cradle-to-Grave A1-C4 impacts
- y-axis: Cradle-to-Cradle A1-D impacts

As stated in the Chapter 2 explaining the methodology of the study, only Cradle-to-Grave impacts are accounted on the building level, therefore the same will apply to this analysis. Regardless, the purpose of this analysis is to not only compare how each solution performs in terms of total life cycle but also how much the results change when we account for the D module and what it means for the building considering that a solution with stored biogenic carbon is proposed. Two scenarios will be reported:

- 1st scenario: all the solutions are durable as the service life of the building (50 years);
- 2nd scenario: 1 replacement of the timber and metal panels during the building service life.

The baseline GWP impact of the envelope solution in precast concrete panels reported in the Chapter 4.1. is **859,120 kgCO₂e**, or that being in total 4.33% of embodied impacts among all the building materials. This solution belongs to the solution named „Precast panel 2“, which is the combination with medium density EPS and 70% of pre- and post-consumer recycled steel rebars. The concrete mix is made with CEM II/A-LL. Among 117 assessed solutions, considering the total GWP of the Cradle-to-Grave (CtG) approach, the baseline is ranked as 95th, while considering the Cradle-to-Cradle (CtC) approach, it is ranked as 88th best solution. The following diagrams report the results of the analysis for all the solutions:

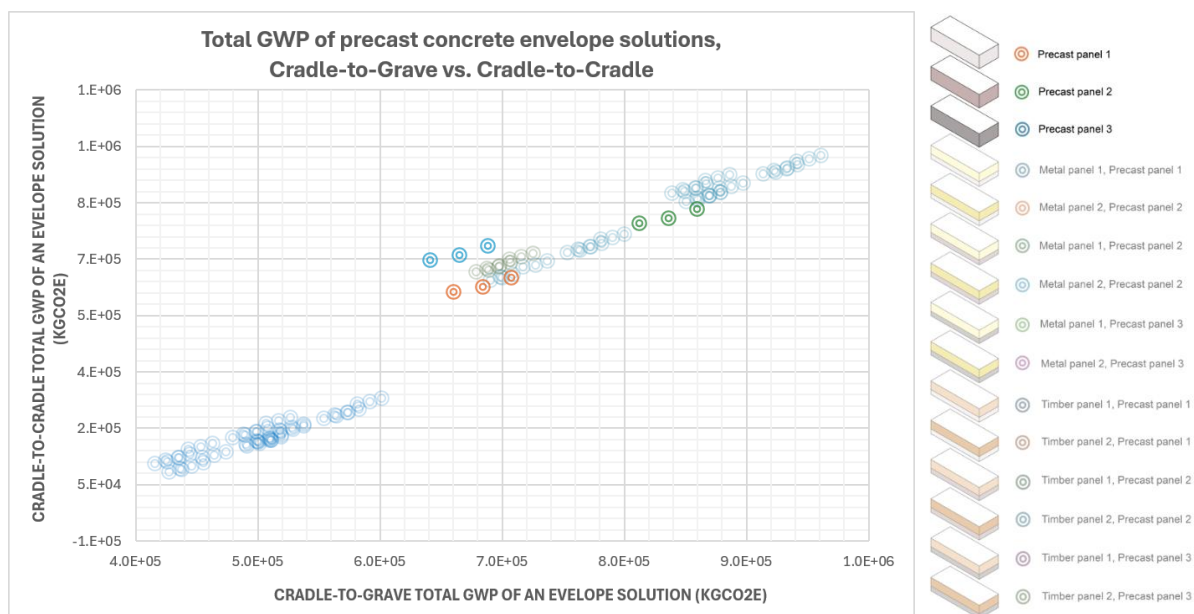


Figure 92: Cradle-to-Grave vs. Cradle-to-Cradle GWP of precast concrete envelope solutions, no envelope replacement stage included.

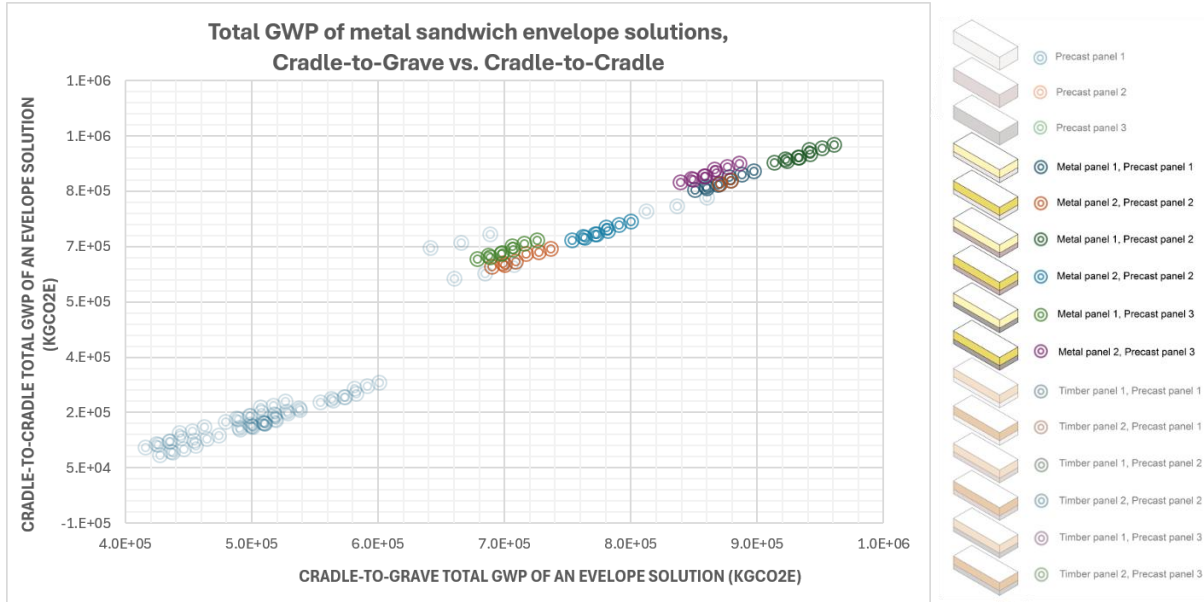


Figure 93: Cradle-to-Grave vs. Cradle-to-Cradle GWP of metal sandwich envelope solutions, no envelope replacement stage included.

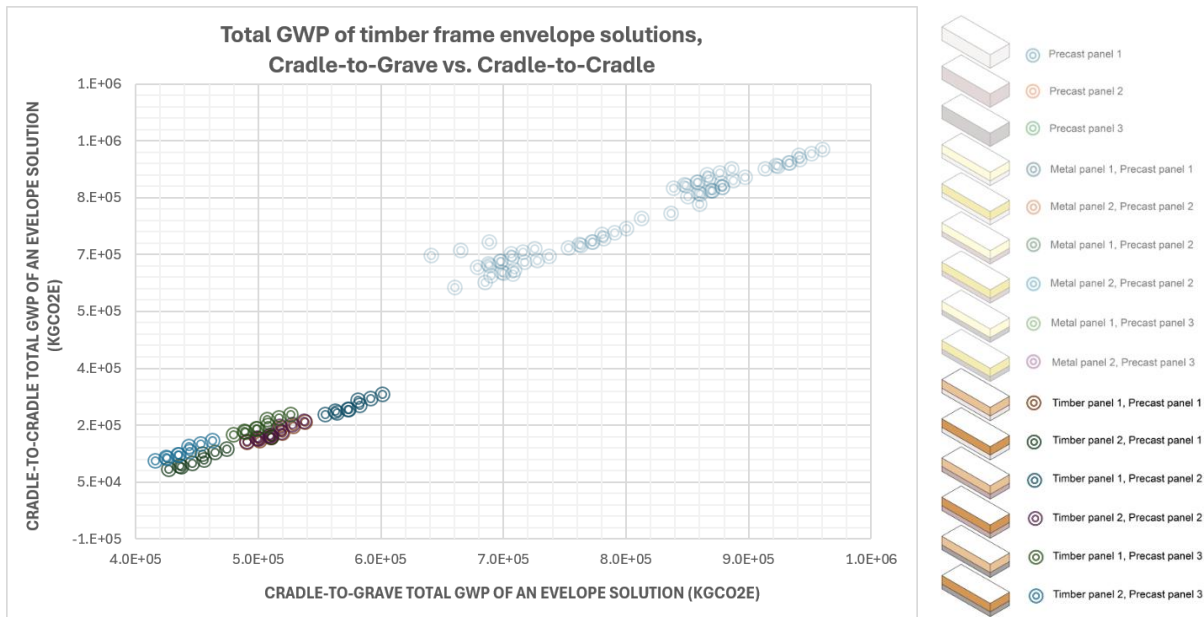


Figure 94: Cradle-to-Grave vs. Cradle-to-Cradle GWP of timber frame envelope solutions, no envelope replacement stage included.

Out of the 9 solutions for precast concrete panels, panel 3 with lower EPS density shows the best result in CtG impact and panel 1 with higher density in CtC impact. The best results are achieved with the highest percentage of recycled steel. Panels with EPS density of 20 kg/m³ show worse results than EPS of 10 kg/m³ the percentage of virgin content being equal for both, that being 100% of virgin content. However, it is interesting that 30 kg/m³ EPS performs better than 20 kg/m³ EPS with highest difference observed in A1-A3 stage where higher density EPS has around 32%

less impact than the medium one (55,000 kgCO₂e in the whole facade vs. 80,500 kgCO₂e, respectively). This impact is result of the fact that this EPS has 15% non-virgin content that reduces its A1-A3 impact. The lowest density EPS although having 100% virgin content still performs the best, the result of 32,000 kgCO₂e being attributed to its density. The lowest impacting solution of precast panels is in fact the solution with lowest EPS density and highest recycled content of rebars (Precast panel 1), in total 640,809 kgCO₂e for the whole envelope, corresponding to 46.18 kgCO₂e/m² of the envelope.

D module also shows interesting differences. The CtC impact shows that the panels with the highest density EPS are rewarded the most, considering that the percentage of the material that is not recycled is incinerated but the waste is used for energy recovery, unlike the other two solutions that are incinerated in the landfill without the energy recovery. Therefore, the lowest impacting solution is indeed the one with highest density EPS (Precast panel 3) due to its net benefits for the next life cycle, the impact being in total 556,677 kgCO₂e or 40.59 kgCO₂e/m² of the envelope.

When it comes to metal sandwich panels, the general trend shows that the majority of the poorest performing solutions among all the assessed ones actually belong to solutions with metal panels. The highest impacts among metal sandwich panels are the ones using polyisocyanurate foam as insulation, with the precast concrete base panel filled with medium EPS density. The poorest performing set of solutions is „Metal panel 1, Precast panel 2“, where the highest impact is the solution with also the lowest recycled content of vertical steel mullions. The highest impact solution results in 960,257 kgCO₂e or 69.21 kgCO₂e/m² of the envelope. On the other hand, the best set of solutions is „Metal panel 2, Precast panel 3“ which is a solution with mineral wool inside of the sandwich panel and lowest density EPS of the concrete panels. The best solution has also highest content of recycled steel, whose total impact is 678,363 kgCO₂e or 48.89 kgCO₂e/m² of the envelope. This solution performs better than some with a full precast concrete coverage, such as the ones using medium density EPS.

Timber panels solutions show a great variation of results, due to the difference of impact in mineral wool insulation and cellulose infill. In total, mineral wool emits around 61,000 kgCO₂e in the whole facade for A1-A3 stage with low EoL impacts (3.8%), while cellulose infill has a positive impact in the production stage with -62,000 kgCO₂e, which is then compensated in incineration scenario for EoL (around 67,000 kgCO₂e), but still the net total is significantly lower than mineral wool. Therefore, generally the two best set of solutions are „Timber panel 2, Precast panel 3“ and „Timber panel 2, Precast panel 1“. In terms of total GWP impact considering both CtG and CtC approach, envelope solutions with timber panels show the best results among all assessed scenarios. The absolute best performing scenario is a timber panel with cellulose infill with a concrete panel base with EPS of lower density and highly recycled steel. The following tables report the least impacting solutions.

Table 84: Top 5 least impacting solutions in terms of GWP based on the whole life cycle A1-C4 (Cradle-to-Grave).

Least impacting solutions based on the whole life cycle A1-C4 (Cradle-to-Grave)							
Ranking no.	Envelope type	Variable parameters				Total GWP (kgCO ₂ e)	GWP per envelope surface area (kgCO ₂ e/m ²)
		Insulation type	% of recycled steel frame	% of recycled rebars	Density of EPS (kg/m ³)		
1	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	10	415,563.9	30.0
2	Timber frame envelope with precast concrete base	Cellulose	89.0	98.0	10	424,322.9	30.6
3	Timber frame envelope with precast concrete base	Cellulose	97.0	76.4	10	425,600.4	30.7
4	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	30	426,955.7	30.8
5	Timber frame envelope with precast concrete base	Cellulose	89.0	76.4	10	434,359.3	31.3
55	Fully precast concrete envelope	EPS	-	98.0	10	640,809.8	46.2

Table 85: Top 5 least impacting solutions in terms of GWP based on the whole life cycle A1-D (Cradle-to-Cradle).

Least impacting solutions based on the whole life cycle A1-D (Cradle-to-Cradle)							
Ranking no.	Envelope type	Variable parameters				Total GWP (kgCO ₂ e)	GWP per envelope surface area (kgCO ₂ e/m ²)
		Insulation type	% of recycled steel frame	% of recycled rebars	Density of EPS (kg/m ³)		
1	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	30	85,683.3	6.2
2	Timber frame envelope with precast concrete base	Cellulose	97.0	76.4	30	91,344.5	6.6
3	Timber frame envelope with precast concrete base	Cellulose	89.0	98	30	94,860.4	6.8
4	Timber frame envelope with precast concrete base	Cellulose	89.0	76.4	30	100,488.5	7.2
5	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	10	107,324.2	7.7
55	Fully precast concrete envelope	EPS	-	98.0	30	563,262.3	40.6

It is interesting to compare the best solution between CtG and CtC approach, because it shows the importance of the positive impact that is obtained through the D module. In the CtC scenario, the best solution shows total impact of 85,683.3 kgCO₂e or 6.2 kgCO₂e/m². In the CtG scenario, this solution (Ranking no. 4) showed 426,955.7 kgCO₂e. The total positive D-stage impact of the best solution compared to CtG stage is therefore around -341,000 kgCO₂e of difference, out of which timber panel members contribute 86%, in particular spruce wood, OSB and cellulose insulation. The rest comes from the EPS, recycled steel and recycled concrete aggregates. The EPS panels of higher density according to their EPDs are also more rewarded than the ones of

the lower density, therefore the best solution when the D-stage is included is the solution with EPS panels of 30 kg/m³ and not 10 kg/m³ like in the CtG scenario, with the amount of recycled steel being the same. In conclusion, solutions with timber panels show the lowest GWP in both approaches.

So far the performed analysis considers that all three type of panels are suitable for 50-year durability, the same period as the building's reference service life (RSL). However, to not consider the materials durability is to not give the full picture of possible impacts due to replacements after a certain period of time.

Although all of the EPDs used to perform the LCA of all materials composing the three envelope types report the reference service life of minimum 50 years, this information coming from the producers directly assumes perfect execution, without any unforeseen moisture infiltration, or any material failure or mechanical damage.

In particular, metal sandwich panels and timber panels could be more susceptible to durability risks due to weather events, because finishings of these panels are not covered by reinforced concrete, as is the case with precast concrete panels. These high-mass panels are designed for the particular exposure class of the location, with its dense exterior reinforced concrete surface providing protection from degradation. The other two solutions are lightweight and multi-layered assemblies and are therefore under a higher risk of a degrading hygrothermal performance over time. These systems lack the thermal mass to drive out the moisture, so the panels therefore experience accelerated ageing and degradation over time [82], [83] and the existing research confirms that the service life is in fact lower than 50 years [84], [82] although the vapor barrier EPD states an RSL of 50 years, even a minor defect and mechanical ageing in this layer can lead to undesired moisture accumulation.

For these reasons, this study will include a secondary „Replacement scenario“ for metal and timber panels, with the total of 1 replacement during the building service life. This scenario considers the complete replacement of these panels, as the „worst-case“ scenario. The replacement scenario is calculated in the following way for the CtG approach:

$$B4_{envelope} = \sum C1 \text{ to } C4_{old \text{ panels}} + \sum A1 \text{ to } C4_{new \text{ panels}}$$

For the CtC approach, the B4 stage adds the impacts/benefits of the D module:

$$B4_{envelope} = \sum C1 \text{ to } C4_{old \text{ panels}} + D_{old \text{ panels}} + \sum A1 \text{ to } C4_{new \text{ panels}} + D_{new \text{ panels}}$$

Therefore, the B4 Replacement module of LCA for one replacement of 100% of surface area of metal and timber panels within 50 years includes:

1. Disassembly of the panels, transport to the waste treatment facility, waste treatment and final waste disposal – i.e. the C1-C4 module of the existing panels that reached their EoL;
2. Raw materials extraction, transport to the factory, production and fabrication of the new, substituting panels, their transport to the construction site, installation on site;
3. The C1-C4 module of the substituting panels that will be disposed of as the building reaches its end of life.

The results are the following:

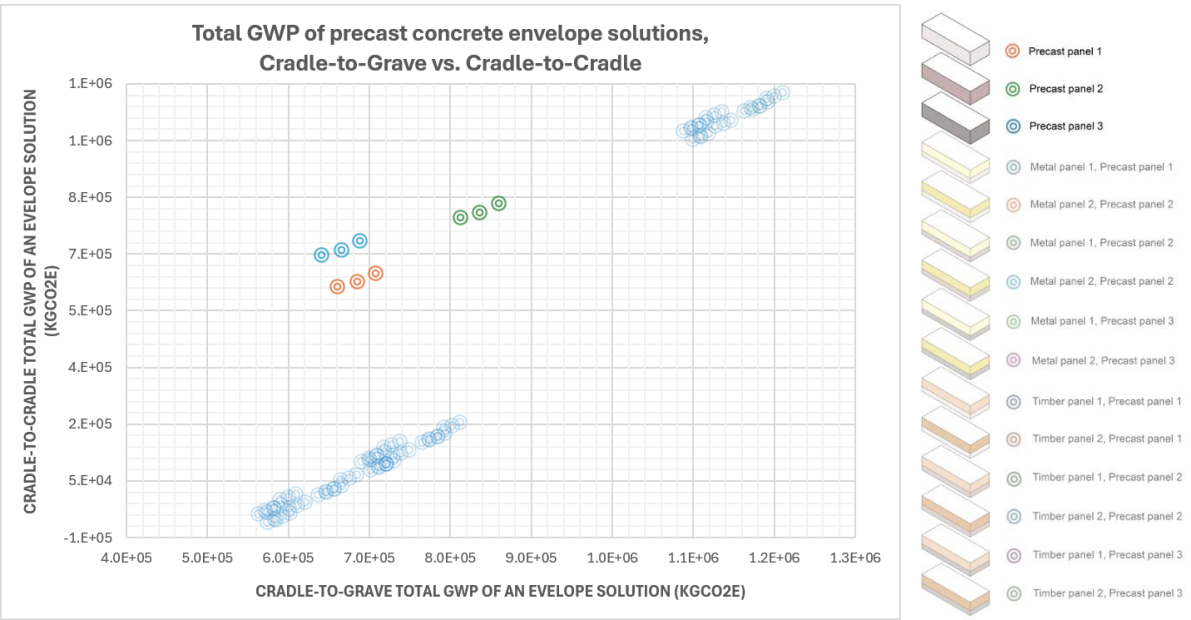


Figure 95: Cradle-to-Grave vs. Cradle-to-Cradle GWP of precast concrete envelope solutions, replacement scenario included.

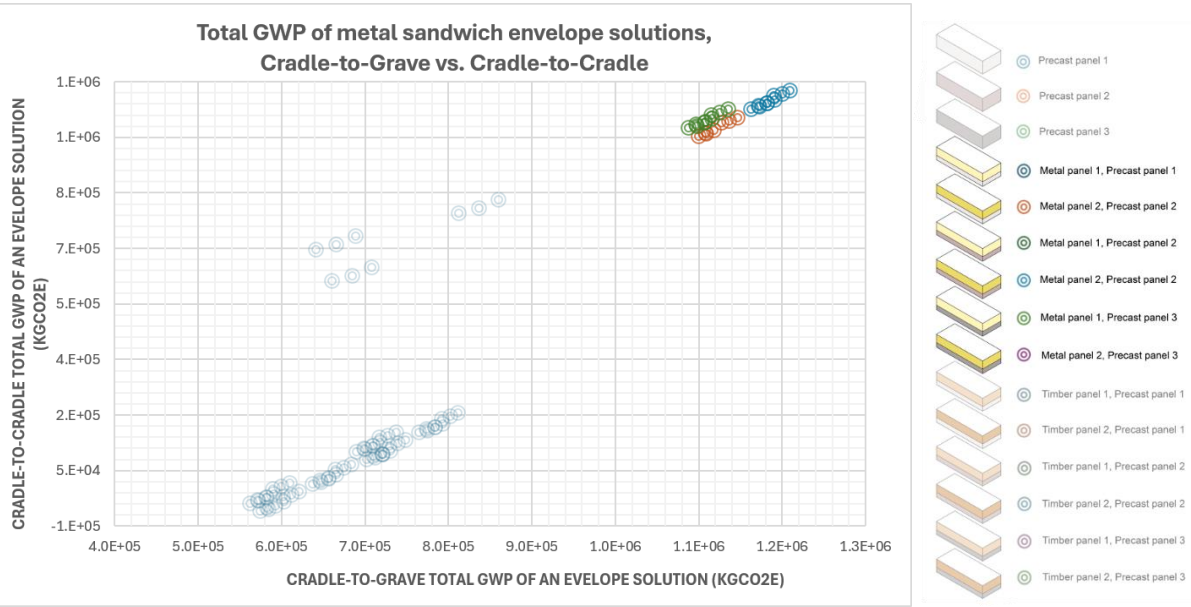


Figure 96: Cradle-to-Grave vs. Cradle-to-Cradle GWP of metal sandwich envelope solutions, replacement scenario included.

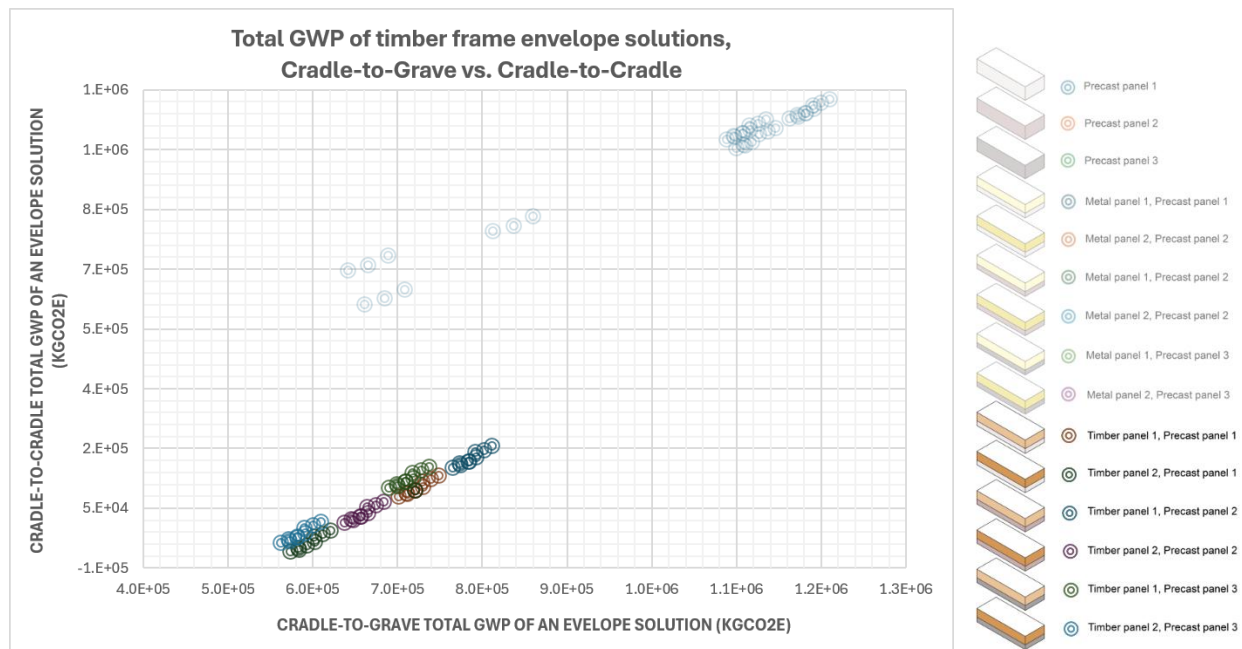


Figure 97: Cradle-to-Grave vs. Cradle-to-Cradle GWP of timber frame envelope solutions, replacement scenario included.

Analyzing the results of the Replacement scenario, the division gaps between distinct envelope solutions are visible. The trend shows that in terms of CtG approach, timber frame envelope solutions show again the best results, regardless the additional impact of replacing timber panels that contributes to their total impact being higher. It is interesting that the best performing concrete solution is somewhere among the timber frame solutions (being 19th best solution overall in the CtG scenario, while in total there are 54 timber frame solutions). This emphasizes the importance of recycled content of steel and type of insulation inside the timber panels. On the other hand, metal sandwich panels consistently show the highest GWP in both CtG and CtC scenarios.

Taking a look at the total GWP of the CtC scenario, we observe a clear distinction: all timber panel solutions perform better than the any concrete panel solution. The impact of D module is clearly shown in the Replacement scenario because on one hand, including inside the final results the possible benefits of energy recovery from incineration of spruce wood, OSB and bio-based insulation helps significantly reduce the GWP and make a strong case for implementation of timber panels even if they have to be replaced once during the building's service life.

As it is reported in the tables below, the best solution of the Replacement scenario of CtC scenario is therefore significantly different than the best solution of the CtG scenario, with the impacts being -58,259.0 kgCO₂e (-4.2 kgCO₂e/m² of envelope) and 561,956.8 kgCO₂e (40.5 kgCO₂e/m² of envelope), respectively. This shows the potential that strategies such as energy recovery coming from incineration can bring to the total results of the GWP and importance of thinking long-term about the future life of a product even when its own life comes to completion, i.e. the potential that including the D-stage holds in the materials' life cycle assessment.

Table 86: Top 5 least impacting solutions in terms of GWP based on the whole life cycle A1-C4 (Cradle-to-Grave), including the replacement stage.

Least impacting solutions based on the whole life cycle A1-C4 (Cradle-to-Grave)							
Ranking no.	Envelope type	Variable parameters				Total GWP (kgCO ₂ e)	GWP per envelope surface area (kgCO ₂ e/m ²)
		Insulation type	% of recycled steel frame	% of recycled rebars	Density of EPS (kg/m ³)		
1	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	10	561,956.8	40.5
2	Timber frame envelope with precast concrete base	Cellulose	89.0	98.0	10	570,714.9	41.1
3	Timber frame envelope with precast concrete base	Cellulose	97.0	76.4	10	571,992.5	41.2
4	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	30	573,347.8	41.3
5	Timber frame envelope with precast concrete base	Cellulose	89.0	76.4	10	580,751.4	41.9
19	Fully precast concrete envelope	EPS	-	98.0	10	640,809.8	46.2

Table 87: Top 5 least impacting solutions in terms of GWP based on the whole life cycle A1-D (Cradle-to-Cradle), including the replacement stage.

Least impacting solutions based on the whole life cycle A1-D (Cradle-to-Cradle)							
Ranking no.	Envelope type	Variable parameters				Total GWP (kgCO ₂ e)	GWP per envelope surface area (kgCO ₂ e/m ²)
		Insulation type	% of recycled steel frame	% of recycled rebars	Density of EPS (kg/m ³)		
1	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	30	-58,259.0	-4.2
2	Timber frame envelope with precast concrete base	Cellulose	97.0	76.4	30	-52,468.6	-3.8
3	Timber frame envelope with precast concrete base	Cellulose	89.0	98.0	30	-48,919.7	-3.5
4	Timber frame envelope with precast concrete base	Cellulose	89.0	76.4	30	-43,291.5	-3.1
5	Timber frame envelope with precast concrete base	Cellulose	97.0	98.0	10	-36,455.9	-2.6
55	Fully precast concrete envelope	EPS	-	98.0	30	563,262.3	40.6

Regardless of the great potential that the timber solutions give for reduction of the GWP even if they have to be replaced, to be consistent with methodology of the study and with assessment of other building parts, the best solution will be considered as the one that has the lowest impact in the Replacement scenario following the CtG approach (i.e. excluding the D module).

However, inclusion of D module in this analysis gives us a great insight on how bio-based materials that store biogenic carbon have a non-negligible potential to contribute to circular economy and strengthen the design with intention, completely aligning with DfD approach. It is

important, however, to acknowledge the uncertainty associated with the assumptions underlying module D, specifically regarding future reuse, recycling and pathways of energy recovery, as well as the extents to which these processes may effectively substitute primary production in subsequent product systems in the next life cycle.

As these benefits depend on long-term scenarios that are difficult to predict, as underlined in the Methodology section, the best envelope solution excluding the D module is a timber frame envelope solution with the total impact of 561,956.8 kgCO₂e (40.5 kgCO₂e/m² of envelope). Compared to the baseline that has the impact of 859,592 kgCO₂e (61.9 kgCO₂e/m² of envelope), the reduction of total GWP achieved for the vertical building envelope is 34.66%. Compared the best precast concrete solution which reports 640,809.8 kgCO₂e (46.2 kgCO₂e/m² of envelope), this is an improvement of 12.33%.

5.2.5.3. Contributions to GWP of single materials within the envelope

Besides the overall results showing which envelope system impacts the environment the least in terms of the GWP, it is also interesting to analyze a breakdown of single materials in terms of their total impact through Cradle-to-Grave. In the fully precast envelope system, the concrete alone contributes to about 72% of total GWP although it contributes to only about 38% of the volume of a thermally insulated panel. The second biggest contribution is due to EPS panels with almost 20% of contribution, that take about 60% of the volume.

In terms of timber panels, cellulose insulation infill represents 60% of the volume of one timber panel with 3.2m in length, 2m of height and 0.2m depth of insulation, which means the highest contribution in terms of volume, but significantly less GWP impact, as seen from the table below. Its 17,984.1 kgCO₂e is 42% less than impact of vapor barrier (31,864.3 kgCO₂e) that contributes to less than 0.2% of the panels volume. Non-negligible impact is also reported for cement fiber board that with its only 6.3% of volume contribution actually has more impact on GWP than all the timber joists combined.

When it comes to wood-based materials, OSB board has almost the same impact that timber joists have, although OSB is only around 10% of volume of the panel, while timber joists represent 28% of the volume. Expanding the impacts comparison from just timber panels to the whole assembly with precast base included, it is interesting to observe that the cumulative impact of spruce joists and cellulose infill represents less than 15% of GWP contribution of the entire facade assembly, although the volume contribution to the whole assembly is 46.52%. This means that although the cellulose and spruce used over the whole envelope represents a significant amount, i.e. almost half of the volume, their cumulative carbon footprint does not even reach one-fifth of the impacts compared to other envelope materials, such as concrete that with less than 20% of contribution to the volume actually shows 26.6% of GWP impact.

Table 88: Percentage of contribution to the GWP of single materials within the three envelope systems.

Envelope system	Material	Cradle-to-Grave GWP (kgCO _{2e})	% of material contribution to GWP
Fully precast panels	CLS 30 CEM II/A-LL 42,5 R	463,579.9	72.3%
	Steel rebars	50,397.7	7.9%
	EPS polystyrene insulation	126,832.2	19.8%
	Total	640,809.8	100.0%
Timber frame system	OSB board	52,753.9	9.7%
	Vapor barrier	31,864.3	5.9%
	Spruce - vertical joists	30,124.5	5.6%
	Spruce - horizontal joists	29,638.8	5.5%
	Cellulose infill	17,984.1	3.3%
	Cement fiber board	90,170.7	16.7%
	Steel connections	32,501.5	6.0%
	Vertical steel studs	64,802.7	12.0%
	CLS 30 CEM II/A-LL 42,5 R	143,958.0	26.6%
	Steel rebars	15,985.2	3.0%
	EPS polystyrene insulation	31,763.6	5.9%
	Total	561,956.0	100.0%
Metal sandwich system	Rock wool panel	822,363.1	75.6%
	Vertical steel studs	66,973.4	6.2%
	CLS 30 CEM II/A-LL 42,5 R	146,128.7	13.4%
	Steel rebars	18,155.9	1.7%
	EPS polystyrene insulation	33,934.3	3.1%
	Total	1,087,555.4	100.0%

The breakdown of materials impact can also be summarized in terms of contribution of the whole envelope systems that the warehouse envelope is composed of:

Table 89: Breakdown of the contribution of timber and metal sandwich panels vs. the precast concrete panels of the three envelope systems.

Envelope system	Material	Cradle-to-Grave GWP (kgCO _{2e})	% of material contribution to GWP
Fully precast panels	Fully precast concrete envelope	640,809.8	100%
	Total	640,809.8	100%
Timber frame system	Timber frame part of the envelope	349,840.5	63%
	Precast concrete base	191,706.8	37%
	Total	561,547.4	100%
Metal sandwich system	Sandwich panels part of the envelope	822,363.1	76%
	Precast concrete base	191,706.8	18%
	Total	1,087,555.4	100%

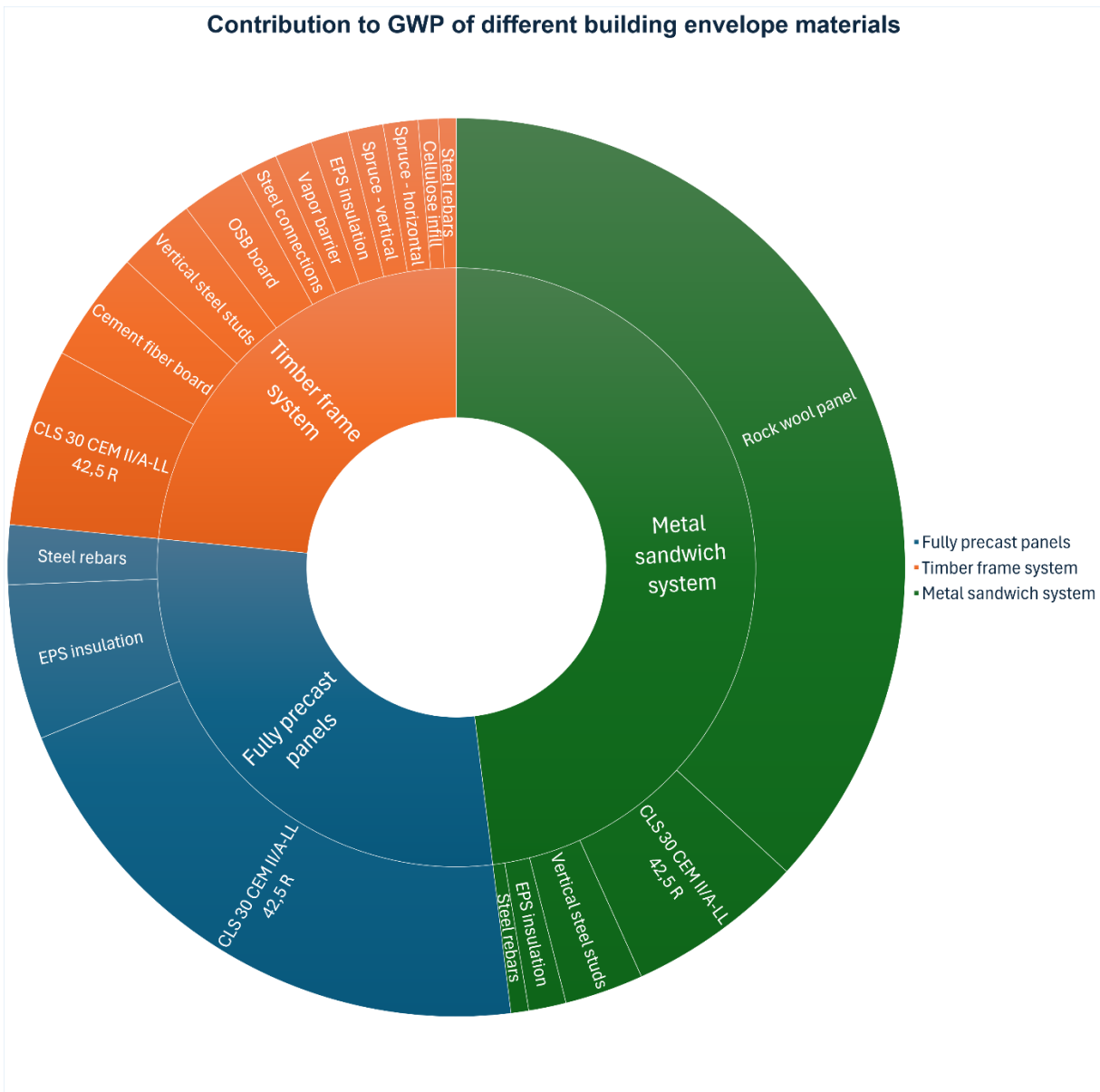


Figure 98: Contribution to GWP of different building envelope materials of the three analyzed envelope systems.

As discussed, the best result in terms of environmental impact for Cradle-to-Grave life cycle including the replacement stage is reported for a timber frame envelope system. In this system, 63% of the GWP impact comes from the timber frame envelope that contributes to 61% of the whole warehouse envelope surface area. The rest of the impact (37%) comes from the precast concrete panels base contributing to 39% of the surface area. Considering the materials' contributions breakdown of timber frame panels alone, we can understand that there are certain materials that disproportionately impact the environment compared to their actual volume content inside of the panel, such as a vapor barrier and cement fiber board. While both are essential parts

of this frame system to regulate moisture and condensation risk, possible substitution of these materials can be considered with less impacting alternatives. However, in case of an alternative solution, a careful consideration should be given to the durability and weather performance of these materials, especially the exterior protection of the facade. On the other hand, the disproportionate carbon footprints of materials compared to the actual volume they take up in the envelope assembly shows us the benefit of using biogenic materials such as spruce for joists and biogenic insulation materials like cellulose, which becomes even more relevant when there is a replacement scenario that must be considered, such as in this case.

5.3. Operational carbon optimization

Decarbonization of the industrial sector is an increasingly discussed topic and there is no one single answer to what is the best approach according to the typology of the warehouse building, although recent research papers are starting to propose a more structured classification framework to tackle the question of the life cycle assessment of a warehouse, as has been discussed in the literature review. One of the prominent topics that the reviewed research papers have in common is the potential of decarbonization using energy efficient systems and integration of renewable technologies to reach the target of a zero-energy building, that is becoming a requirement.

The case study presented uses a highly efficient direct expansion VRF system for heating and cooling of regularly occupied spaces, while ventilation for these spaces is provided via heat recovery units. Lighting systems are completely LED-based with integrated possibility of smart control with dimming profiles. Comparing this complete set of the project-based mechanical systems to be installed in this building to research papers of warehouse buildings presented in literature review, that include optimization of operational energy, it is reasonable to state that the present systems in the case study already belong to the proposed high-efficiency systems of the optimized cases within literature. Those systems are heat pumps for space conditioning with integration of photovoltaics, that replace baseline consisting of boilers running on natural gas, centralized AHU units for regularly occupied spaces and fluorescent lighting instead of LED. Therefore, the decision for this case study was to focus on exploring the potential that the renewable energy systems such as photovoltaic (PV) systems have with regards to covering the energy needs and possibly making the building zero-energy.

To understand the energy needs of the case study, the energy simulation was performed as it has been introduced in the Chapter 3.4.5. After running the energy simulation in the IES-VE software without any integration of renewable systems, the total electrical energy consumption results in 829,517.98 kWh, or expressed per net floor area of the building, 17.61 kWh/m². In terms of the operational carbon, the impact results in around 21.7 million kgCO₂e or 461.60 kgCO₂e/m² during the total building's service life of 50 years.

Table 90: Total electrical energy consumption of the case study building and operational carbon footprint per one year.

TOTAL EL. ENERGY	Energy use	Energy demand [kW]	Hours ON [h]
Total energy consumption [kWh]	829,517.98	280.01	2,962
Total energy consumption [kWh/m ²]	17.61		
Residual mix emission factor	0.52	kgCO ₂ e/kWh	
Total Operational carbon, annual	434,833.33	kgCO ₂ e	
Total Operational carbon, annual	103.79	kgCO ₂ e/m ²	
Total Operational carbon, 50 years	21,741,666.5	kgCO ₂ e	
Total Operational carbon, 50 years	461.60	kgCO ₂ e/m ²	

As reported the baseline of the total embodied carbon during the building's life equals to 21,609,566.0 kgCO₂e, meaning that the operational carbon is the just slightly higher than 50% of all the embodied carbon emissions.

5.3.1. Integration of the photovoltaic system

Geometry of the roof of the case study building allows a favorable condition for the integration of the photovoltaic system. With its flat roof and total net surface area of around 48,000 m², the project has a great potential to exploit the irradiation onto the roof surface and generate electricity on site.

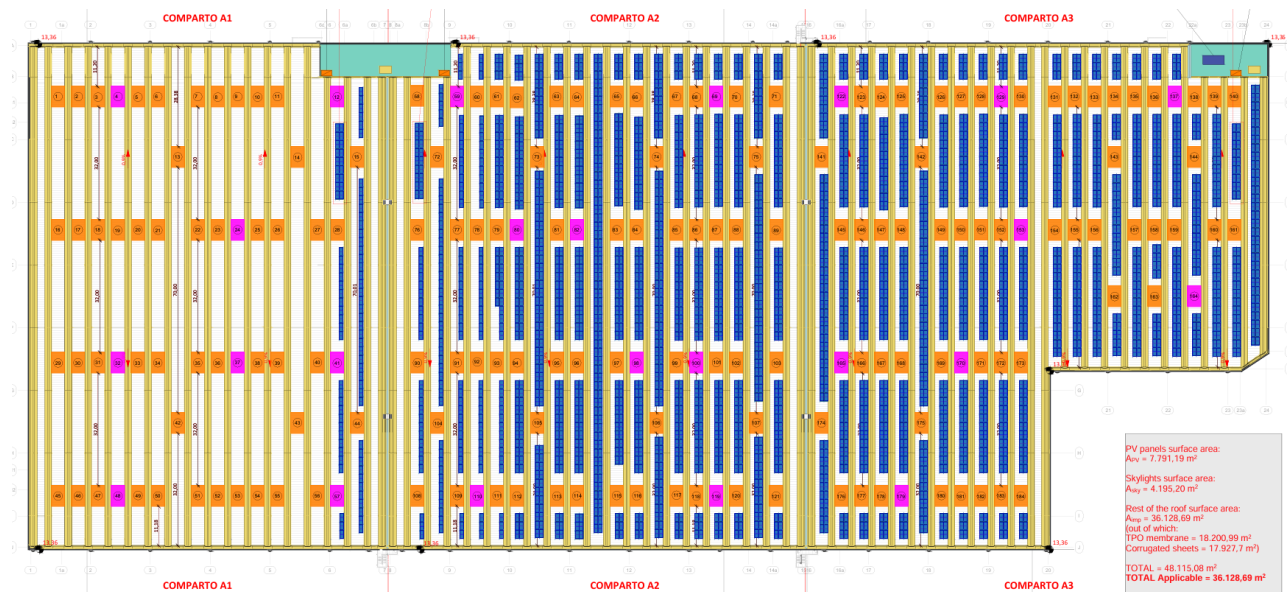


Figure 99: Roof plan of the warehouse building with illustrated disposition of the PV panels (in blue).

Table 91: Geometry of the roof and available surface area for the installation of PV panels.

Roof areas	Surface area (m ²)
Total roof area available	48,115.08
TPO membrane coverage	18,200.99
Corrugated metal sheets coverage	17,927.7
Polycarbonate skylights coverage	4,195.2
Available area for PV panels	7,791.19

A photovoltaic system has been therefore integrated on the roof of the warehouse building. Table below presents information about the chosen module's specifications and the number of modules installed. The number of modules corresponds with the number reported in the available project documentation that served as the baseline for the model and the case study. The module "Hi-MO 7 SERIE LR7-72 HGD" was tested under Standard Test Conditions (STC), meaning Air Mass 1.5, 1000 [W/m²] of solar irradiance and 25°C of cell temperature of the solar cells. The total peak power installed is 1800.11 [kWp], with 2951 panels installed, which is 7.791.19 m² installed. Additionally, the azimuth is determined measured in degrees clockwise from the north, set up as 213.35°, considering the orientation of the building is 33.35° in clockwise direction with respect to the north. Inclination degree from the horizontal is zero, meaning that the modules are installed flat.

Table 92: Technical specifications and peak power of the photovoltaic system installed.

Photovoltaics specifications	
Covering the building's roof area	
Module name	HI-MO 7 SERIE LR7-72 HGD
Testing condition	STC
Operational temperature [°C]	-40 to +85
Module efficiency [%]	22.6
Temperature coefficients of Pmax [%/°C]	-0.280
Peak power per module [Wp]	610
Length of one module [m]	2.382
Width of one module [m]	1.134
Thickness of one module [m]	0.03
Area of one module [m ²]	2.701
Module nominal efficiency [kWdc/m ²]	0.226
Number of panels installed	2,951
Total power installed [Wp]	1,800,110
Total power installed [kWp]	1,800.11
Total area installed [m²]	7,791.19

The aim of the study of PV system integration on the roof surface of the warehouse building is to analyze performance of the system in terms of electricity on-site generation and consideration to a possible battery system installation, as well as a cost-benefit analysis, integrated with LCA analysis in terms of additional embodied carbon emissions due to the systems installation. The end of this study will present from an operational point of view, a trade-off between possible reductions of operational carbon with increases of embodied carbon, while from the cost point of view, payback time with final Net Present Value (NPV) after 50 years will be presented for different cases. Therefore, this analysis will be divided into the PV system performance analysis and the cost-benefit analysis.

5.3.2. Performance of the PV system

As according to the project design, the total number of panels installed remains a constant. Output of the energy simulation shows that with the given number of panels, the azimuth and the inclination, the total electrical energy generated with the PV system during one year is 2,193,015 kWh or 2193 MWh. Knowing the total annual building energy needs, we can understand the building's self-consumption. Two scenarios will be distinguished:

1. Dedicated withdrawal without battery energy storage system
2. Dedicated withdrawal with battery energy storage system.

The Dedicated Withdrawal scheme (known in Italy as „Ritiro Dedicato“ or RID) is a commercial arrangement with the GSE (*Gestore dei Servizi Energetici*) that allows renewable energy producers to sell surplus electricity fed into the national grid. Instead of offsetting grid withdrawals, producers are paid directly for the excess power generated.

Self-consumption of a building is the immediate and localized usage of generated electrical energy on site that satisfies the building's simultaneous electricity demand. In an hourly simulation performed, whenever solar production is equal or lower than the consumption, then 100% of the generated energy goes directly to satisfy the warehouse load.

In case of dedicated withdrawal when there is no battery energy storage system (BESS) present, the moment solar production exceeds what the warehouse can physically use (which commonly happens during peak sun hours at noon or on weekends when warehouse operations slow down), the entire surplus is instantly injected into the public grid. On the other hand, the exact moment solar production is lower than the building's energy needs (during passing clouds, early mornings, or completely during late evening and night hours), the deficit must be handled instantly, therefore electricity must be withdrawn from the grid. Figure below reports the functioning logic of the dedicated withdrawal system without BESS.

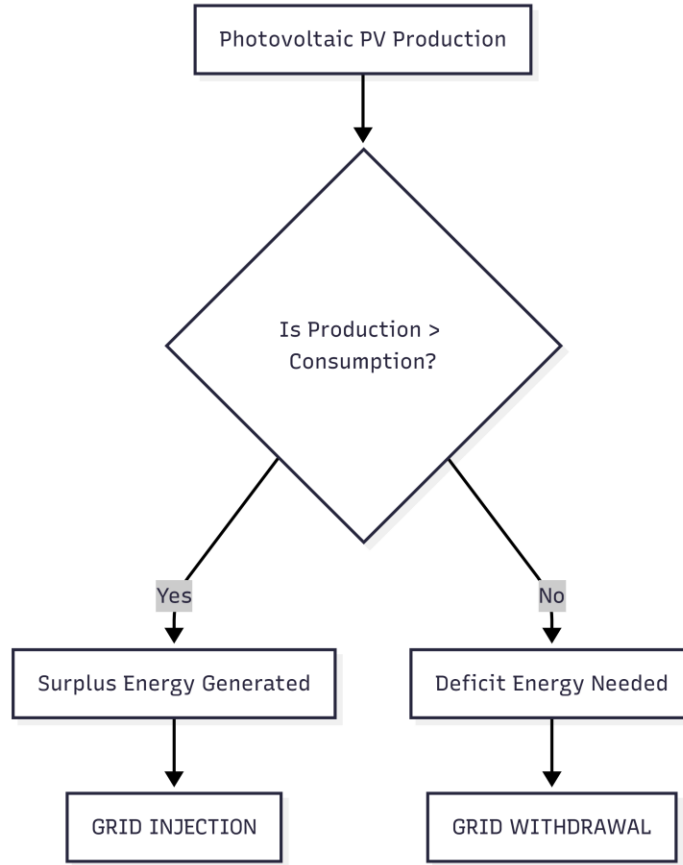


Figure 100: Functioning scheme of the dedicated withdrawal system without BESS.

Self-consumption is determined based on the annual hourly simulation and in the system without BESS equals to 580,208.00 kWh. The electricity that is withdrawn from the grid is therefore the result of subtraction of self-consumed energy from the total energy needs and it can be expressed in the following way:

$$EE_{fromGrid} = EE_{need} - EE_{self\ cons}$$

$$EE_{fromGrid} = 829,517\ kWh - 580,208\ kWh = 249,310\ kWh$$

To compare how much of the generated energy is self-consumed compared to the building's energy needs, we can calculate the PV fraction, representing the portion of the needs covered solely by generated electricity on site:

$$PV\ fraction = \frac{580,208\ kWh}{829,517\ kWh} = 0.7 = 70\%$$

Likewise, to compare how much of the generated energy is actually used for the satisfying the building's needs through self-consumption, the percentage of self-consumption can be calculated:

$$\% of\ self\ consumption = \frac{EE_{self\ cons}}{EE_{PV,gen}}$$

$$\% \text{ of self consumption} = \frac{580,208 \text{ kWh}}{2,193,015 \text{ kWh}} = 0.26 = 26\%$$

We can see that although the PV fraction is quite high, the percentage of self-consumption is on the lower end, since more than 2 million kWh are produced annually yet only a quarter of it is indeed used for satisfying the building's needs immediately. This is a parameter that will be attempted to be optimized, through integration of the battery energy storage system.

The dedicated withdrawal system with integrated BESS on the other hand is more complex, because when the daytime production exceeds the immediate demands of the warehouse, instead of the electrical energy generated being directly injected into the grid, it is directed towards to the integrated battery energy storage system. When electricity generated is routed to the battery, it is in the charging state, acting as a local storage. During low-solar intervals when the generated energy is not sufficient to meet the building's energy needs, the battery discharges the stored energy directly to the warehouse. This shifts self-consumption to hours of zero production, preventing in this way the facility from having to purchase grid power. Only in case when the battery storage is already completely charged to 100% capacity, excess generated energy is then injected into the grid. In contrast, when generation does not meet the need and only when the battery storage has been completely depleted to its minimum state-of-charge, then the electricity must be drawn from the grid, which of course incurs the billing tariffs for energy purchasing. The logic of this system is reported as well in the following figure:

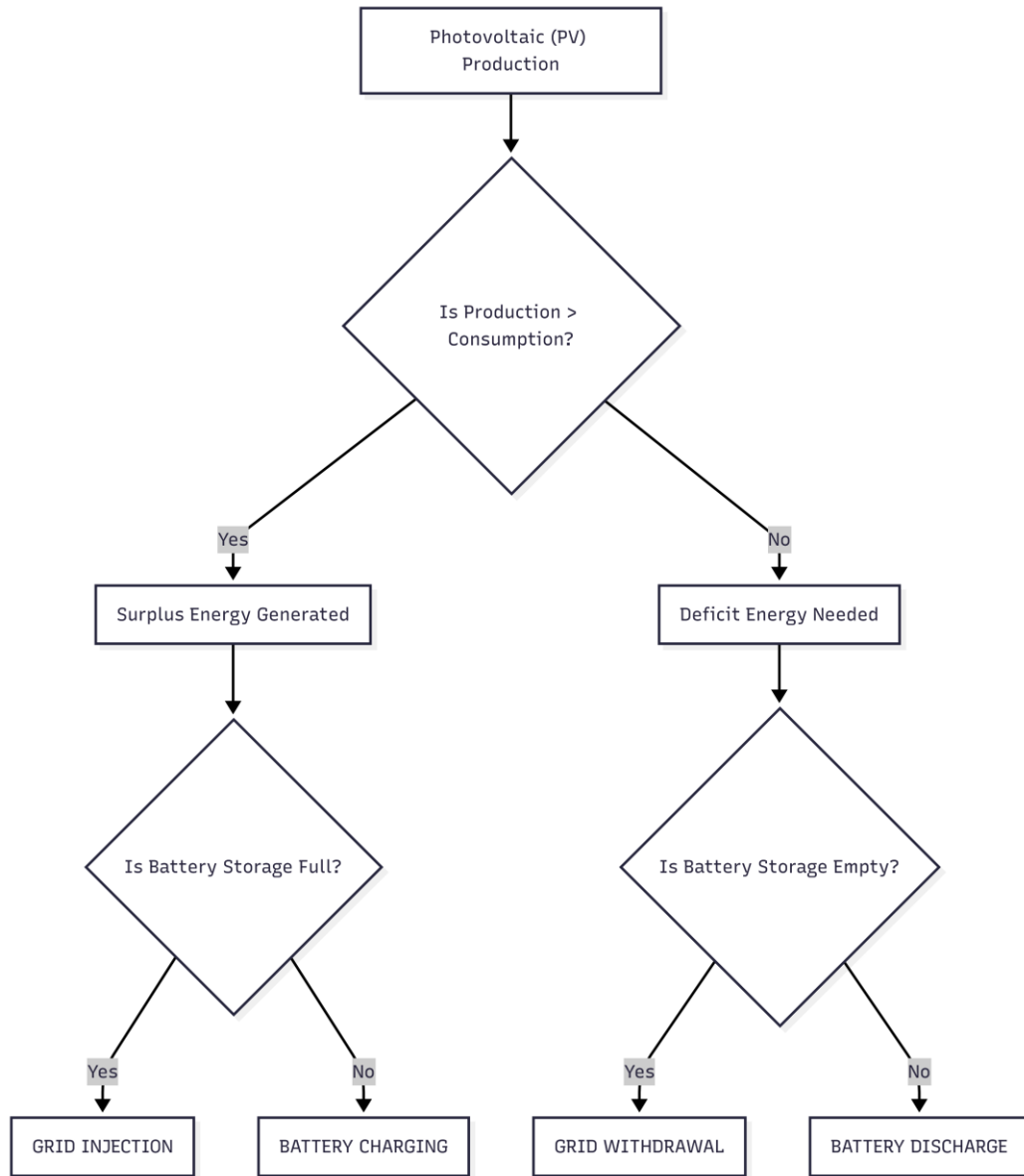


Figure 101: Functioning scheme of the dedicated withdrawal system with BESS.

For the purpose of optimization of the PV fraction, more scenarios will be performed with batteries of various sizes, in proportion with the building's energy generation on the roof.

But first it is useful to understand when the building would have the need for usage of the stored electricity and at what times of the day. The table below reports monthly averages of Global and Diffuse horizontal irradiance on the roof surface. It tells us that January is the month with the lowest average irradiance, both Global and Diffuse, while the highest averages are reported for the month of July, having 4.5 times higher average Global horizontal irradiance and 3.5 times higher average Diffuse horizontal irradiance.

Table 93: Monthly averages of Global and Diffuse Horizontal Irradiance (W/m²).

Month	Monthly average of Global Horizontal Irradiance (W/m ²)	Monthly average of Diffuse Horizontal Irradiance (W/m ²)
Jan	58.5	22.8
Feb	106.5	37.3
Mar	151.7	49.0
Apr	217.7	70.1
May	252.6	80.9
Jun	280.3	75.2
Jul	282.0	81.7
Aug	239.7	67.5
Sep	175.4	53.5
Oct	112.1	40.6
Nov	62.1	26.5
Dec	62.2	24.6

Therefore we can take a closer look into the months of January and July, and compare the energy needs with the generated energy by the PV plant. It is interesting to look at particular days of these months, i.e. the lowest irradiance in January and the highest irradiance in July. The extreme days (lowest production in January and highest production in July) are January 4th and July 9th, as reported in the following diagrams. From these diagrams reporting total building's electricity consumption and generated electricity by the PV plant during 24 hours, we observe that even during the night-time there is a certain amount of electricity consumption, which is attributed to exterior lighting energy consumption, computers, servers, routers and warehouse IT infrastructure (standby or phantom loads) that draw continuous power, as well as emergency lighting such as exit signs and security cameras.

On the extreme day of January 4th, we notice that there is not a singular moment in which PV generation exceeds the building's energy consumption, meaning that 100% of electricity generated will be used for self-consumption. This means that for days in which there is such a trend present, there is no energy that will be stored. However, for days such as July 9th, the story is the opposite, because PV generation curve almost completely exceeds the energy needs for every hour of the day except for the night-time (PV production starting at around 5.30AM and ending at around 9.30PM). In this case, there is a large potential for storing the electrical energy due to high difference in needs vs. production. During the night-time electrical energy needs can be covered with the stored energy from previous days that generated significant amount of energy. However, since there is such a gap between generation and consumption for a whole season of the year, battery necessarily reaches its maximum storage capacity so the electricity must be injected into the grid.

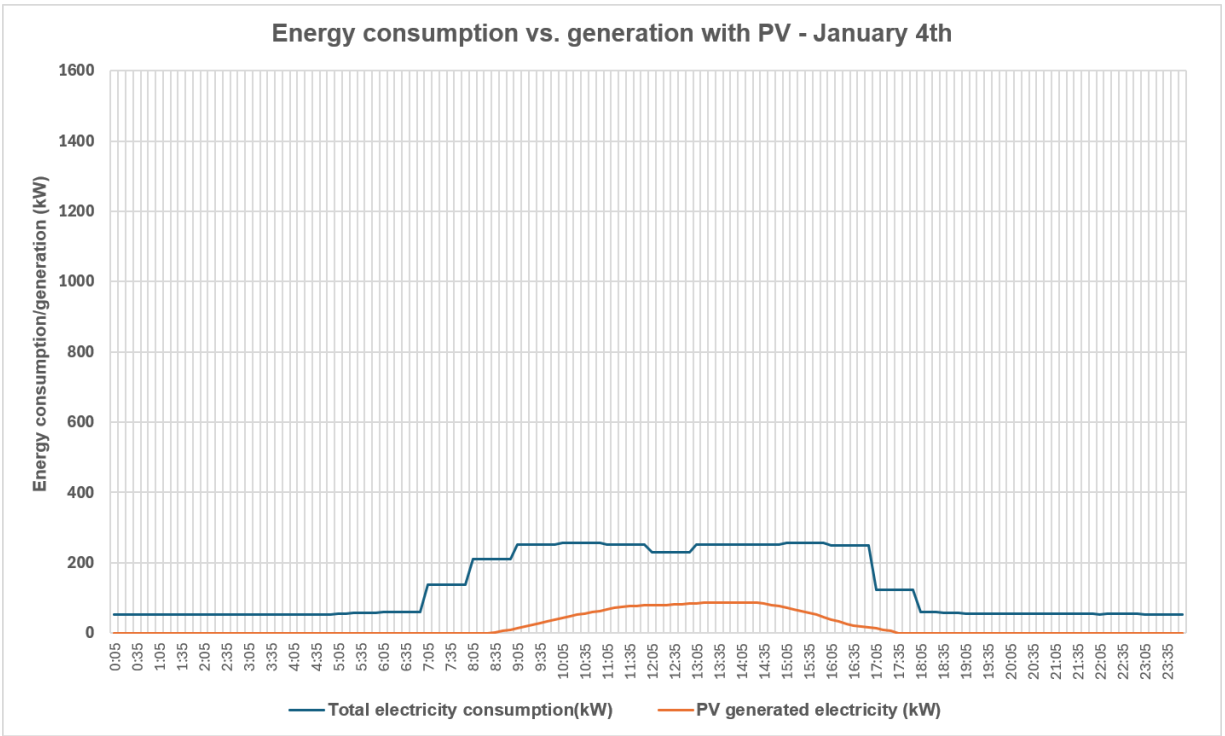


Figure 102: Energy consumption vs. generation for the 4th of January.

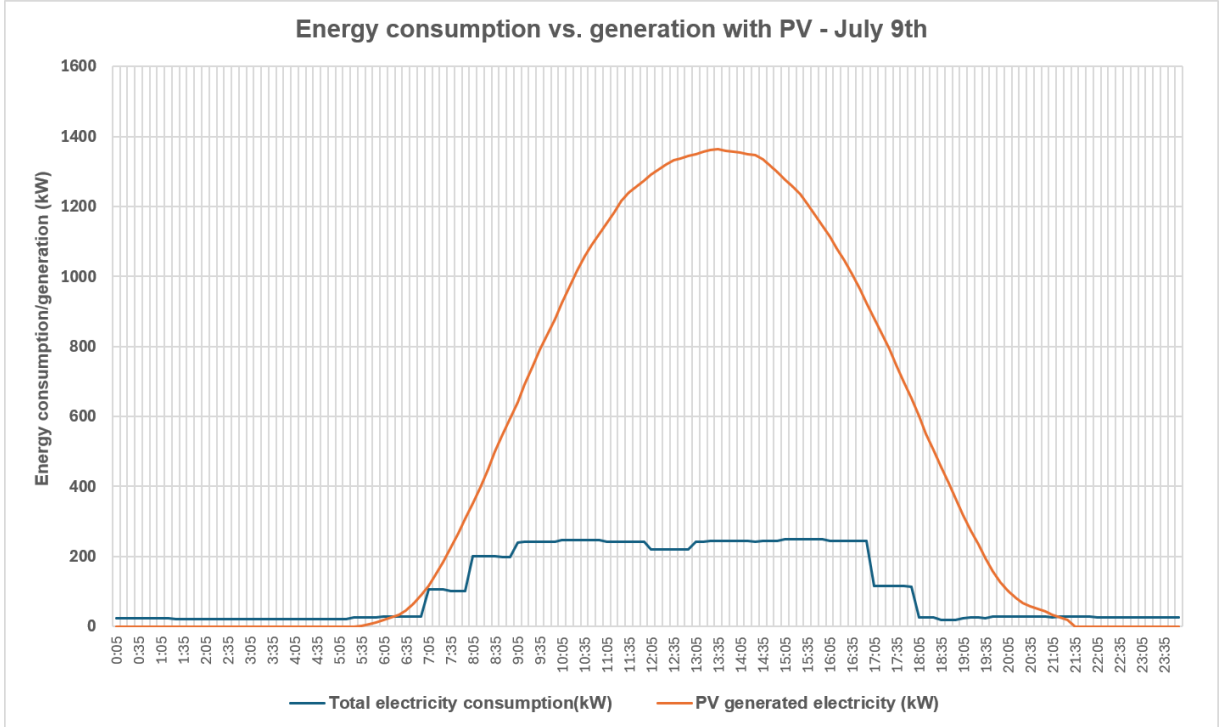


Figure 103: Energy consumption vs. generation for the 9th of July.

Although January 4th shows that PV generation is always lower than consumption, it is not the case for every day of this month (that shows lowest irradiance on average). January 29th is taken as the average day of the month as its irradiance reaches the daily average of 60.8 W/m², aligned with the monthly average of 58.5 W/m². We see that although for the majority of the day consumption exceeds generation, there is a portion of the day (from 10AM to 2.30PM) where production is actually dominant. For winter days this is very important because the winter season is the one that suffers the most for the lack of stored energy. Days like these show that even in winter battery storage is possible and can be utilized to cover a portion of energy needs rather than purchasing electricity from the grid.

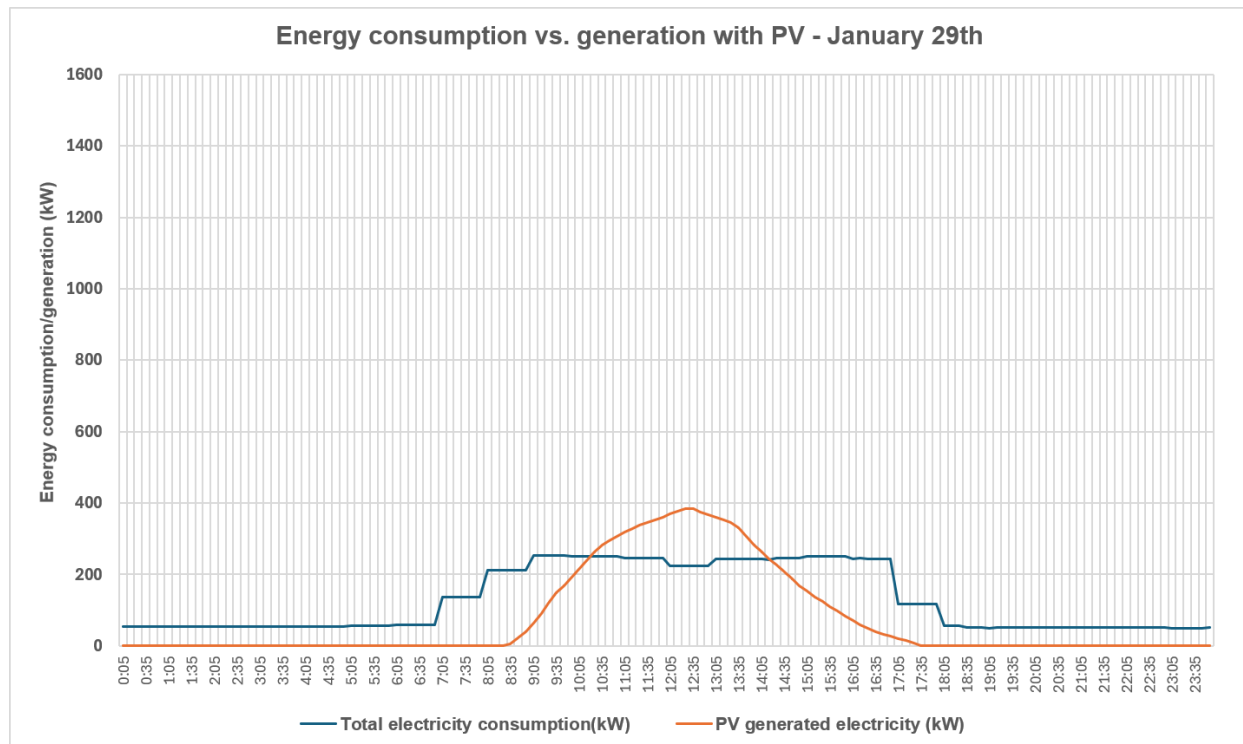


Figure 104: Energy consumption vs. generation for the 29th of January.

When it comes to battery storage assessment, the optimization scenarios will range in battery storage sizes from 100 kWh to 3,000 kWh. It will be important to define how much would be an optimal size of the battery, which theoretically is the point at which the self-consumed amount of electricity would not increase at a significant rate with the increase of the battery size. For this reason, as well as from the cost-benefit point of view that will be discussed later, it is important to use the battery with a suitable size.

Figure below presents the amount of self-consumption (blue line), the amount of electrical energy withdrawn from the grid (grey line), the amount of electrical energy injected to the grid (orange line) and the building's energy need (yellow line). It is an apparent trend that with increasing the battery size the amount of energy which is withdrawn from the grid decreases. Increasing the

battery size we also observe that the energy injected to grid decreases as well, which is due to the larger battery capacity. The amount of self-consumption increases as the system is able to store the energy which is generated during the peak hours in terms of solar irradiation instead of injecting it to the grid. The graph demonstrates that the curve of self-consumption shows a steeper slope until it reaches 750 kWh, while after 1,250 kWh of battery storage up to 3,000 kWh, the curve is almost flat, i.e. it becomes asymptotic with the increase of the battery size. For this reason it is decided to pursue the analysis between the withdrawal system with and without BESS, for the battery sizes of 750 kWh, 1,000 kWh and 1,250 kWh.

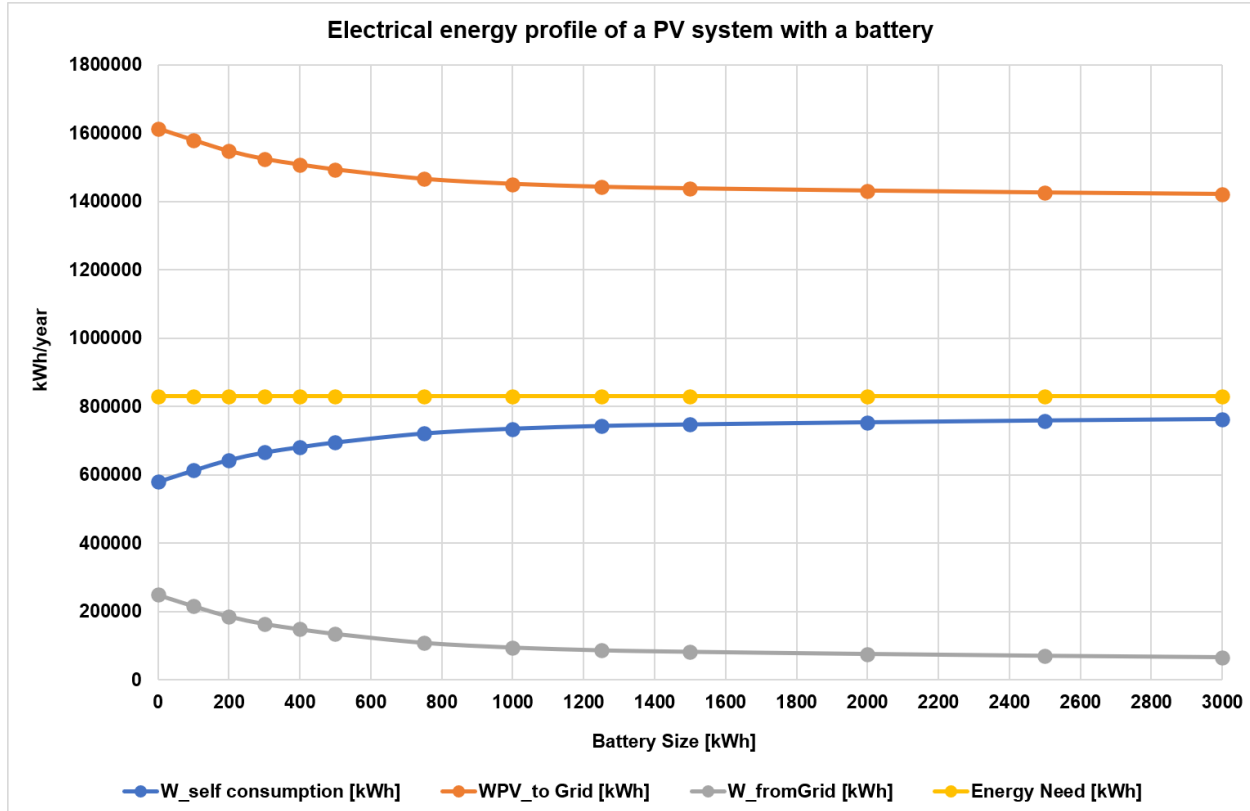


Figure 105: Variation of withdrawn, injected and self-consumed energy with increasing the battery storage size.

Considering the presence of the BESS system of variety of battery storage sizes, an iterative process was performed to obtain the amount of self-consumed, withdrawn energy from the grid and energy injected into the grid, with results reported in the following table:

Table 94: PV fraction and self-consumption percentage for various battery storage sizes.

Battery Size [kWh]	EE_Need [kWh]	EE_PV Generation [kWh]	EE_self consumption [kWh]	EE_to Grid [kWh]	EE_from Grid [kWh]	PV fraction [%]	Self-consumption [%]
0	829,517	2,193,015	580,208	1,612,808	249,310	70%	26%
100	829,517	2,193,015	613,214	1,578,854	216,304	74%	28%
200	829,517	2,193,015	643,657	1,546,738	185,861	78%	29%
300	829,517	2,193,015	665,497	1,523,560	164,021	80%	30%
400	829,517	2,193,015	681,051	1,507,082	148,467	82%	31%
500	829,517	2,193,015	694,601	1,492,770	134,917	84%	32%
750	829,517	2,193,015	720,877	1,465,005	108,641	87%	33%
1000	829,517	2,193,015	734,731	1,450,364	94,787	89%	34%
1250	829,517	2,193,015	742,787	1,441,822	86,731	90%	34%
1500	829,517	2,193,015	747,054	1,437,301	82,464	90%	34%
2000	829,517	2,193,015	753,405	1,430,602	76,113	91%	34%
2500	829,517	2,193,015	758,720	1,425,001	70,798	91%	35%
3000	829,517	2,193,015	762,846	1,420,648	66,671	92%	35%

The results show that between the storage of 1,250 kWh and 3,000 kWh the increase in PV fraction and self-consumption is only 1%, while the storage size is more than doubled, demonstrating that such a large storage system is inefficient regardless its great performance. The difference in improvement of performance between the storage of 750 kWh and 1,250 kWh in size is small as well, yet it will be interesting to compare this interval in terms of cost-benefit analysis.

5.3.3. Cost-Benefit analysis (CBA)

After analyzing the energy performance of the PV system, the Cost-Benefit analysis (CBA) is performed to support the choice of the more appropriate scheme to implement with the most economically feasible option, with or without the battery storage. In this analysis as well, two case studies will be compared:

1. Dedicated withdrawal without battery energy storage system (BESS)
2. Dedicated withdrawal with battery energy storage system.

5.3.3.1. Dedicated withdrawal without BESS

Based on the magnitude of the peak power that the PV plant on the roof of the warehouse is able to produce, it is possible to calculate the expenditure over the span of the building's service life which is 50 years. Capital and operating expenditure will be both considered (CAPEX and OPEX, respectively). CAPEX is defined as the the upfront, one-time investment to buy and install the solar equipment, while OPEX is an ongoing service model throughout the operation of the PV plant, where the developer pays for the operation and maintenance. Capital expenditure for

investing into the plant is taken as 1,400 (€/kW) while the operating expenditure is considered as 25 (€/kW). Knowing that the peak power of the plant is 1,800.11 kWp, the total CAPEX equals to 2,520,154 €. The developer is assumed to pay the capital expenditure on the equity/loan principle, where 30% of the CAPEX is a downpayment upon signing the contract, while the rest 70% is a bank loan that is spread out over a 10-year repayment period. On the other hand, OPEX is an expenditure that will be paid annually throughout the building's 50-year service life. With the peak power installed, the total OPEX will result in 45,003.8 €, that spread over the course of 50 years will result in 2,250,137.5 €.

To obtain the cash flow over the years for each year of building's service life, the costs of energy buying and benefits of energy selling must be calculated. In terms of energy buying, according to „EUROSTAT“ and the report of electricity prices for non-household consumer in the European Union (EU), electricity price for the second part of 2025 was 0.183 €/kWh excluding the Value-Added Tax (VAT) and other recoverable taxes.

In terms of energy selling, the asset relies on grid monetization via the *Gestore dei Servizi Energetici* (GSE). Since the project is geographically located in Bologna (Emilia-Romagna region), it falls strictly within the Northern Market Zone (*Zona di Mercato Nord*). Therefore to calculate the cash flow, the hourly Zonal Price P_z (*Prezzo Zonale*) must be used to simulate grid revenues. In accordance with the Italian wholesale electricity market structures regulated by the GME (*Gestore dei Mercati Energetici*), the annual average for the Northern Zonal Price is considered as 0.115 €/kWh.

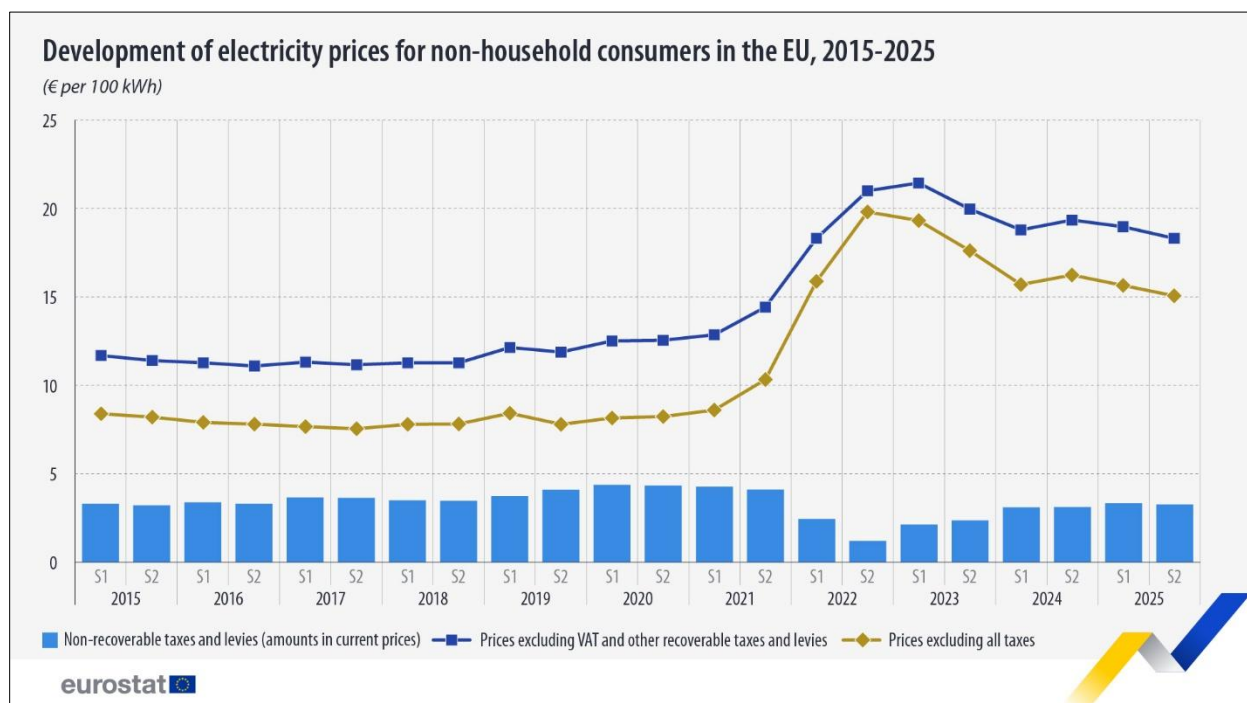


Figure 106: Electricity prices for non-household consumers in the EU, 2015-2025.

Table 95: Price of electrical energy for energy purchasing and energy selling to the grid.

	Amount	Unit	Source
Energy purchasing	0.183	€/kWh	GME, Average zonal price
Energy selling	0.115	€/kWh	EUROSTAT

Finally, besides the economic benefits of injecting the electricity into grid, this case study also considers an incentive on a national level that large-scale industrial (non-residential) projects receive for production clean energy. To account for this public support available for industrial renewable energy investments in Italy, the economic analysis includes the incentive provided under the “*Transizione 5.0*” scheme¹¹. This measure supports investments that contribute to a certified reduction in energy consumption and provides a tax credit calculated as a percentage of the eligible investment cost. For the present study, it is assumed that the PV plant installation qualifies for the highest incentive tier, corresponding to a 45% tax credit on the eligible CAPEX. This assumption is based on this significant contribution of the PV system to the warehouse energy balance, since the PV plant covers 70% of energy needs without any battery, as demonstrated through PV fraction percentage. The resulting tax credit is therefore estimated as 45% of the total PV investment cost.

Table 96: Tax credit achievable for the case study eligible for the *Transizione 5.0* scheme.

INVESTMENT BAND	Production unit: 3%-6% / Process affected by the investment: 5%-10%	Production unit: 6%-10% / Process affected by the investment: 10%-15%	Production unit: >10% Process affected by the investment: >15%.
0 - 10 mln €	35%	40%	45%
10 - 50 mln €	5%	10%	15%

$$CAPEX = 2,520,154 \text{ €}$$

$$CAPEX \text{ with tax reduction} = 2,520,154 \text{ €} \cdot 0.45 = 1,134,069.3 \text{ €}$$

$$\text{Tax reduction over 5 years} = \frac{1,134,069.3 \text{ €}}{5} = 226,813.8 \text{ €}$$

Although the incentive is not received as a direct cash payment, it reduces the amount of taxes that the company would otherwise be required to pay. From an economic perspective, this represents a financial benefit equivalent to a reduction in future cash outflows and is therefore

¹¹ “*Transizione 5.0*” is an Italian incentive scheme that supports energy-efficiency and renewable-energy investments through tax credits granted to projects that achieve certified reductions in energy consumption. Source: [Transition 5.0 implementing decrees: how to benefit from the incentives | Enel Energia](#)

included in the cash-flow analysis. To avoid overestimating the short-term economic benefit and to better represent the practical utilization of the tax credit over time, the total incentive value is assumed to be distributed evenly over a five-year period rather than being applied entirely in the first year.

Finally, to find the cash flow for the respective years, we must sum the following prices/costs for that year:

- Money saved due to installation (overall bill money saving) through 50 years,
- Tax exemption from the incentive for 5 years,
- Investment costs for the first 10 years,
- Operative costs throughout 50 years.

To provide a more realistic evaluation, the actualized cash flow takes into account an inflation rate r of 2% considered for this study, with a discount factor F_r . Including the inflation rate slightly changes the cash flow, which is named as discounted cash flow (DCF_t) expressed with the following equation:

$$DCF_t = CF_t \cdot F_r$$

$$F_r = \frac{1}{(1 + r)^t}$$

The following table presents as an example, showing the summary of the cashflow for the period of the first five years for installing a PV system:

Table 97: Cumulative cash flow for the period of the first five years after the installation of the PV plant in year 0.

YEAR	0	1	2	3	4	5
	PV "overnight" construction	Operation -->				
Overall bill money saving	-	300,303	300,303	300,303	300,303	300,303
Exemption	-	226,813	226,813	226,813	226,813	226,813
Investment costs	-756,046	-176,411	-176,411	-176,411	-176,411	-176,411
Operative costs		-45,003	-45,003	-45,003	-45,003	-45,003
Cash Flow	-756,046	305,703	305,703	305,703	305,703	305,703
Actualized Cash Flow	-756,046	299,708	293,832	288,070	282,422	276,884
Cumulative Cash Flow	-756,046	-456,338	-162,506	125,565	407,987	684,871
DPP	Year 3					
NPV_50 years	5,982,807 €					

As we can understand from the table, the cumulative cash flow is increasing from year 0 onwards to zero, and at one point reaching a positive value. The point in time in which the cumulative cash flow becomes a positive value is called the discounted payback period (DPP) and for this case

study it happens during the third year of the building's operation. Considering the evaluated span of 50 years, at year 50 the discounted cumulative cash flow is called the Net Present Value (NPV) and for this case study it reaches 5,982,807 €.

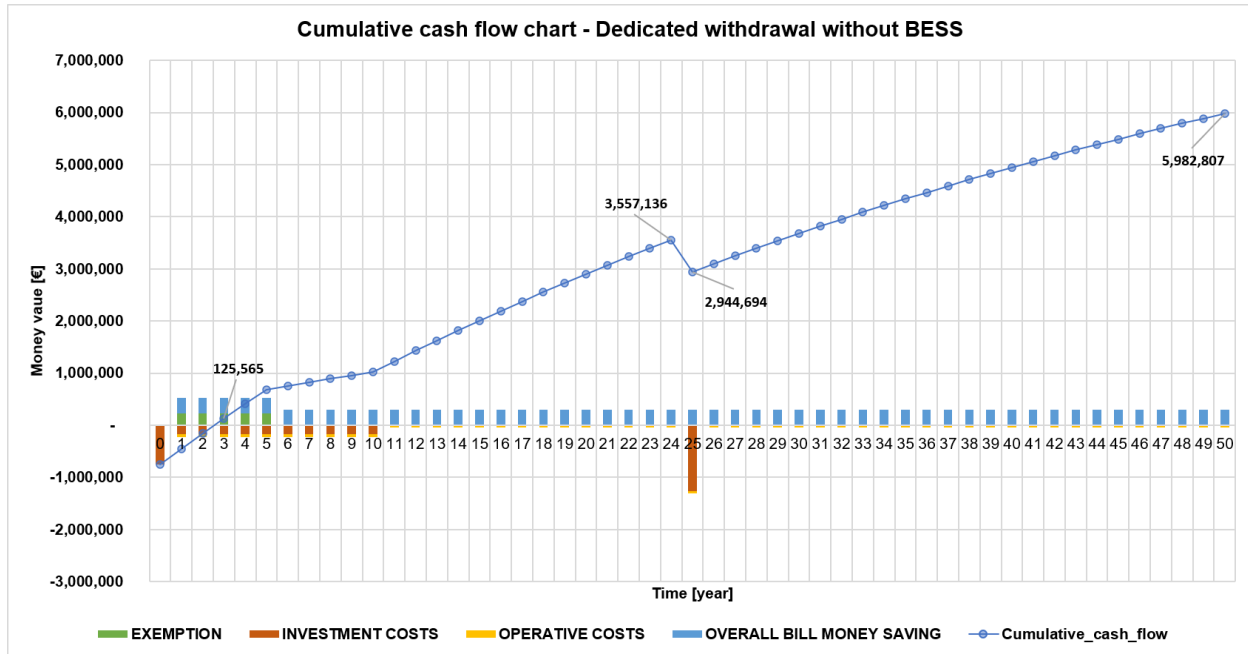


Figure 107: Cumulative cash flow chart of the case study of dedicated withdrawal without BESS.

However, in the graph the sudden drop in cumulative cash flow is observable, precisely in year 25. As the service life of the PV panels is 25 years, intervention in replacing the degraded PV modules with the new plant is planned. For the new modules, rather than introducing speculative interest rates or government subsidised and incentives 25 years into the future, the hardware replacement cost is modeled as 100% equity (downpayment) cash outflow. This assumes zero external debt or loans since the asset has already generated savings between years 11 and 24 (after paying off completely the capital expenditure) to cover the expenses „out of pocket“. Due to the long-term unpredictability of national policies for sustainable energy in the future, the exemption rate is kept as zero.

5.3.3.2. Dedicated withdrawal with BESS

Three scenarios regarding the scheme of dedicated withdrawal with battery energy storage system will be discussed: integration of battery storage capacities of 750 kWh, 1000 kWh and 1250 kWh, as outlined in the chapter discussing optimization of the PV plant performance as a function of PV fraction. The purpose of the analysis is to understand how integrating the battery storage system will influence the cumulative cash flow. It is intuitive that the upfront cost of CAPEX will increase, for the installation of the battery storage. The CAPEX considered for its installation for all the scenarios is 400 €/kWh.

Regardless of increasing the CAPEX of the initial investment, which might seem like a downside, it will be interesting to see if this scheme is going to provide a financial advantage for the project's long-term NPV by the year 50 of the building's operation. Namely, without the battery the warehouse is forced to sell its excess solar energy back to the grid for 0.115 €/kWh when the energy needs are lower than the electricity generated, while with the battery the warehouse saves that excess energy on the annual basis as reported in Table 94 instead of purchasing from the grid 0.183 € each kWh, and uses it in the amount depending on the season and amount of generation.

Through the timespan of 50 years, because this price difference repeats every day for decades, the long-term bill savings accumulate and actually end up being higher than the bill savings achieved when no battery is being implemented. Ultimately, adding the battery results in a higher project NPV than building a solar system without storage.

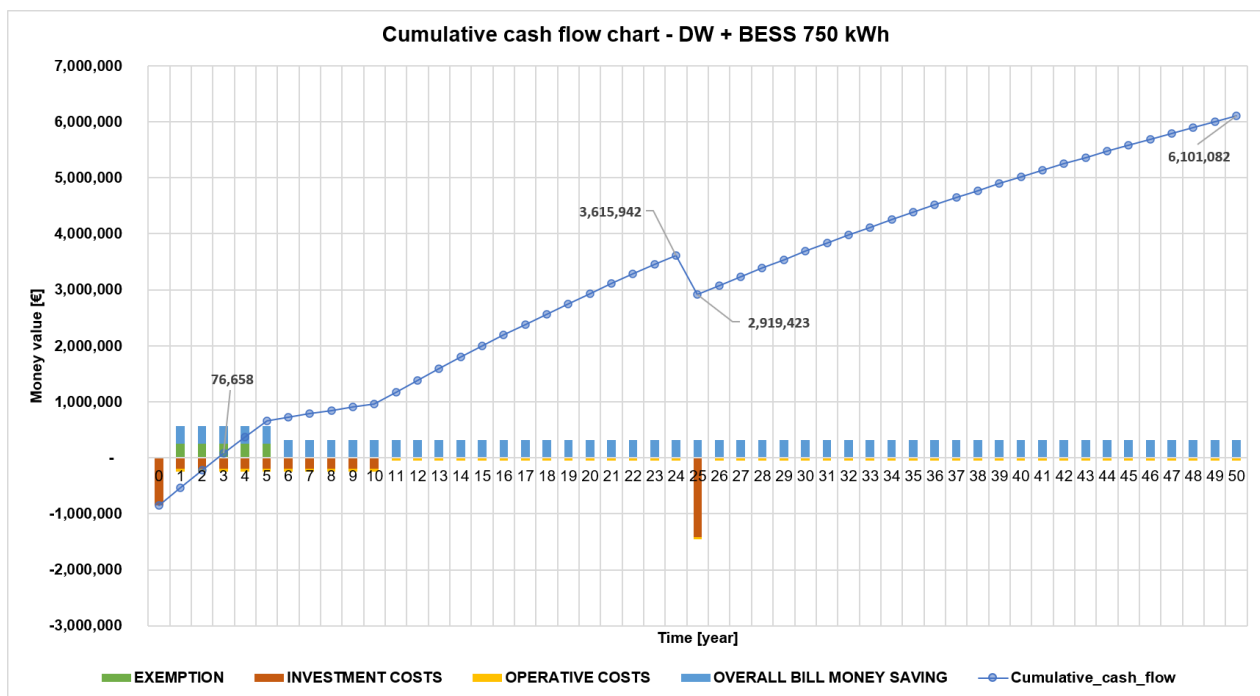


Figure 108: Cumulative cash flow chart of the case study of dedicated withdrawal with BESS of 750 kWh.

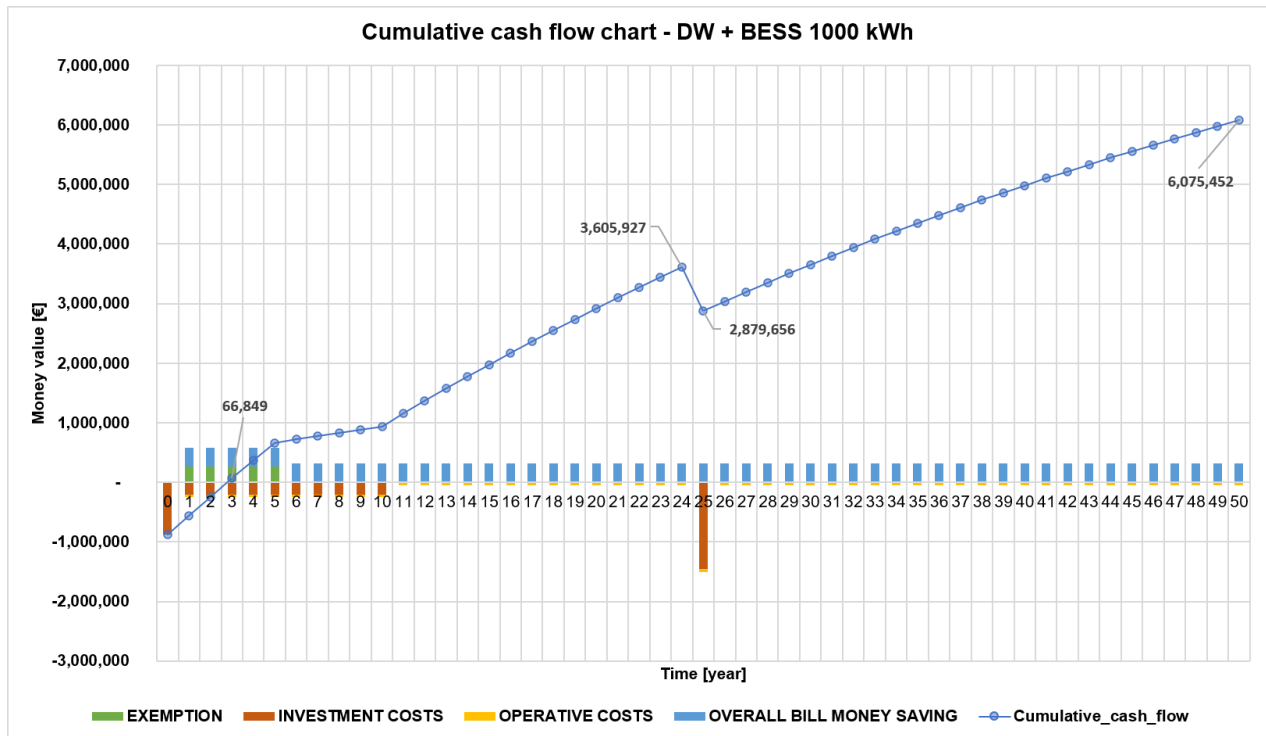


Figure 109: Cumulative cash flow chart of the case study of dedicated withdrawal with BESS of 1000 kWh.

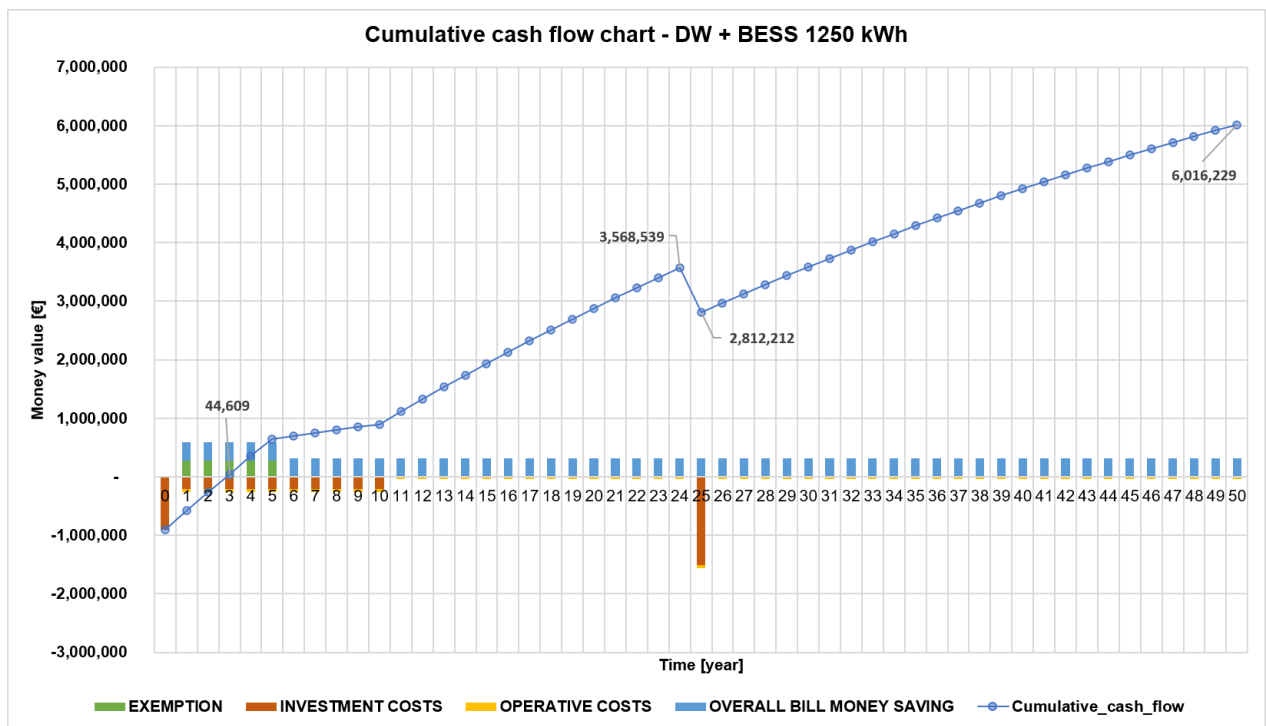


Figure 110: Cumulative cash flow chart of the case study of dedicated withdrawal with BESS of 1250 kWh.

The diagram reports below the summary of the cost-benefit analysis for 4 different scenarios, showing the results anticipated in previous paragraphs. All 4 scenarios show the payback period being three years, and OPEX remains equal for all the scenarios. As the battery size increases, so does the CAPEX, increasing for 16% from DW scheme with no BESS to DW scheme with battery of 1250 kWh (increase in around 400,000 €). On the other hand the total savings increase for 15%, in total 2,296,160 € more than the scheme without storage.

Although the scenario with 1250 kWh battery storage shows the highest bill savings due to installation, finally the NPV value after 50 years is not the highest for this solution, but for the solution with 750 kWh battery storage, which is a balance between CAPEX, replacement costs, bill savings and tax reductions. Initially higher CAPEX also means higher replacement costs in the year 25, which negatively affects the final NPV compared to the solutions with lower initial CAPEX. Ultimately, the NPV value of the scenario with 750 kWh battery storage is the highest, but barely 2% higher than the initial solution without the storage. Although the bill savings are higher if we install the storage because we withdraw less electricity from the grid, the final cost-analysis results show that the BESS system is only slightly more beneficial in terms of the final NPV. The BESS system would indeed have to be more efficient to consider it as a more viable solution long-term, to justify the higher capital expenditure of the initial installation. For this reason, the first scenario of dedicated withdrawal without BESS would be the most optimal one. However, the LCA analysis must be conducted to decide which is going to be the final optimized solution.

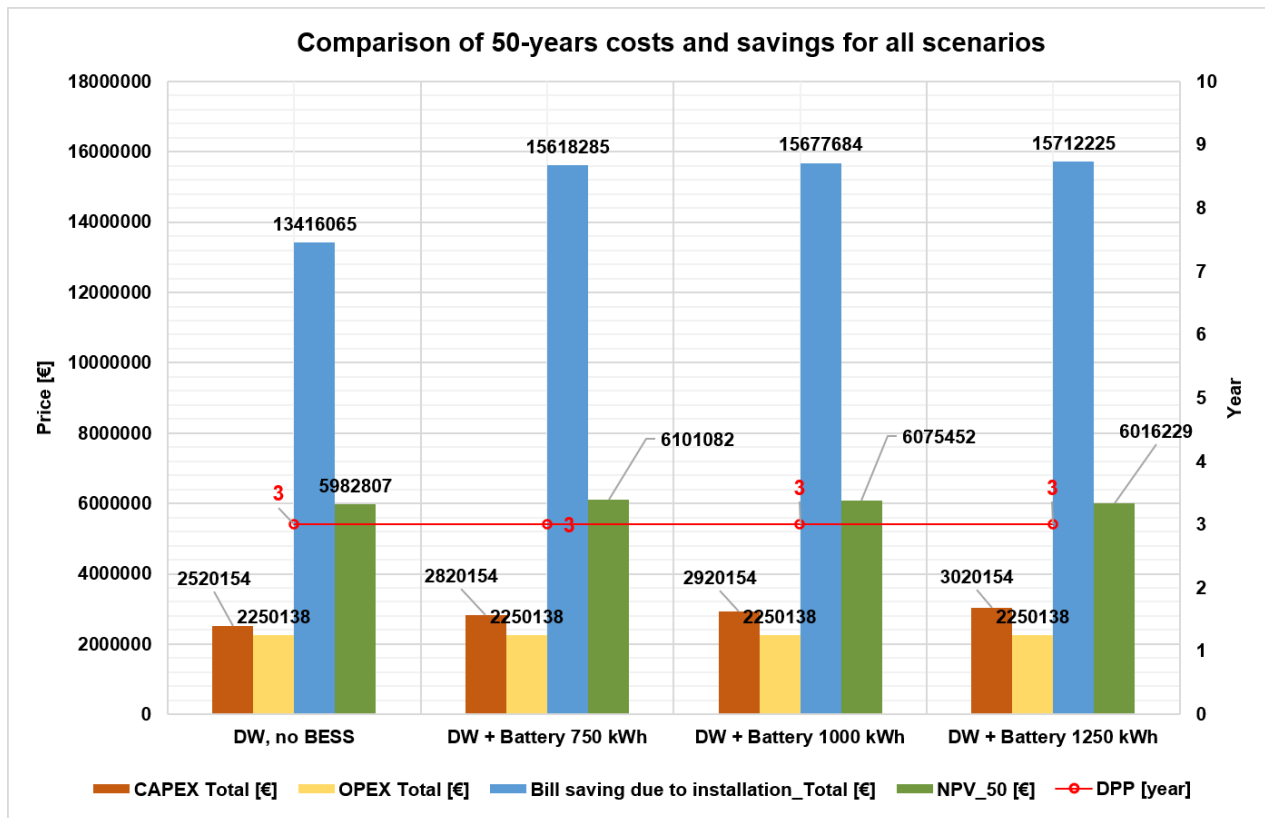


Figure 111: CBA comparative analysis of 50-years costs and savings for the evaluated scenarios.

5.3.3.3. Whole life carbon impacts of the analyzed scenarios

Having performed the building energy simulation and the analysis of the photovoltaic system on the building's roof, now it is possible to complete the whole life LCA, including the operational carbon impacts from the B6 stage and the additional embodied carbon impacts of the installed PV plant with the battery storage.

The tool One Click LCA prompts us to insert the required input of how much electricity the building consumes, and it is possible to add the exported energy if the building generates it on site, which is applicable to this case study. Based on the hourly simulation performed and results obtained from the energy model, it was possible to calculate how much energy is exported/injected to the grid, for the scenarios with and without the BESS. The results are reported in the Table 94 under the column „EE_from Grid [kWh]” for the energy withdrawn from the grid and under the column „EE_to Grid [kWh]” for the energy injected into the grid, for each performed scenario. To obtain the operational carbon impact of the B6 stage of LCA of the electrical energy withdrawn, emission factor of 0.522 kgCO₂e/kWh of the residual mix for the Italian market is used.

Energy consumption, annual* ∨

Delete (0) Lock (0)

Resource Name	Category	Details	Quantity	Unit
☐ Electricity, Italy, residual mix, 2024 (One Click LCA)	Electricity use			kWh
☐ Electricity, Italy, 2023 (One Click LCA)	Exported energy			kWh

Figure 112: Required input of electricity consumption and exported energy in One Click LCA.

In regards to embodied carbon impacts, to the building's baseline also the impact of PV modules and battery storage is added. The total embodied impact of 2951 modules with 1800.11 kWp installed equals to 638,000 kgCO₂e for the A1-A3 production stage, while total Cradle-to-Grave embodied carbon impact from PV modules equals to 1,950,100 kgCO₂e. The significant increase in other life cycle stages is due to the replacement B4-B5 stage that happens in the year 25 of the building's operation, where dismantling and disposing of old modules followed by production and installation of new modules must be accounted for.

Therefore, as reported in the following summary table, additional embodied carbon impacts of the PV system without BESS for the A1-A3 stage increase for 3.3%, while in terms of total Cradle-to-Grave life cycle, the increase is 8.2% compared to the baseline. Having an increase of more than 8% in the whole-life embodied carbon due to addition of the PV plant is a non-negligible percentage, even without adding any battery storage. However, to get the complete picture, we must look at the whole-life carbon, including the operational B6 stage.

Table 98: Total GWP impact of the building with and without the PV plant – comparison of embodied vs. operational carbon for various scenarios.

PV system	Battery Size (kWh)	A1-A3 stage (kgCO ₂ e)	Total Cradle-to-Grave, embodied (kgCO ₂ e)	B6 stage (kgCO ₂ e)	% of operational vs embodied	Total Cradle-to-Grave, embodied + operational (kgCO ₂ e)	% of total reduction compared to baseline
DW, no BESS	0	19,371,690	23,559,666	6,535,116	22%	30,094,782	31%
DW+BESS	100	19,381,583	23,600,814	5,669,936	19%	29,270,750	32%
	200	19,391,476	23,641,962	4,871,939	17%	28,513,901	34%
	300	19,401,369	23,683,110	4,299,451	15%	27,982,561	35%
	400	19,411,262	23,724,258	3,891,737	14%	27,615,995	36%
	500	19,421,155	23,765,406	3,536,554	13%	27,301,960	37%
	750	19,445,887	23,868,276	2,847,786	11%	26,716,062	38%
	1000	19,470,620	23,971,146	2,484,633	9%	26,455,779	39%
	1250	19,495,352	24,074,016	2,273,463	9%	26,347,479	39%
	1500	19,520,085	24,176,886	2,161,613	8%	26,338,499	39%
	2000	19,569,550	24,382,626	1,995,135	8%	26,377,761	39%
	2500	19,619,015	24,588,366	1,855,814	7%	26,444,180	39%
	3000	19,668,480	24,794,106	1,747,634	7%	26,541,740	39%
No PV	0	18,733,690	21,609,566	21,741,666	50%	43,351,232	(baseline)

Considering the carbon impacts of the operational B6 stage with and without the PV plant changes the whole-life carbon results drastically. Namely, in the baseline scenario where no PV modules are considered on the roof, the percentage of the operational carbon is slightly higher than the whole-life embodied carbon, representing 50.1% of total impacts or 21,741,666 kgCO₂e. On the other hand, although the installation of 2951 PV modules increases the embodied carbon for 8.2%, the operational carbon decreases for 70%, or 31% of the whole-life carbon compared to the baseline, reducing the total carbon impact for more than 13,000,000 kgCO₂e. In this scenario (named in the Table as „DW, no BESS“), operational carbon now represents only 22% of the GWP impacts compared to the impacts of the stages related to the embodied carbon.

Integrating the battery storage, the impacts are even more substantial. In the cost-benefit analysis the battery storage sizes of 750, 1000 and 1250 kWh were compared. Starting with the battery of 750 kWh, whole-life embodied carbon is now increased for 9.1% compared to the baseline, but the operational carbon decreases for 86% compared to the baseline and 56.5% compared to the DW scenario with no BESS. This means a 38% reduction of whole-life carbon compared to the baseline and cutting down more than 16,000,000 kgCO₂e for the whole life cycle.

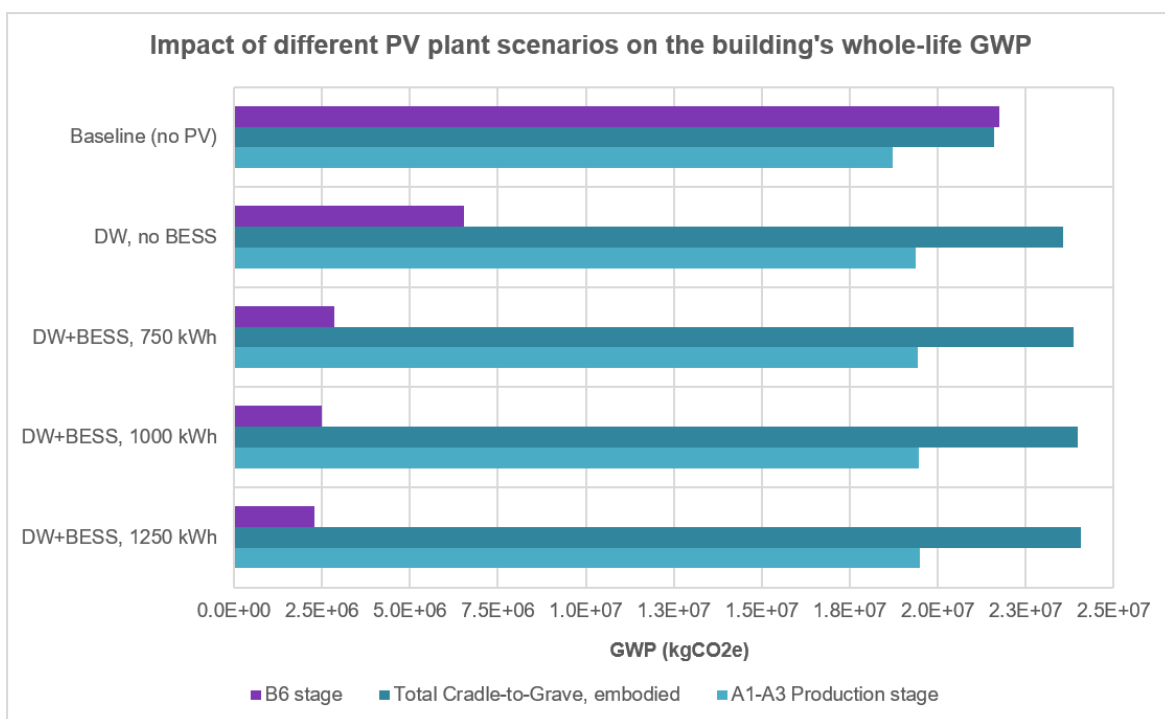


Figure 113: Impact of different PV plant scenarios on the building's total GWP (embodied + operational).

Comparing the DW scenario without BESS with the DW scenario with BESS of 750 kWh, cost-benefit analysis reveals that the latter turned out to be more expensive without increasing significantly the NPV after 50 years (only 1.9%), but LCA results show much more significant differences – the operational carbon being cut for more than half in case battery of 750 kWh is installed. Although the embodied carbon increases for about 300,000 kgCO₂e (1.3%), the operational carbon reduction equals to around 3,600,000 kgCO₂e (56.4%). Conversely, storage arrays of 1,000 kWh and 1,250 kWh successfully lower operational emissions but impose higher upfront expenditure that actually depress the project's long-term financial viability. Consequently, the DW+BESS 750 kWh configuration is selected as the final optimal design solution.

Table 99: Comparative analysis of different PV scheme scenarios – multi-criteria optimization between LCA and CBA.

PV plant scheme	LCA		CBA	
	Whole-life embodied carbon (kgCO ₂ e)	Whole-life operational carbon (kgCO ₂ e)	CAPEX (€)	NPV after 50 years (€)
DW, no BESS	23,559,666	6,535,116	2,520,154	5,982,807
DW+BESS, 750 kWh	↑ 1.3% 23,868,276	↓ 56.4% 2,847,786	↑ 10.6% 2,820,154	↑ 1.9% 6,101,082
DW+BESS, 1000 kWh	↑ 1.7% 23,971,146	↓ 62.1% 2,484,633	↑ 13.7% 2,920,154	↑ 1.5% 6,075,452
DW+BESS, 1250 kWh	↑ 2.1% 24,074,016	↓ 65.2% 2,273,463	↑ 16.6% 3,020,154	↑ 0.6% 6,016,229

5.4. Whole life carbon optimization

Methodology of this case study introduced the matrix of the workflow followed throughout this study. The optimization measures were grouped into three axes: embodied carbon reduction through structural optimization, embodied carbon reduction through envelope optimization, and operational carbon reduction through on-site renewable energy generation. The baseline case (Scenario 0), representing the warehouse without any optimization measures, results in a total whole-life global warming potential (GWP) of 43.35 million kgCO₂e over the 50-year reference study period.

Table 100: Matrix of GWP optimization axes on the building level, performed in the study.

Optimization axis	Scenario #	As-is building structure	Improved building structure	As-is building envelope	Improved building envelope	As-is building energy use	Improved energy use with PV plant
Baseline	Scenario 0	x		x		x	
Embodied carbon	Scenario 1		x	x		x	
	Scenario 2	x			x	x	
	Scenario 3		x		x	x	
Operational carbon	Scenario 4	x		x			x
Whole building carbon	Scenario 5		x	x			x
	Scenario 6	x			x		
	Scenario 7		x		x		x

The embodied carbon scenarios (Scenarios 1-3) achieve relatively modest reductions in whole-life carbon emissions compared to the baseline. Structural optimization (Scenario 1) reduces the whole-building GWP by approximately 1.08 million kgCO₂e, corresponding to a 2.5% improvement. Envelope optimization (Scenario 2) achieves a smaller reduction of approximately 0.30 million kgCO₂e, equivalent to only 0.7% improvement compared to the baseline. When both measures are combined (Scenario 3), the total reduction reaches 1.38 million kgCO₂e, corresponding to a 3.2% improvement. These results indicate that, within the scope defined in this study, structural optimization has a greater influence on embodied carbon reduction than envelope optimization. However, it should be noted that the structural assessment was limited to the precast reinforced concrete columns and reinforcement steel used in the cast-in-situ structure. Therefore, the achieved reductions should be interpreted as an indication of the potential of structural optimization rather than its maximum achievable impact. Inclusion of the entire structural system could lead to significantly larger embodied carbon savings.

In contrast, operational carbon optimization through the installation of a photovoltaic system produces substantially greater reductions in whole-life carbon emissions. Scenario 4, which introduces renewable electricity generation while maintaining the baseline structure and envelope, reduces the whole-building GWP by 18.89 million kgCO₂e, corresponding to a 43.6% improvement compared to the baseline. The combined scenarios (Scenarios 5-7), which integrate both embodied and operational carbon optimization measures, achieve the lowest whole-life

carbon footprints, with Scenario 7 reaching the best overall performance at 23.08 million kgCO₂e, representing a 46.8% reduction relative to the baseline case.

Table 101: Final results of the whole-life building carbon optimization.

Scenario #	Embodied GWP (kgCO ₂ e)	Operational GWP (kgCO ₂ e)	Whole life building GWP (kgCO ₂ e)	% improvement compared to baseline
Scenario 0	21,609,566	21,741,667	43,351,231	(baseline)
Scenario 1	20,526,248	21,741,667	42,268,344	2.5%
Scenario 2	21,311,623	21,741,667	43,053,735	0.7%
Scenario 3	20,228,305	21,741,667	41,970,394	3.2%
Scenario 4	21,609,566	2,847,786	24,457,804	43.6%
Scenario 5	20,526,248	2,847,786	23,374,464	46.1%
Scenario 6	21,311,623	2,847,786	24,159,855	44.3%
Scenario 7	20,228,305	2,847,786	23,076,514	46.8%

Table 102: Final results of the whole-life building carbon optimization expressed per functional units of gross floor area and gross volume.

Scenario #	Whole building GWP (kgCO ₂ e / m ²)	Whole building GWP (kgCO ₂ e / m ³)	% improvement compared to baseline
Scenario 0	786.6	78.8	(baseline)
Scenario 1	766.2	76.9	2.5%
Scenario 2	780.4	78.3	0.7%
Scenario 3	760.8	76.3	3.2%
Scenario 4	443.3	44.5	43.6%
Scenario 5	423.7	42.5	46.1%
Scenario 6	437.9	43.9	44.3%
Scenario 7	418.3	42.0	46.8%

Finally, the significantly greater impact of operational carbon optimization can be explained by the temporal distribution of emissions. Embodied carbon reductions occur primarily at the construction stage and, where applicable, during replacement events, whereas operational carbon savings are accumulated continuously throughout the entire 50-year service life of the building. The cumulative effect of reduction in grid electricity consumption over several decades becomes substantial. Consequently, the integration of on-site renewable energy generation stands out as the most effective carbon reduction strategy within the scope of this study, while embodied carbon optimization remains an important complementary measure that can deliver additional reductions when combined with operational improvements.

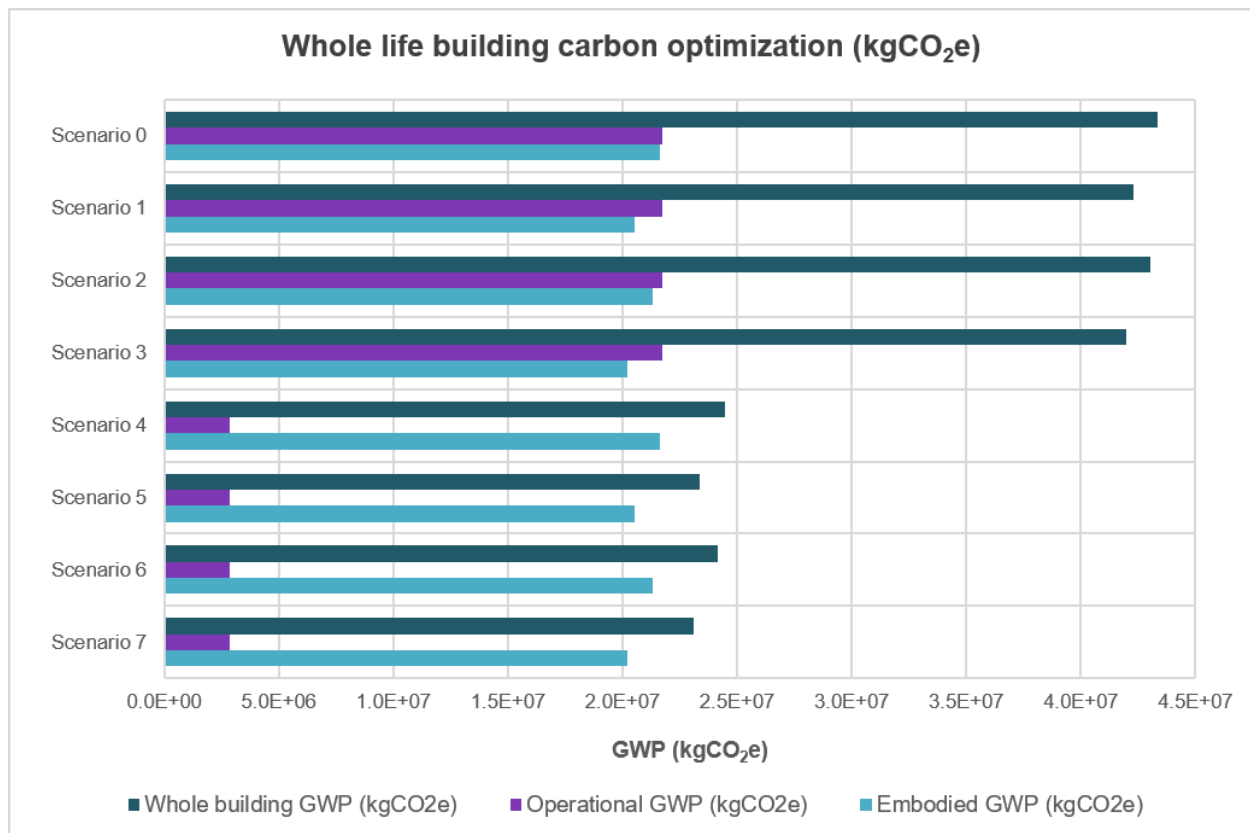


Figure 114: Final results of the whole-life building carbon optimization.

6. Findings, limitations and future work

6.1. Main findings

This thesis was framed around four research gaps identified in the reviewed literature: the lack of LCA case studies of warehouses and their under-representation, difficulty of comparability between the published studies due to different functional units reported, lack of case studies integrating embodied and operational carbon in a single decarbonization framework, and the inconsistent inclusion and treatment of end-of-life and D module representing the net benefits beyond the system boundary. All four gaps informed the structure of this study that sought to provide a direct response to them.

6.1.1. Embodied carbon impacts

Starting from material impacts, with regards to concrete, the literature review established that the most environmentally impacting variable in concrete the binder, i.e. the cement chemistry, particularly the clinker-to-SCM ratio, rather than transport or aggregates and their percentage of recycled or recovered content. By testing 46 concrete mix recipes that were sourced from peer-reviewed experimental literature and applying them to structural precast pillars of the warehouse, the best performing solution is revealed to be a composite cement CEM V/B (S-V) concrete, therefore with cement combining siliceous fly ash and GGBS. This concrete solution reached a GWP of just 121.8 kgCO₂e/m³ compared to 460.8 kgCO₂e/m³ for the baseline CEM I concrete. This represents a carbon reduction of approximately 74%, which aligns closely with the results that Proske et al. (2013) report in their study on eco-friendly concretes with reduced water and cement contents, in terms of GWP per one cubic meter of a concrete sample.

The mixes used demonstrate that a targeted use of additions like superplasticizers and particle packing can reduce both water and cement content at the same time, but without compromising mechanical strength. The compressive strengths achieved in the top-ranked solutions for composite cement, GGBS-based cement and LC3 concrete, revealed as three categories with great potential for carbon reductions, are well above the C30/37 strength class of the baseline (50.9 Mpa for CEM V/B, 54 Mpa for CEM III/B and 50 to even 70 MPa for LC3). This confirms the nuanced conclusion reached from the literature review, that using more cement mass within a cubic meter sample of concrete to reach a higher strength class is resolved in terms of carbon impacts when low-clinker binders are used, with a careful design of the mix and usage of appropriate superplasticizers.

At the same time the study also focuses on the Italian market context of sustainable concrete production, with reference to the roadmap outlined in the report of ETH Zurich (2018) [31] for cement decarbonization. Considering the best-ranked concrete solution contains siliceous fly ash, this study also states that reliance on this SCM is becoming constrained as coal-fired power production is being slowly phased out across Europe. This is particularly acknowledged in the literature addressing the potential of LC3 concrete and regionally available alternatives such as

volcanic ash (natural pozzolanic material) and limestone for which Italy has documented extraction volumes that reach tens of millions of tonnes annually. Therefore, the transition towards more sustainable concrete in the Italian market is actually technically feasible, but it will require both the industrial and regulatory support and additional efforts in laboratory testing for non-standards concrete mixes.

For steel reinforcement, comparing six Italian producers based on their EPD revealed that the main drivers of carbon footprint reduction of rebars are the electricity emission factor and the total scrap rate (TSR). Producer 1 that is using a supplier-specific electricity mix fully backed by Guarantees of Origin (GOs), and achieves a total recycled content of 98.9%, reports a GWP of 353 kgCO₂e/t, which is a 67.2% reduction compared to the baseline generic dataset. This shows that decarbonization goes beyond the mix design of reinforced concrete, because the route to low-carbon is grid decarbonization during the construction process and also maximizing the post-consumer scrap content in the Electric Arc Furnace process.

Further topic discussed is the envelope system that in the literature review is highlighted as a gap in terms of lack of case studies proposing an alternative solution for its optimization, important considering the large surface area involved. A systematic matrix of 117 combinations of three envelope technologies is presented: fully precast concrete panels, metal sandwich panels and timber frame panels. Analysis of the study reveals that timber frame solutions in combination with a precast concrete base consistently delivered the lowest Cradle-to-Grave GWP. The selected optimal solution is a timber frame envelope with cellulose insulation that achieved 40.5 kgCO₂e/m² of envelope surface, which compared to 61.9 kgCO₂e/m² for the baseline made of fully precast concrete panels, represents a 34.7% reduction. The findings of Kovacic et al. (2015) [28] showed even higher reductions, but offering a solution with a completely CLT-based envelope system, that achieved up to 80% lower embodied carbon than steel-based alternatives.

A particularly important finding of this thesis relates to the D module (Cradle-to-Cradle approach) that shows the potential and benefits beyond the system boundary of end-of-life recovery and recycling. When module D is included, the best timber frame solutions show the negative GWP contributions from the envelope, reaching as low as -4.2 kgCO₂e/m² of envelope. Inclusion of the module D aligns with one of the key research gaps identified which is the under-reporting of the end-of-life benefits in warehouse LCA studies. Although this study does not pursue inclusion of the D module on the whole building level, it is a step forward to see how different impacts can result if this stage is included or not, as for bio-based envelope materials including timber and cellulose insulation, the potential is not negligible. At the same time, the study is transparent about uncertainties that accompany calculations of Module D, therefore the optimized solution was selected based on Cradle-to-Grave results to remain methodologically consistent with the rest of the work.

6.1.2. Operational carbon impacts

On the operational side, the baseline scenario reports a balanced results between operational and embodied carbon, referring to the 50-year service life: 394.5 kgCO₂e/m² of the building vs

392.1 kgCO₂e/m², respectively, which is almost exactly a 50/50 split between the two. This is aligned with the literature findings on modern warehouses, such as Bonamente and Cotana [23] reporting results per functional unit aligned with the results of this thesis. On the other hand, this contrast sharply with older warehouse studies where operational carbon actually dominates at 75-85% of total impacts. The baseline results therefore already positions this case study as a high-performing warehouse, with optimization scenarios are then distributed between materials and energy.

Installation of a PV system on the warehouse roof is a strategy consistently recommended across all the critical case studies as a priority measure for warehouse decarbonization, therefore the installation of a 1,800 kWp PV plant (with total of 2,951 modules) is integrated and produces the single largest reduction in the whole-life carbon. Without any battery storage, generation of electrical energy by the PV plant enables the coverage of 70% of the building's annual energy needs. This resulted in the reduction of operational carbon by 70% compared to the baseline and cutting the total whole-life building carbon by 31%. Integrating a 750 kWh battery energy storage system further increased self-consumption and reduced operational carbon to 86%, that being a 38% reduction in total whole-life GWP. The cost-benefit analysis revealed that both schemes (with and without BESS) are economically sensible, both with the discounted pay back period of three years under the Transizione 5.0 incentive scheme. The selection of the 750 kWh BESS as the final optimized solution was based on a multi-criteria comparison between LCA and CBA. Although the NPV improvement of the scheme with no BESS is only 1.9%, the LCA benefit is substantially more significant, with operational carbon cut by more than half compared to the no-BESS configuration.

6.1.3. Total whole-life carbon impacts

Combining all three optimization axes introduced in the Methodology section of this study, which are: building structure, building envelope and on-site renewable energy generation, the final optimized scenario (named as Scenario 7) achieved a whole-life building GWP of 23.08 million kgCO₂e or 418.3 kgCO₂e/m², compared to the baseline of 43.35 million kgCO₂e (786.6 kgCO₂e/m²). Expressed per gross volume, the optimized result reaches 42.0 kgCO₂e/m³ compared to 78.8 kgCO₂e/m³ of the baseline. These results fall within the range of modern warehouse case studies reported in the literature and also present a reference point for future benchmarking of large prefabricated industrial buildings in the Italian and European context.

Across all optimization strategies, the thesis demonstrates what the literature consistently suggests, which is that no single measure alone is sufficient. Embodied carbon optimizations (represented by Scenarios 1-3) achieve 2.5-3.2% improvements, while the operational carbon optimization alone (Scenario 4) achieves 43.6%. Although this is a significantly higher percentage of improvement compared to the first three scenarios, they actually only represent a portion of the structure that can be optimized, therefore embodied carbon has potential to be substantially more improved. Overall, the strategies of proposed improvements of the case studies of the reviewed

literature directly inspired the structure of this thesis, that attempted to be both a response to research gaps and a step forward to benchmarking for future research.

6.2. Limitations and future work

The results of this thesis reflect the assumptions and boundary conditions defined during the goal and scope phase, and some limitations should be acknowledged to correctly interpret the findings and identify directions for future research.

In terms of structural assessment, the concrete embodied carbon optimization was limited to the precast reinforced concrete columns and the reinforcing steel used in cast-in-situ structural elements. The columns were analyzed without a finite element model (FEM), relying instead on a simplified structural scaling approach based on compressive strength. A full FEM model would allow more accurate determination of volumes across all structural elements, including foundations, beams, slabs, and connections. This could reveal additional material savings not captured in this study. The achieved reductions in embodied carbon from the structural optimization should therefore be interpreted as an indication of the potential rather than its maximum extent. A full structural optimization, including different concrete mixes for foundations or the ground floor slab, would require a significantly deeper structural analysis and was deliberately out of scope here, but it represents a valuable next step.

Regarding concrete mix solutions, the best-performing alternatives identified in this study, including CEM V/B composites with fly ash and GGBS, and LC3 systems, actually are not yet standard in the Italian construction market and in some cases do not have Environmental Product Declarations (EPDs) certified and published in Italy (notably LC3). Before these solutions can be applied in practice, further testing and laboratory verification would be required to confirm their durability under real-world exposure conditions, including resistance to carbonation and chloride penetration, which are particularly relevant for precast structural elements. The availability of fly ash is also a structural market constraint as discussed in the thesis, and alternative SCMs should be further explored in the Italian context.

For the building envelope, if the timber frame panel solution is to be implemented, a detailed hygrothermal performance assessment would be required to verify its suitability for a warehouse environment, where humidity control and thermal bridging at panel joints are critical. No cost analysis was performed for the envelope alternatives in this study; a full life cycle cost analysis (LCCA) could reveal significant differences between timber and concrete panel systems, which might shift the preferred solution depending on the project budget and investor priorities. Furthermore, the timber frame panel geometry assumed in this study could be further optimized. For example, by exploring configurations with reduced steel framing content or adjusted insulation thickness, in order to lower both the GWP and potential cost.

The treatment of Module D in this thesis represents a methodological area where the broader research community has not yet reached consensus. The modelling and interpretation of beyond-system-boundary benefits remain actually an active methodological discussion in LCA research, and the results presented in this thesis for the building envelope carry inherent uncertainty around future end-of-life scenarios and substitution assumptions. While this thesis includes a dedicated

discussion of Module D for the envelope, extending this analysis consistently across all building materials would be a meaningful contribution in a future study, which requires a deeper investigation into the appropriate calculation of D modules for the most impacting materials in the inventory.

On the operational side, the PV analysis could be extended with a parametric study exploring different panel orientations, tilt angles, and configurations to further deepen the combined analysis of energy performance, cost-benefit, and life cycle impacts. Additionally, the analysis could be repeated with a PV system sized to cover exactly 100% of the building's energy demand, rather than the current system sized based on available roof area. This could be done to evaluate whether a smaller plant with a more targeted battery storage system could be more cost-effective or deliver a better LCA result per unit of investment.

Finally, it is worth noting that decarbonization of the electrical grid itself, through increased use of Guarantees of Origin (GOs) for steel and concrete production, and higher post-consumer scrap rates in electric arc furnace steelmaking, indeed represents a significant lever that was assessed in this thesis for steel but could be extended further. Future studies covering the entire concrete supply chain with supplier-specific low-carbon electricity data could reveal additional reductions that are not captured by the generic emission factors used here. In conclusion, the path taken in this study is an important starting point, and the total 46.8% reduction achieved should not be read as a ceiling, but rather as a demonstration of the direction and magnitude of improvement that is achievable within realistic design constraints for a modern prefabricated warehouse in Italy.

7. Conclusions

This thesis performs a whole-life carbon assessment of a real, modern prefabricated warehouse building located in Bologna, Italy, and sets out to propose a multi-axis decarbonization strategy combining embodied and operational carbon optimization. The study was motivated by the growing regulatory pressure on LCA reporting in the built environment reinforced by the updated EPBD framework, as well by the recognized gap in the scientific literature of empirical, whole-life warehouse case studies that address both material and energy impacts together.

The baseline scenario, established through a Cradle-to-Grave LCA of the building and its exterior works, produced a total embodied carbon of 392.1 kgCO₂e/m² and a total operational carbon over 50 years of 394.5 kgCO₂e/m², resulting in a whole-life building GWP of 786.6 kgCO₂e/m² (78.8 kgCO₂e/m³). The near-equal split between embodied and operational carbon positioned the building as a high-efficient one and confirms that a decarbonization strategy must address both dimensions simultaneously.

Three optimization axes were then developed and assessed. On the structural side, carbon reduction of precast concrete pillars is analyzed. By applying the best-performing concrete mix which is a CEM V/B composite with fly ash and GGBS reaching 74% lower GWP per cubic meter than the baseline CEM I concrete, combined with switching to the lowest-carbon Italian steel rebar producer (353 kgCO₂e/t, backed by 100% GOs) yielded a 2.5% reduction in whole-life GWP. For the building envelope, replacing the baseline fully precast concrete facade with a timber frame panel system with cellulose insulation and a precast concrete base, delivered a 34.7% reduction in envelope GWP (from 61.9 to 40.5 kgCO₂e/m² of envelope surface), contributing a 0.7% improvement at the whole-building scale. The envelope analysis also revealed the substantial potential of Module D for bio-based materials. Inclusion of the D module allows the best envelope solution to reach even -4.2 kgCO₂/m² of envelope surface, which supports the emerging argument in the literature that beyond-system-boundary benefits should be more consistently integrated in future warehouse LCA studies due to the significant potential of materials that store biogenic carbon or materials with high recycling potential like reinforcing steel bars.

The most impactful strategy was the integration of a 1,800 kWp photovoltaic system on the warehouse roof, paired with a 750 kWh battery energy storage system selected through a joint LCA and cost-benefit analysis. This combination reduced operational carbon by 86% compared to the baseline and yielded a 38% reduction in total building GWP. The discounted payback period of three years, supported by the Italian Transizione 5.0 incentive scheme, confirmed the economic viability of this investment alongside its environmental performance.

When all three axes are applied simultaneously in the final optimized Scenario 7, the total whole-life GWP reaches 23.08 million kgCO₂e, or 418.3 kgCO₂e/m² (42.0 kgCO₂e/m³), representing a total of 46.8% reduction compared to the baseline. Importantly, this combined result is greater than the sum of the individual optimization contributions, confirming a synergetic effect between the three strategies: the material optimizations lower the embodied carbon footprint, while the PV system addresses the operational side, and together they reshape the entire life cycle carbon profile of the building.

Finally, this study's aim was to perform a comprehensive, transparent, whole-life carbon assessment of a real warehouse building, to then propose and quantify optimization strategies and contextualize the results within the existing scientific literature.

Therefore, it can be considered that this thesis fulfilled its aim. Future work can build on this foundation by extending the structural analysis to a full FEM model, conducting hygrothermal and lifecycle cost analyses of the timber envelope system, and exploring the consistent inclusion of Module D across all building materials. The 46.8% carbon reduction achieved here should be seen not as the final optimization result, but as a starting point and a benchmark for the decarbonization of modern prefabricated industrial buildings in the Italian and European context.

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Appendix

LEVEL(s) FRAMEWORK - CONTRIBUTING MATERIALS			
Building Parts	Related building elements	Material	GWP (kgCO ₂ e), stage A1-A3
1.1. Foundations (substructure)	1.1.2. Basements	Ventilated crawlspace	1.80E+03
		Ready-mix concrete	1.81E+05
		Reinforcing steel	9.87E+04
	1.1.3. Retaining walls	Ready-mix concrete	1.70E+05
		Reinforcing steel	1.11E+05
1.2. Load bearing structural frame	1.2.1. Frame (beams, columns, and slabs)	Prefabricated structure	3.27E+06
		Ready-mix concrete	1.02E+05
	1.2.2. Upper floors	Cement screed	6.80E+04
		Ready-mix concrete	6.10E+05
		Reinforcing steel	3.61E+04
1.3. Non-load bearing elements	1.3.1. Ground floor slab	Ready-mix concrete	3.63E+06
		Reinforcing steel	7.64E+05
		Structural joints	3.64E+05
	1.3.2. Internal walls, partitions and doors	Steel profiles	2.26E+04
		Gypsum plasterboard	1.64E+04
		Prefabricated facade	2.00E+05
		Mineral wool insulation	3.77E+04
		Wooden door	1.67E+04
		Sound insulation	6.10E+03
		Concrete Masonry Unit CMU	4.10E+04
	1.3.3. Stairs and ramps	Steel profiles	3.90E+03
		Steel staircase	7.27E+05
1.4. Facades	1.4.1. External wall systems, cladding and shading devices	EPS insulation	9.64E+02
		Prefabricated facade	8.83E+05
	1.4.2. Facade openings	Warehouse door	1.72E+05
		Polycarbonate	2.16E+05
		Aluminium windows	6.67E+04
1.5. Roof	1.5.1. Structure - Roof	Fire protection door	3.50E+04
		Prefabricated structure	2.21E+06
	1.5.2. Weatherproofing - Roof	Aluminium sheet	7.00E+03
		EPS insulation	4.32E+05
		TPO waterproofing roof	2.65E+05
		Steel profiles	6.20E+04
		Plastic vapor membrane	4.10E+02

2.1. Fittings and furnishings	2.1.2. Cupboards, wardrobes and worktops	Electric equipment	6.80E+04
	2.1.4. Wall and ceiling finishes	Interior paint	5.19E+04
	2.1.5. Floor coverings and finishes	Aluminium sheet	4.20E+02
		Epoxy floor finish	3.84E+03
2.2. In-built lighting system	2.2.1. Light fittings	Stone tiles finish	8.50E+03
		Lighting fixture	1.58E+05
	2.2.2. Control systems and sensors	Control system	3.30E+01
		Warehouse door	1.10E+02
2.3. Energy system	2.3.1. Heating & cooling plant and distribution	Heat pump	2.00E+04
		VRV unit	1.10E+03
	2.3.3. Electricity generation and distribution	Electric equipment	4.43E+05
2.4. Ventilation system	2.4.1. Air handling units	Air handling unit AHU	7.21E+04
	2.4.2. Ductwork and distribution	MEV ventilation	1.00E+03
		Control system	2.80E+02
		Foam insulation	5.00E+02
2.5. Sanitary systems	2.5.1. Hot & cold water distribution	Black steel piping	2.03E+03
		Control system	2.10E+04
	2.5.3. Water treatment systems	Copper piping	9.39E+02
	2.5.4. Drainage system	Foam insulation	1.09E+04
		PE piping	1.13E+05
2.6. Other systems	2.6.1. Lifts and escalators	Elevator	3.80E+02
	2.6.2. Firefighting installations	Electric equipment	2.60E+04
		PE piping	1.90E+03
		Sprinklers and flame retardants	4.27E+04
		Control system	6.60E+02
	2.6.3. Communication and security installations	Control system	1.54E+03
		Lighting fixture	1.10E+01
	2.6.4. Telecoms and data installations	Control system	2.00E+02
		Electric equipment	4.80E+01
3.1. Utilities	3.1.2. Substations and equipment	Electric equipment	1.63E+04
3.2. Landscaping	3.2.1. Paving and other hard surfacing	Exterior paving (incl. asphalt)	9.92E+05
		Ready-mix concrete	5.20E+05
		Reinforcing steel	5.66E+04
	3.2.2. Fencing, railings and walls	Exterior paving	8.52E+04
	3.2.3. Drainage systems	PVC-U piping	4.85E+04
		Exterior paving	3.40E+04
		Black steel piping	6.21E+05
		PE piping	9.31E+05
		Prefabricated elements	9.19E+04

Figure 115: Detailed results of the baseline LCA of embodied carbon in the product stage.

Number	Concrete mix	Clinker1 - CEM I 52.5 R	Clinker 2 - CEM I 42.5 R	Clinker 3 - CEM I 32.5 R	GBGS	Fly Ash (EN 450)	Calcined clay	Limestone (powder 1)	Gypsum	Water	Superplasticizer	River sand 0-2mm	River gravel 4-8mm	River gravel 16mm	w/c	28d compressive strength, f _{cm,cube} (N/mm ²)
1	C1-270-FA10-w165	270					10			162	2.8	597	446	847	0.579	53.9
2	C2-270-FA10-w65			270			10			162	1.9	603	446	847	0.579	40.8
3	C3-270-FA10-w165			270			10			162		603	446	847	0.579	34.7
4	C1-240-w180	240								180		601	444	842	0.750	33.6
5	C3-240-w180			240						180	1.3	601	444	842	0.750	24
6	C1-240-FA160-w1180	240					160			179	1.7	569	394	748	0.448	46.8
7	C1-240-FA160-w145	240					160			142	4	509	446	846	0.355	69.4
8	C1-200-FA200-w145	200		200			200			142	4.1	515	440	834	0.355	57
9	C1-175-FA225-w145	175		175			225			142	3.9	519	436	828	0.355	55
10	C1-150-FA250-w145	150		150			250			142	3.1	523	434	823	0.355	42.7
11	C1-150-FA125-LS145-w145	150		150			125	145		142	4	524	434	823	0.338	38.8
12	C1-150-LS288-w125	150		150				289		142	5.1	524	434	823	0.323	27.6
13	C1-150-FA250-w125	150		150						120	6.9	542	444	843	0.300	55.3
14	C1-150-LS288-w125	150		150				289		142	6.5	542	444	843	0.273	37.8
15	C4-90-GBRS60-FA250-w145			90		60	250			143	2.4	523	434	823	0.358	50.9
16	C4-90-GBRS60-FA225-LS145-w145			90		60	125	145		142	3.3	524	434	823	0.338	45.4
17	C4-90-GBRS60-LS288-w145			90		60		289		142	4.5	524	434	823	0.323	40.8
18	C1-125-FA275-w145	125		125			275			143	3.1	528	429	814	0.358	39.3
19	C1-100-FA300-w145	100		100			301			144	1.9	534	424	804	0.359	26.3
20	Mix1; CEM I	380				0	0			190	2	806	413	615	0.500	40
21	Mix2; CEM II/B-V	247				0	133			190	2	794	407	606	0.500	40
22	Mix3; CEM III/B	114				266	0			190		800	410	610	0.500	40
23	100 OPC	390.4								156.3	3.9	739	447	671	0.400	42
24	50 FA	190.3				190.3				152.4	3.81	721	436	654	0.400	24
25	50 BFS	195.4				195.4				156.5	3.91	740	448	671	0.400	56
26	70 BFS	117.3				273.6				156.4	3.91	738	447	671	0.400	54
27	25 FA/25 BFS	191				95.5				153	3.82	723	438	656	0.401	41
28	G30 CEM I	341								180	3.4	701	463	694	0.528	30
29	C30 CEM IIIA	170.5				170.5				180	3.4	701	463	694	0.528	30
30	C40 CEM I	424								180	4.2	636	456	685	0.425	40
31	C40 CEM IIIA	212				212				180	4.2	636	456	685	0.425	40
32	C50 CEM I	499								180	5	586	445	668	0.361	50
33	C50 CEM IIIA	249.5				249.5				180	5	586	445	668	0.361	50
34	Baseline OPC C30	320								175	0	870	406	609	0.547	30
35	Baseline OPC C50	400								165	1.05	783	426	639	0.413	50
36	Baseline OPC C70	500								185	1.5	600	458	687	0.370	70
37	Low-binder LC3 C30	112.5					67.5	33.75	11.25	123	0.45	757	463	695	0.547	28.8
38	Low-binder LC3 C50	140					84	42	14	116	2.33	792	425	637	0.414	49.7
39	Low-binder LC3 C70	175					105	52.5	17.5	130	3.75	855	420	631	0.371	69.6
40	Baseline OPC	370					0	0	0	175		780	420	630	0.473	31.2
41	LC3-50	185					120.25	55.5	9.25	153.2	1.97	780	420	630	0.416	34.4
42	LC3 30 Mpa	137.5					63	37.5	12	137.5	2.13	500	477	715	0.550	28.1
43	LC3 40 Mpa	149.8					74.2	42	14	134.4	3.6	560	448	673	0.480	41.5
44	LC3 50 Mpa	187					84.32	50.66	15.98	132.6	4.2	680	426	639	0.392	54.3
45	LC3 60 Mpa	156.56					149.34	56.62	17.1	132.62	6.4	760	390	584	0.349	59.4
46	C1-170-FA168-w175		170			158			17.75	175	2.485	795	485	540	0.506	37

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