



Horizon 2020



D.4.6: Report on replication made on Innovative Lighting and Energy and CO2 efficiency in existing airport Terminals – PART 3: Energy and CO2 efficiency in Zagreb's Airport Terminal

Grant Agreement number: 101036871

Project acronym: OLGA

Project title: HOListic & Green Airports

Funding scheme: Innovation Action (IA)

Start date of the project: 1st October 2021

Duration: 60 months

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OLGA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 101036871

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DOCUMENT INFORMATION

Document Name	Report on replication made on Innovative Lighting and Energy and CO2 efficiency in existing airport Terminals – PART 3: Energy and CO2 efficiency in Zagreb's Airport Terminal
Version	V1
Version date	22/09/2026
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Security	Public

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DOCUMENT HISTORY

Version	Date	Modification	Authors
V0	31/03/2026	Initial version	Juraj Čukelj (FMENA), Marino Grozdek (FMENA), Irina Stipanovic (IPK), Daniel Rodik (IPK), Marta Erceg (IPK), Petar Paic (GDi), Ivan Lukic (GDi)
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1. Executive Summary

1.1. Introduction

The replication case study is applied to the Zagreb Franjo Tuđman Airport (Zagreb Airport), located in city of Zagreb, Republic of Croatia. The building was built between 2013 and 2017.

Objectives of this sub-task are to replicate the innovative methodology proposed within the deliverable *D4.5. Report including a methodology proposal for design and conception of refurbished airport Terminals*.

The replication case study consists of:

- Step 1: analysis of the proposed methodology and its application for Zagreb Airport. Also, a specific approach is to use the lessons learned in developing the methodology by the Paris' team (D4.5, 2025).
- Step 2: hourly energy assessment, model calibration using Pleiades.
- Step 3: Assessment of environmental impacts for terminal building for embedded construction materials and for the energy usage for heating and cooling processes.

1.2. Brief description of the replication case study

The methodology described in Deliverable D4.5 was analyzed and adapted for application to Zagreb Airport. The proposed approach consists of building modelling, dynamic energy simulation, life-cycle assessment, and calculation of possible energy saving.

The building geometry was initially developed in the Revit BIM environment and subsequently exported as an IFC file. However, the IFC geometry was not directly suitable for energy simulation within the Pleiades software environment. Numerous corrections were required, including adjustments to curtain wall definitions, fixing indoor wall connections, and defining thermal properties of envelope elements such as walls and windows.

After preparing the geometry, the building was divided into thermal zones according to the functional use of spaces. In total, 16 zones were defined. A weather file for the Zagreb location was then prepared and imported into Pleiades.

The weather data consist of hourly climatic values from the Croatian national methodology defined in the Ordinance on Rational Use of Energy and Thermal Protection in Buildings (Official



Gazette NN 128/15, 70/18, 73/18, 86/18, 102/20). The dataset includes hourly values of air temperature, relative humidity, and total and diffuse solar radiation on a horizontal surface.

Dynamic simulation results were compared with measured energy consumption to calibrate the model. Challenges were encountered in defining realistic schedules of internal gains related to equipment operation and passenger occupancy.

Data about the construction materials used in the project were extracted from the BIM model (quantities and type of materials) and enriched with the data from the project documentation, if necessary. This data was used for LCA analysis.

1.3. Limits of the replication case study

Zagreb new Terminal building was constructed in the period of 2013-2017 and designed and built as highly energy efficient building. Therefore, the focus of the replication study was on the development of BIM digital model of the building, development of the energy model and calibration with the usage data, calculation of the environmental impacts for the embedded construction materials and for the energy usage.

The calibration process is limited by the availability and resolution of measured energy consumption data.

Natural gas consumption is measured at a central meter located in the boiler room. The data are available daily for the years 2024 and 2025. No measurements of thermal energy consumption are available at the level of individual zones or specific end users within the terminal.

A similar limitation applies to electricity consumption data. Only total electricity consumption for the terminal building is available, while the contribution of cooling equipment represents only a small portion of the total electricity use.

Additional limitations relate to the zoning strategy adopted for the simulation model. In contrast to the detailed zoning used in the Paris Charles de Gaulle airport model, the Zagreb replication model uses a 16-zone configuration based on the main functional areas of the terminal. Increasing the number of zones could potentially improve simulation accuracy but would significantly increase computational effort in terms of simulation time and memory requirements.

The selected zoning configuration therefore represents a compromise between model complexity and the objectives of the study, namely dynamic energy simulation and model calibration.



2. Replication Of Proposed Methodology for Zagreb Terminal

The methodology proposed in Deliverable D4.5 was replicated for the Zagreb Airport terminal by adapting the data collection, model preparation and calibration steps to the available building information and monitoring data.

Below is a brief analysis of what was done for the replication case study at Zagreb Airport in relation to what was proposed in *D4.5: Report including a methodology proposal for design and conception of refurbished airport Terminals* (Peuportier, B., et al. 2025).

2.1. Data collection

2.1.1. Building Information Model

The French team tested both approaches deriving the thermal model from the BIM model and rebuilding the geometry directly in the energy simulation software. Based on the difficulties they encountered with BIM generation and import, they recommended the floor-plan-based approach as a more robust and time-efficient workflow. The Cluj-Napoca replication team followed this recommendation and used floor plans to define the geometric model in the simulation environment, enabling them to focus on dynamic simulation, calibration, and subsequent optimization steps. In contrast, for our case study we developed the thermal model directly from the BIM model. Significant efforts were made to enable the implementation of the complex BIM model into Pleiades software, which is described in chapter 3.2.1.

2.1.2. Occupancy Scenarios

Data were estimated regarding the use of the different premises, in the form of hourly-daily scenarios specifying over time:

- The number of people present (passengers flow, staff members, employees of companies operating within the terminal perimeter),
- The set-point temperature (heating and cooling),
- Internal heat gains linked to electricity consumption (including shops),
- The supply and exhaust mechanical ventilation flow rates,

2.1.3. Climate Data

A typical year file was used for location of Zagreb Airport, including hourly values for external ambient air temperature, global horizontal and diffuse solar radiation, relative humidity.



2.2. Energy simulation

The dynamic building energy simulation was performed using the Pleiades software environment with geometry model created and exported from Revit BIM model. The results in terms of energy consumption were compared with gas consumption measurements (daily period) and BMS electricity consumption measurements (weekly period).

Model calibration focused on highly uncertain inputs in passenger area such as internal gains of electrical devices and occupancy. These inputs both consume electricity and contribute internal heat gains that affect the building energy balance. As regards infiltration an inherently uncertain input parameter, alongside the mechanical ventilation systems a constant rate of 0.5 ACH was assumed.

2.3. Life cycle assessment

Building Life Cycle Assessment (LCA) is a scientific, ISO-standardized method (ISO 14040/14044) to quantify the environmental impacts (e.g., carbon emissions, energy usage) of a building throughout its life cycle, from material extraction through construction, use, and disposal. In Zagreb case study two main life cycle phases are covered, namely the construction phase (from cradle to gate) and operational phase related to the energy usage.

The process of LCA is basically a comprehensive study structured in four key phases, according to EN-ISO 14044:2006, as presented in Figure 2-1:

1. **Goal & Scope Definition:** Defining the system boundaries, functional units, and impact categories.
2. **Life Cycle Inventory (LCI):** The compilation and quantification of inputs and outputs for a product throughout its life cycle (data collection on raw material extraction, production, transportation, usage, and end-of-life disposal)
3. **Life Cycle Impact Assessment (LCIA):** Understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
4. **Interpretation:** Evaluation of the findings to reach conclusions and recommendations

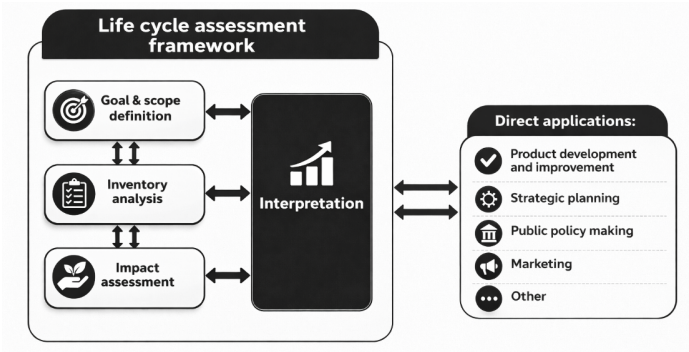


Figure 1 - Stages of LCA according EN ISO 14044

According to EN 15804 key stages of the life cycle are following (Figure 2-2):

- Production & Construction (A1–A5): Raw material extraction, transport, and construction, covering upfront carbon.
- Use Phase (B1–B5): Environmental impacts from maintenance, repair, and replacement of materials.
- End-of-Life (C1–C4): Deconstruction, transportation, and waste processing



Figure 2 - Desired life cycle of the construction products (Puskas & Moga, 2015).

Important aspect of the LCA is to define a system boundary, as a set of consecutive stages with modules each representing one part of the product system. For example, modules A1-A3 are covering product stage for product system, therefore all input and output data describing raw material supply, transport of raw materials and manufacturing shall be collected and used to calculate impact. This stage is also called “cradle to gate” and it is mandatory when manufacturers of a construction products are developing an EPD. All other stages are optional to include in LCA, for example construction process stage with transport and installation of finished products, use stage with use of product, maintenance, repair, replacement etc., and end of life stage such as waste disposal (Stipanovic et al. 2024).

	CONSTRUCTION WORKS ASSESSMENT INFORMATION																	
	CONSTRUCTION WORKS LIFE CYCLE INFORMATION														SUPPLEMENTARY INFORMATION BEYOND CONSTRUCTION WORKS LIFE CYCLE			
	A1 - A3			A4 - A5		B1 - B7							C1 - C4					
	PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE					
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4		
	Raw material supply	Transport	Manufacturing	Transport	Construction - Installation process	Use	Maintenance	Repair	Replacement ¹	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal		
	scenario	scenario		scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario	scenario		
Cradle to gate with modules C1-C4 and module D	Mand.	Mand.	Mand.										Mand.	Mand.	Mand.	Mand.		
Cradle to gate with optional modules C1-C4 and module D	Mand.	Mand.	Mand.	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.	Mand.	Mand.	Mand.	Mand.		
Cradle to grave and module D	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.	Mand.		
Cradle to gate ²	Mand.	Mand.	Mand.															
Cradle to gate with options ²	Mand.	Mand.	Mand.	Opt.	Opt.													

Figure 3 - Life cycle stages and modules for the construction works assessment (EN 15804:2019)

Rationale to include or exclude modules or stages (i.e. cut-off criteria) should be based on their contribution to life cycle impact, or mandatory rules should be applied. For example, stages with significant impacts should be included, and the ones with relatively small impact (e.g. % of

contribution in an impact category) could be omitted, but the LCA study (or final EPD) should clearly state what modules are included in the final life cycle impact assessment.

The core stage of LCA is Life Cycle Inventory (LCI), the compilation of input and output flows for a product system in its life cycle. Various LCA software with databases is used to produce LCI and calculate environmental impact. Available databases such as Ecoinvent are necessary tool to execute this process.

For example, if the electricity with its known attributes (e.g. amount, voltage, location, energy mix, etc.) is used in the product system, precisely in particular process, one has to search for the same or at least most similar flow in the database with its linked “provider” – a process consisting of all upstream, downstream and direct environmental impacts for a unit of electricity (e.g. kWh). The same principle will be used for most of energy carriers, materials and elementary flows like water. But if there is no exact flow - for example for some concrete with a specific mix, it is necessary to model new flow and process with available input data.

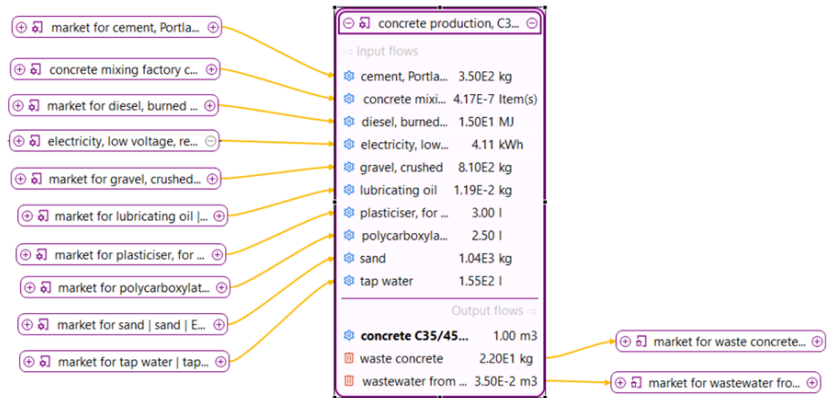
The principle is to assess environmental impacts throughout the entire life cycle of a building, from the extraction and transport of raw materials, manufacturing of building products, and transport to the construction or renovation site, to the construction process, building use, product replacement during the building’s lifetime, and end-of-life stages including demolition and potential recycling (see **Error! Reference source not found.**). Life Cycle Assessment (LCA) considers not only global warming but also other environmental impacts in order to avoid impact shifting—for example, reducing greenhouse gas emissions while increasing impacts on human health (see example in **Error! Reference source not found.**).

Table 1 - Example list of LCA impact indicators (Wurtz et al., 2020)

Impact indicator	unit	Reference
GHG emissions	kgCO ₂ eq.	(IPCC, 2013)
Acidification	kg SO ₂ eq.	(Seppälä et al., 2006 ; Posch et al., 2008)
Eutrophication	kg PO ₄ eq.	(Struijs et al., 2009)
Photochemical ozone production	kg ethylene eq.	(van Zelm et al., 2008)
Cumulative energy demand	kWh	(Hischier et al., 2010)

Water used	m³	(Hischier et al., 2010)
Land use	m².year	(Koellner et Scholz, 2006)
Waste	t	(Hischier et al., 2010)
Radioactive waste	dm³	(Hischier et al., 2010)
Abiotic resource depletion	kg antimony eq.	(Oers, 2016)
Damage to biodiversity	PDF.m².year	(Huijbregts et al., 2016)
Damage to human health	DALY	(Huijbregts et al., 2016)

LCA is becoming increasingly mandatory in the EU construction sector, but the requirements vary by country. At the EU level, LCA is mainly required through building regulations, public procurement, and environmental certification schemes rather than one single EU-wide law. To demonstrated the applicability in the decision making, in **Error! Reference source not found.** an example of a C35/45 concrete production is shown, which is modelled in OpenLCA software as a new flow with Ecoinvent database, using available input data from manufacturer such as amount for each input and output flow. The flows could be material, but also energy or service (e.g. transport). When the product system is complete – modelled with flows and processes the





software will make calculation based on amounts and characterization factors for each environmental impact category.

Figure 4 - Input and output flows modelling for Concrete production in OpenLCA software (Skaric Palic et al. 2025)

Main construction materials present in the Zagreb terminal building will be modelled in the similar manner and used for the environmental impact assessment for embedded construction materials.

Second part of the LCA will be related to the energy usage. The results of energy simulation will be used as input for the life cycle assessment in order to evaluate the environmental impacts of the existing energy systems and to determine potential opportunities for energy saving. For this study we have used Open LCA¹ software with Ecoinvent database².

2.4. Energy savings

In the replication case of the Zagreb Airport New Passenger Terminal, a full optimisation of building envelope parameters was not performed. The terminal building was completed in 2017 and was designed according to relatively high energy performance standards applicable at the time of construction. As a result, the main building envelope components already exhibit favourable thermal characteristics and limited optimisation potential.

For this reason, the analysis did not focus on further optimisation of envelope properties or major structural interventions. Instead, the study concentrated on evaluating additional operational and passive strategies that could further reduce energy consumption, particularly cooling demand, which represents the dominant component of the building's energy balance. The analysis focuses on operational energy-saving measures such as night ventilation, dynamic external shading, and advanced glazing concepts, which can be implemented without major modifications to the existing building structure while still providing measurable reductions in cooling energy demand.

¹ <https://www.openlca.org/>

² <https://ecoinvent.org/ecoinvent-v3-12/>

3. Results for the Replication Case Study: Zagreb Terminal Building

3.1. Presentation of the case study

The case study is new Zagreb Airport, in Republic of Croatia, south façade shown in **Error! Reference source not found.**, aerial view in **Error! Reference source not found.** and interior of the departure terminal in **Error! Reference source not found.**



Figure 5 - Zagreb airport, south facade



Figure 6 - Zagreb airport – aerial roof view



Figure 7 - Zagreb airport - departure terminal

Main terminal's technical characteristics are presented in **Error! Reference source not found..**

Table 2 - Description of studied terminal

Construction year	2017
Gross Area	66,307 m²
Technical data Building envelope	Exterior walls - metal panels thermally insulated with 12 cm mineral wool $U = 0.42 \text{ W/ m}^2\cdot\text{K}$ Curtain walls (double glazed & Aluminum frames with thermal break), $U = 1.8 \text{ W/ m}^2\cdot\text{K}$, $g = 0.41$ Roof metal panels thermally insulated with 16 cm mineral wool $U = 0.34 \text{ W/m}^2\cdot\text{K}$ Floor uninsulated concrete construction
HVAC	Heating – 2 boilers with total heating capacity $2 \times 4.15 \text{ MW}$ and 1 boiler with total heating capacity $1 \times 2.85 \text{ MW}$ at water temperature regime $75/55^\circ\text{C}$ (centralized production in an

	adjacent technical building, for all the buildings of the airport) with dual fuel burners (gas and extra light oil) Cooling – 5 air to water chillers with total cooling capacity 5 x 958 kW at water temperature regime 9/16°C Mechanical ventilation – 30 x AHU with heat recovery, mixing chambers and heating&cooling modules
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3.2. Data collection

3.2.1. Building Digital Model

The objective of this task was to develop a digital building model suitable for energy performance simulation in Pleiades, based on the existing BIM model of Zagreb Airport. Rather than transferring the original design model directly, the aim was to derive a simulation-ready model that would preserve the key spatial, geometric and envelope characteristics of the building while ensuring compatibility with the software requirements for thermal and energy analysis.

The model development process was carried out through an iterative workflow combining BIM model adaptation in Revit and repeated validation in Pleiades. The initial attempt to use the fully detailed BIM model demonstrated that it was not suitable for direct import, due to excessive loading times and incorrect interpretation of the geometry. Consequently, the modelling strategy was revised towards progressive simplification and interoperability testing.

To identify a robust modelling workflow, approximately **150 to 180 test models** were developed and assessed. The first testing phase focused on **GBXML export**. However, this format proved unreliable for the transfer of complex roof geometries, irregular wall-to-roof junctions and curved forms approximated through segmented flat surfaces. Based on these results, the workflow was shifted to **IFC**, which provided more stable and accurate interoperability with Pleiades and was therefore selected as the main exchange format for the subsequent phases of model development.

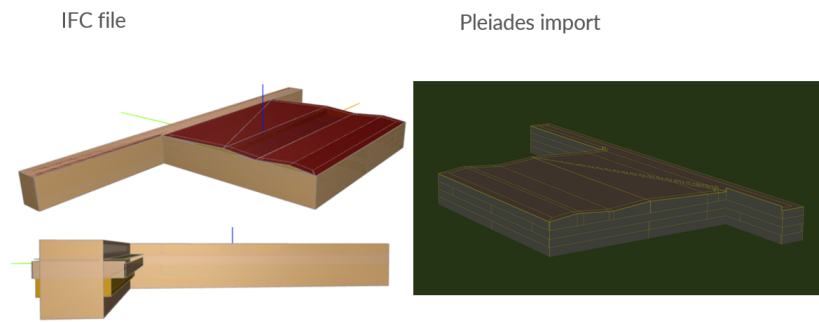
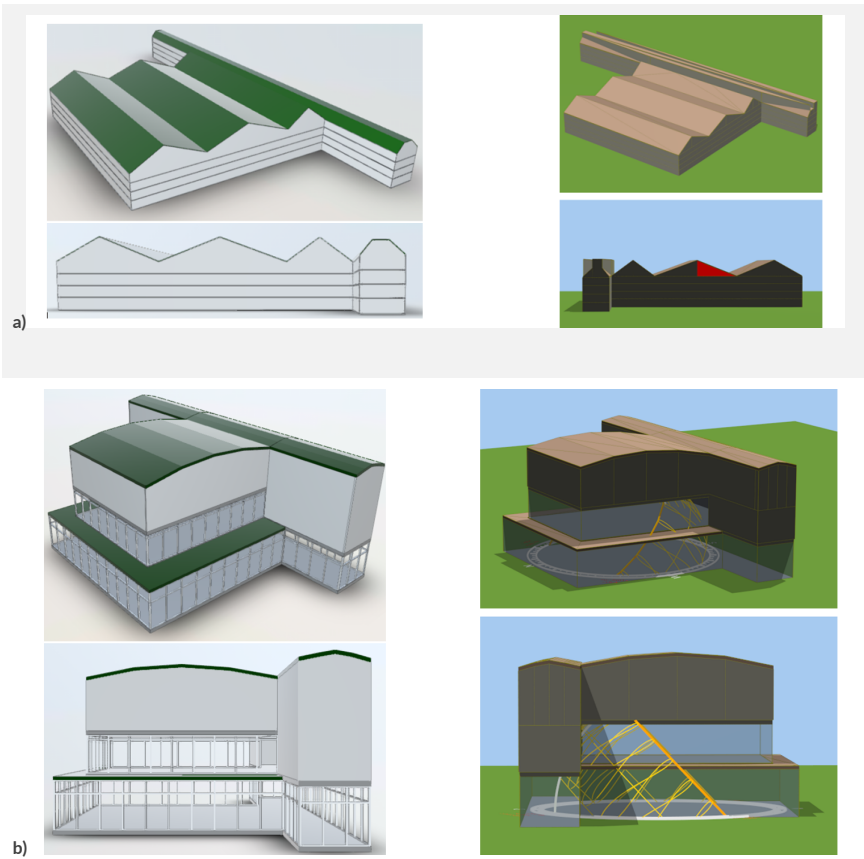
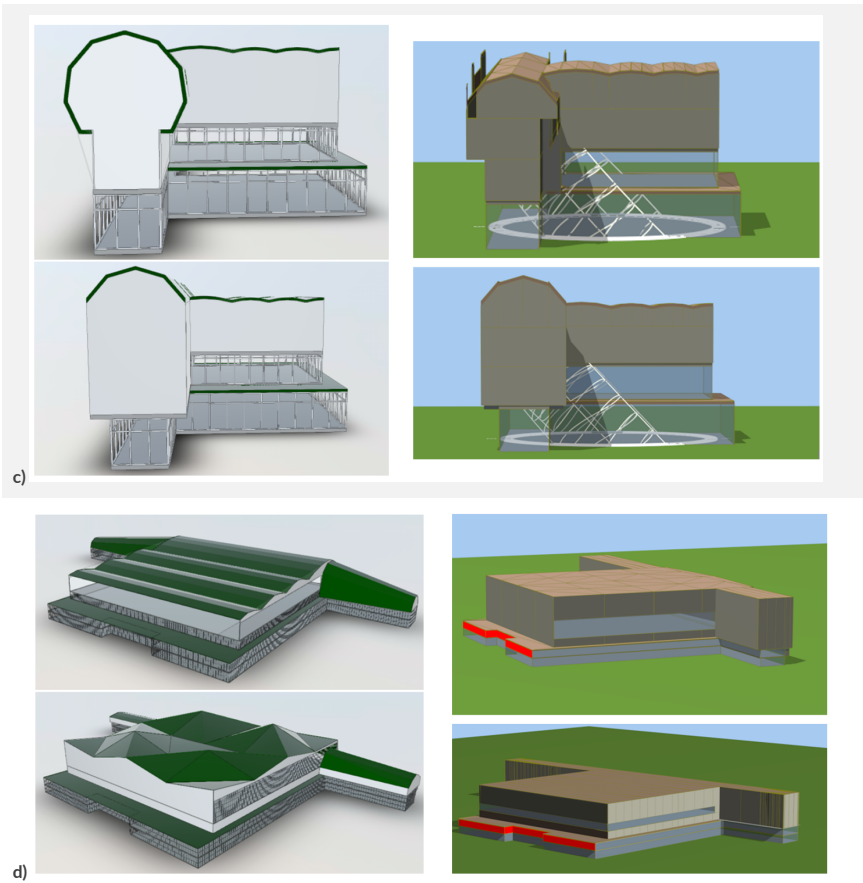


Figure 8 - Initial roof and façade simplifications in BIM model to be implemented and tested in Pleiades

The modelling approach then concentrated on simplifying the geometry of those building elements that had the greatest influence on simulation compatibility, in particular roofs, façade systems and interior spatial subdivisions, as shown in **Error! Reference source not found.** and **Error! Reference source not found.** a) to e). Once a modelling solution was confirmed to perform correctly in Pleiades, it was retained and replicated where possible in order to ensure consistency and reduce the risk of new import errors.

IFC files	Pleiades import
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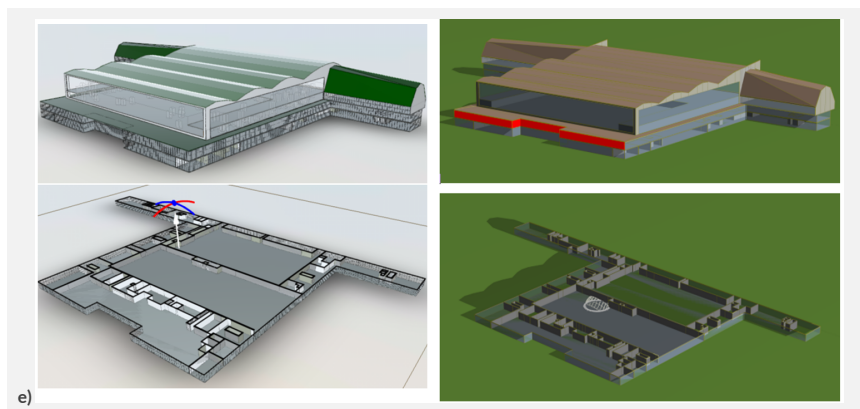


Figure 9 - Iterations of curved roof and glass façade in BIM model to be implemented and tested in Pleiades

Main Findings

The testing process confirmed that the original detailed BIM model had to be substantially simplified in order to become suitable for energy simulation. The main finding was that geometric regularity, continuity and controlled abstraction were essential conditions for successful model transfer. Architectural detail appropriate for design coordination was not directly transferable to the simulation environment.

With regard to interoperability, IFC performed better than GBXML, particularly in the transfer of walls, floors, roof junctions and transparent façade elements. Roof modelling proved to be one of the most critical aspects of the process. Simple sloped roofs and certain segmented curved forms could be imported successfully, provided that their geometry remained regular and did not fold inward. By contrast, cylindrical and semi-cylindrical forms with more complex curvature frequently generated errors or were oversimplified during import. It was also observed that roof elements positioned too close to floor or level references were often misinterpreted by the software. For this reason, only roof geometries that had already been validated were retained and reused through scaling or rotation, instead of introducing additional geometric variations.

The façade modelling tests further showed that curtain walls could be used successfully in some areas of the building, but not directly below roof elements. In such cases, the geometry failed to



close correctly and led to import errors. Likewise, the vertical stacking of different wall types proved unreliable. To address this issue, upper glazed façade zones were represented using regular walls combined with large window elements, which ensured both geometric stability and an acceptable approximation of the intended architectural appearance.

Another important finding concerned the modelling of internal spaces and the control of wall height. The tests confirmed that Pleiades uses building levels, rather than offsets, ceilings or roof constraints, to determine wall termination and enclosed volumes. This required a carefully structured level system throughout the model, particularly for smaller enclosed spaces. Levels therefore acted as control planes for volume recognition and for the proper connection between walls and roof surfaces.

Based on these findings, a set of practical modelling rules was established and applied. These included the use of IFC as the preferred exchange format, simplification of roof and curved geometry, avoidance of inward-folding forms, modelling terraces and open exterior areas as roofs instead of floors, use of regular walls beneath roofs and strict control of wall heights through levels. In addition, all surfaces had to form continuous and closed connections in order to ensure correct recognition of thermal zones and building volumes.

Final Result

The final result of the process was a simulation-ready digital model derived from the original BIM model of Zagreb Airport. The model retained the essential building form, main envelope characteristics, spatial organization and material logic relevant for energy analysis, while excluding or simplifying those features that could not be transferred reliably into the simulation environment.

After more than 150 iterative tests, a complete and functional model was achieved, as presented . The final version included the overall building geometry, roof structures, façades, transparent envelope elements, floors and interior spaces across all relevant levels. Although simplified in comparison with the original architectural BIM model, it provided a stable and sufficiently representative basis for the subsequent thermal and energy performance simulations carried out within the project.

It should also be emphasized that the wall elements in the final simulation model were directly derived from the original detailed BIM model, including all relevant parameters such as material



properties. This ensured that, despite the geometric simplifications applied, the model retained a high level of fidelity in terms of construction and material definition, which is essential for accurate energy performance analysis.

Importantly, the primary source of modelling challenges was not related to the wall systems, but rather to the geometric complexity of the roof. In cases of simpler or more regular roof geometries, it is highly likely that the original detailed BIM model could have been transferred more directly into the simulation environment, without the need for extensive simplification and iterative testing.

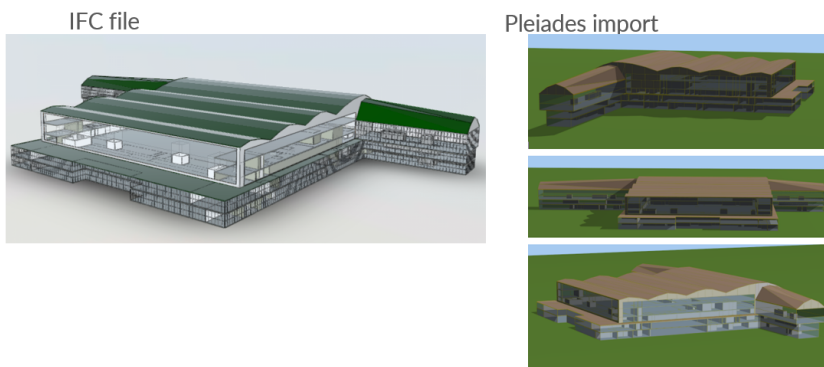


Figure 10 - Final BIM model integrated into Pleiades software for energy simulation

Even with significantly improved geometry in the IFC file, small fixes still needed to be performed in Pleiades. In the following figures problems are shown.

Walls were not connected (**Error! Reference source not found.**) and putting curtain wall through the whole wall was the main problem that could not let calculation complete (**Error! Reference source not found.**). But most importantly, problems with roof generation were nonexistent so there were no changes with roof geometry, see **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**

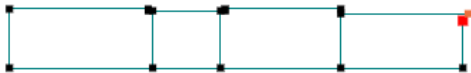


Figure 11 - One of the examples of not connected walls

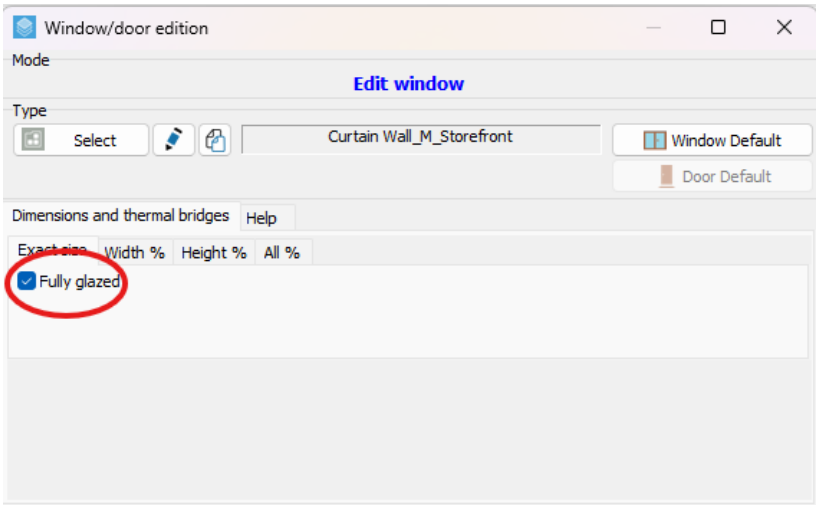


Figure 12 - Pleaides fix for fully glazed wall

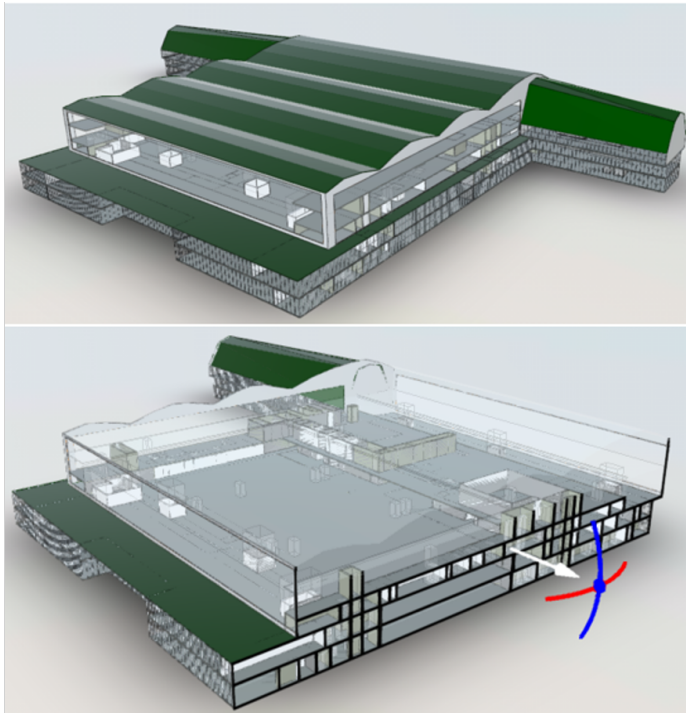


Figure 13 - Output from Revit - .ifc file

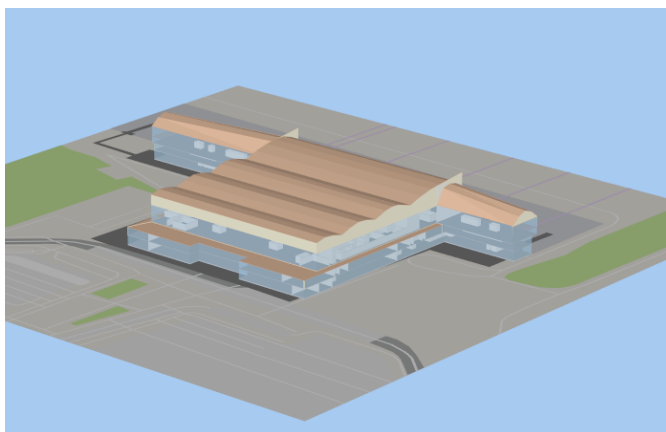


Figure 14 - 3D model in Pleiades

3.2.2. Occupancy Scenarios

The data collected included the following categories of information:

- Occupancy-related data, including:
 - historical records of passenger flows (daily and monthly);
 - the number of airport staff and their working schedules, distinguishing between continuously operated services (24 h/day) and services operating on standard working shifts (8 h/day);
 - the number of employees of companies operating within the terminal
- Operational set-point temperatures for heating and cooling.
- Internal heat gains associated with electricity consumption, including equipment used in commercial areas and shops.
- Mechanical ventilation parameters, including supply and exhaust airflow rates.
- Operational characteristics of building openings, such as the frequency and duration of door opening events and other relevant elements affecting air exchange.

Passenger monthly and daily flow history for one year is presented in **Error! Reference source not found..**

Table 3 - Number of occupants - monthly

No.	Month	Monthly Traffic of Disembarked Passengers	Daily Average of Passengers Disembarked
1	Jan. 25	278.973	8.999
2	Feb. 25	260.411	9.300
3	Mar. 25	314.456	10.144
4	Apr. 25	418.214	13.940
5	May 25	436.514	14.081
6	Jun. 25	436.604	14.553
7	Jul 25.	468.580	15.115
8	Aug. 25	489.803	15.800
9	Sep. 25	468.365	15.612
10	Oct. 25	458.952	14.805
11	Nov. 25	339.490	11.316
12	Dec. 25	334.283	10.783

There are around 317 employees working two shifts every day.

3.2.3. Climate Data

Meteorological conditions were taken from the Croatian national dataset prescribed for building energy calculations under the Technical Regulation on Rational Use of Energy and Thermal Protection in Buildings.

3.2.4. Equipment Data Collection & Hours Of Operation

In addition to the equipment technical data presented in section 3.1, for mechanical ventilation Air Handling Units' specific characteristics are centralized and presented in **Error! Reference source not found..**



Table 4 - HVAC system data

HVAC system data	
Heating system	2 boilers with total heating capacity 2 x 4,15 MW and 1 boiler with total heating capacity 1 x 2,85 MW at water temperature regime 75/55°C (centralized production in an adjacent technical building, for all the buildings of the airport) with dual fuel burners (gas and extra light oil)
Cooling system	5 air to water chillers with total cooling capacity 5 x 958 kW at water temperature regime 9/16°C
Mechanical ventilation	AHU 1 – international departure, 15.000 m3/h, Qh = 73 kW, Qc = 84 kW AHU 2 – domestic departure, 30.000 m3/h, Qh = 134 kW, Qc = 164 kW AHU 3 – restaurant, 7.935 m3/h, Qh = 53 kW, Qc = 25 kW AHU 4.1 – lounge, 16.500 m3/h, Qh = 112 kW, Qc = 118 kW AHU 4.2 – lounge, 16.500 m3/h, Qh = 112 kW, Qc = 118 kW AHU 5.1 – Pier, 11.200 m3/h, Qh = 69 kW, Qc = 30 kW AHU 5.2 – Pier, 24.200 m3/h, Qh = 155 kW, Qc = 63 kW AHU 5.3 – Pier, 16.475 m3/h, Qh = 104 kW, Qc = 40 kW AHU 6 – Commercial area, customs, 8.315 m3/h, Qh = 55 kW, Qc = 25 kW AHU 7.1 – Arrival hall, 18.500 m3/h, Qh = 136 kW, Qc = 118 kW AHU 7.2 – Arrival hall, 18.500 m3/h, Qh = 136 kW, Qc = 118 kW AHU 8 – CNUS, offices, 1.475 m3/h, Qh = 9 kW, Qc = 5 kW AHU 8 – CNUS, offices, 1.475 m3/h, Qh = 9 kW, Qc = 5 kW AHU 9.1 – Baggage claim, 25.500 m3/h, Qh = 104 kW, Qc = 145 kW AHU 9.2 – Baggage claim, 25.500 m3/h, Qh = 104 kW, Qc = 145 kW AHU 9.3 – Baggage claim, 25.500 m3/h, Qh = 30 kW, Qc = 102 kW AHU 10 – Border control, 2.800 m3/h, Qh = 19 kW, Qc = 9 kW AHU 11 – Passport control, 20.000 m3/h, Qh = 61 kW, Qc = 102 kW AHU 12.1 – Departure hall, 26.000 m3/h, Qh = 179 kW, Qc = 153 kW AHU 12.2 – Departure hall, 26.000 m3/h, Qh = 179 kW, Qc = 153 kW AHU 13.1 – Shell & core area, 7.220 m3/h, Qh = 50 kW, Qc = 22 kW AHU 13.2 – Shell & core area, 2.930 m3/h, Qh = 20 kW, Qc = 9 kW AHU 14.1 – Passport control, 30.000 m3/h, Qh = 110 kW, Qc = 139 kW AHU 14.2 – Passport control, 30.000 m3/h, Qh = 165 kW, Qc = 208 kW AHU 15.1 – Departure hall, 24.000 m3/h, Qh = 69 kW, Qc = 106 kW AHU 15.2 – Departure hall, 24.000 m3/h, Qh = 69 kW, Qc = 106 kW AHU 15.3 – Departure hall, 24.000 m3/h, Qh = 69 kW, Qc = 106 kW AHU 15.4 – Departure hall, 24.000 m3/h, Qh = 69 kW, Qc = 106 kW AHU 16 – Kitchen, 3.500 m3/h, Qh = 30 kW, Qc = 13 kW AHU 17 – Departure hall, 6.230 m3/h, Qh = 40 kW, Qc = 18 kW

3.2.5. Zoning Of The Terminal

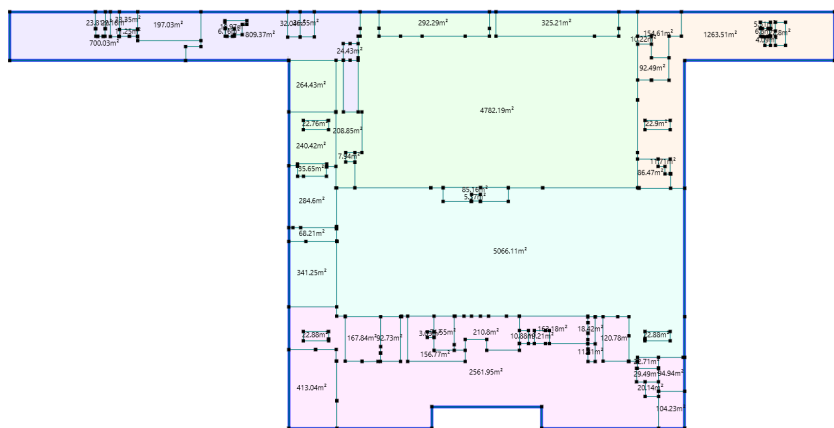


Figure 15 - Ground floor zones



3.3. Configuration of the dynamic thermal simulation

3.3.1. Hourly Climatic Data

Hourly data for the reference station Zagreb–Maksimir typical year were used, including outdoor dry-bulb temperature, relative humidity, and solar radiation components (global/diffuse horizontal irradiation, with the direct component used as needed). Data was converted to .try format and was imported to Pleiades Weather module, see **Error! Reference source not found..** Hourly data for temperature and humidity are presented in **Error! Reference source not found.** and for horizontal radiation in **Error! Reference source not found..**

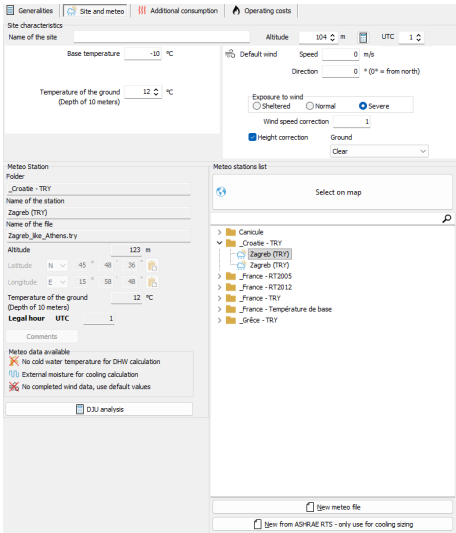


Figure 18 - Weather data import to Pleiades

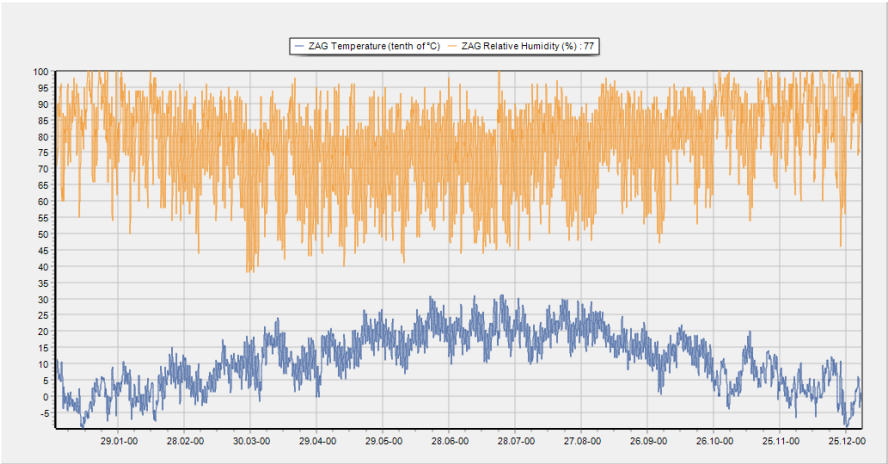


Figure 19 - Hourly climate data - temperature and humidity

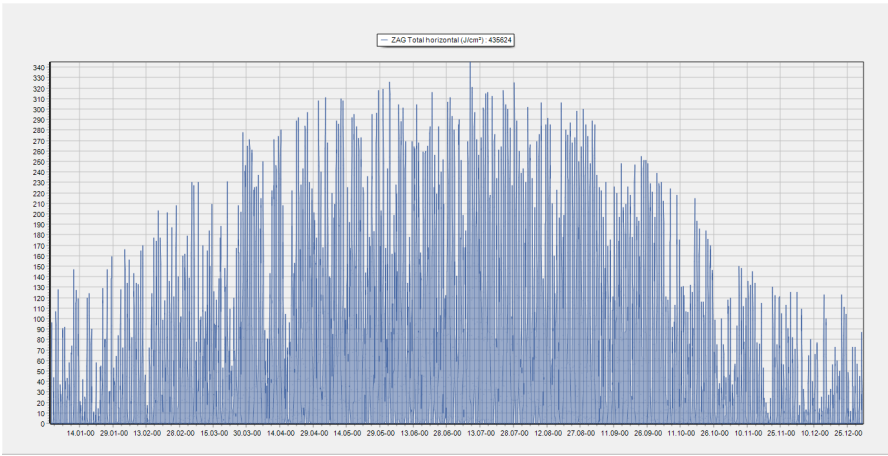


Figure 20 - Hourly climate data – horizontal radiation

3.3.2. Zone Definition

Zoning inside Pleaides was made with using the rules of thermal zoning – zones are decided based on level of the floor, usage patterns, rooms are grouped into zones if usage pattern and indoor temperatures are in +-3 C degree range. Data regarding zones was obtained from sensors set up on passenger terminal, as presented in **Error! Reference source not found..**

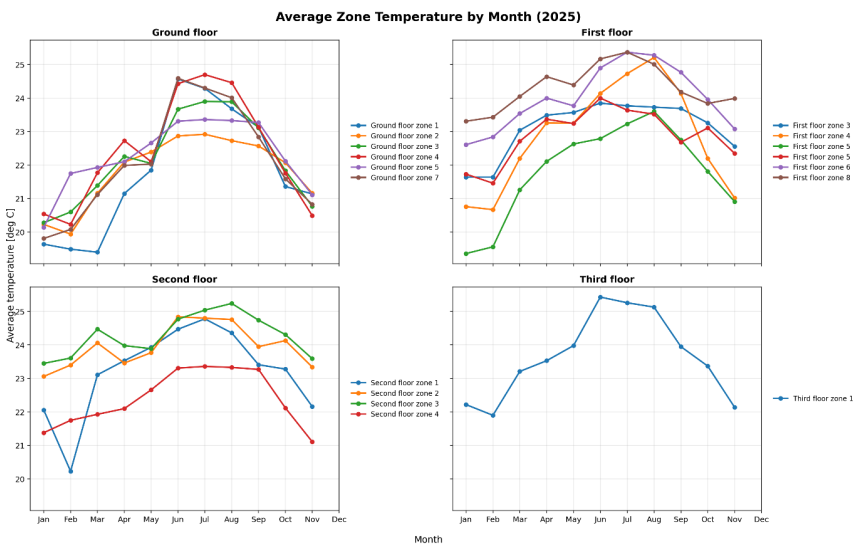


Figure 21 - Average measured zone temperatures

3.3.3. Occupancy Scenario

3.3.3.1. Scenario calibration

The occupancy scenario represents one of the most influential input parameters for dynamic energy simulation of airport terminals. Airport buildings are characterized by highly variable occupancy patterns driven primarily by passenger flows, flight schedules and operational activities.

For the Zagreb Airport replication case study, passenger traffic data were obtained from the airport operator. The dataset contains daily numbers of arriving and departing passengers for the years 2024 and 2025.

This data was used to estimate the number of occupants present in the terminal throughout the day. In addition to passengers, the model also considers accompanying people (greeters), airport staff and employees of companies operating within the terminal

To account for the presence of accompanying people, an additional factor was introduced. Based on operational observations, it was assumed that approximately 50% of passengers are accompanied by an additional person, which is consistent with assumptions used in other airport energy modelling studies. Therefore, the number of greeters was estimated as:

$$Greeters = 0.5 \times \text{number of passengers}$$

The total estimated number of occupants used in the simulation is therefore defined as:

$$Total\ occupants = \text{passangers} + \text{greeters} + \text{airport staff}$$

Passenger traffic data were processed to determine the average daily number of arriving and departing passengers, which were subsequently used to define occupancy schedules within the dynamic simulation model. Airport staff should be near constant value of 317 in two 8-hour shifts.

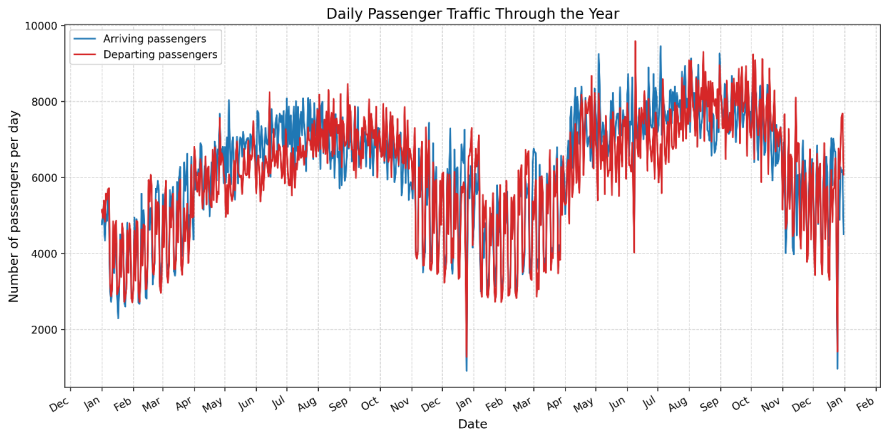


Figure 22 - Daily passenger traffic

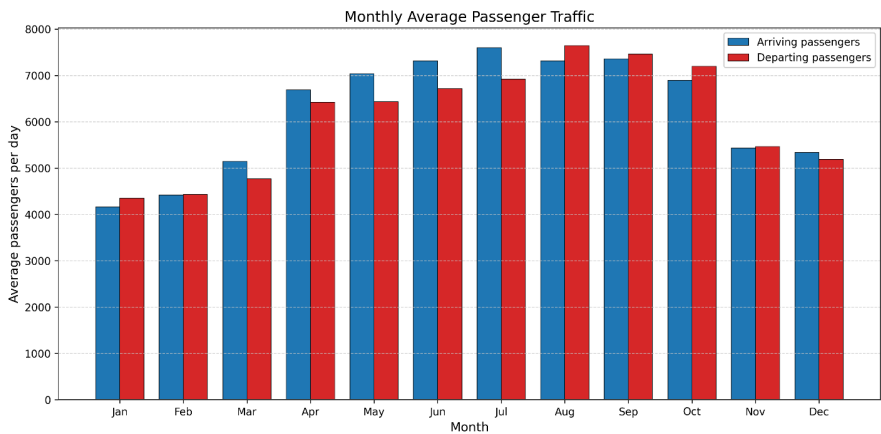


Figure 23 - Monthly average passenger traffic

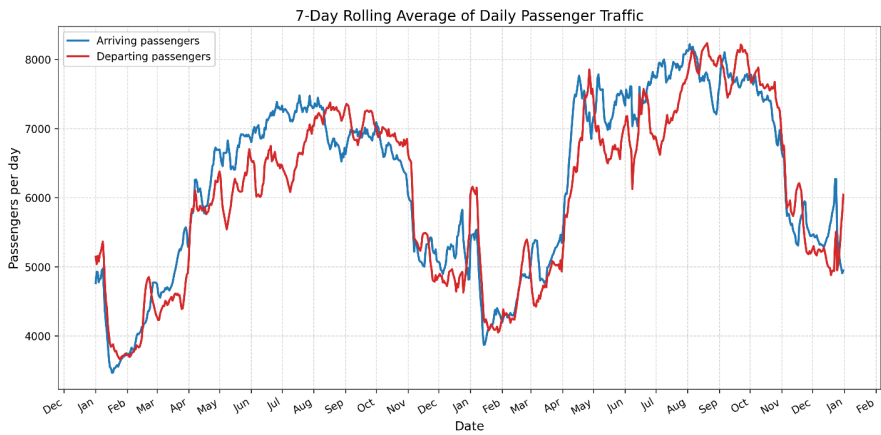


Figure 24 - 7 day average of daily passenger traffic

Electricity consumption data for the New Passenger Terminal were provided by the airport operator for the years 2024 and 2025. The available dataset includes the total electricity consumption at the terminal level. However, detailed sub-metering for all electricity consumers is not available. The missing portion primarily corresponds to loads that are not individually monitored in the Building Management System (BMS) most importantly cooling chillers, lighting systems, auxiliary equipment, and other miscellaneous electrical devices distributed throughout the terminal.

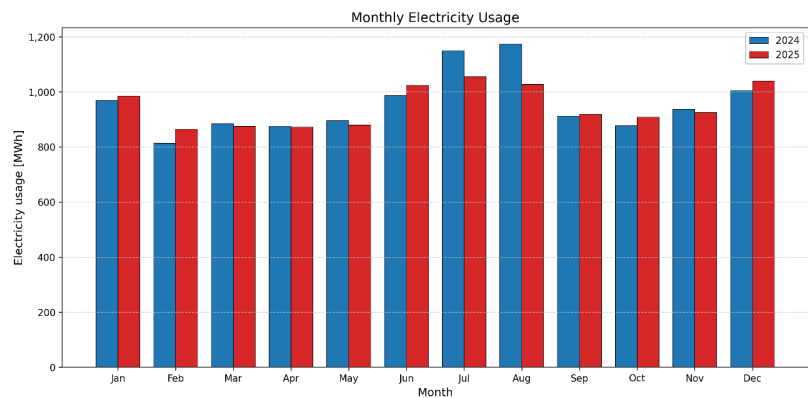


Figure 25 - Electricity consumption measurements

delivered heating energy derived from natural gas consumption measured by the gas meter supplying the heating plant. Daily gas meter readings were used to calculate daily gas consumption, which was converted to thermal energy using a lower heating value of 9.2607 kWh/m³, corresponding to the conversion factor applied by the Croatian gas supplier. Monthly thermal energy consumption was obtained by aggregating the calculated daily energy values.

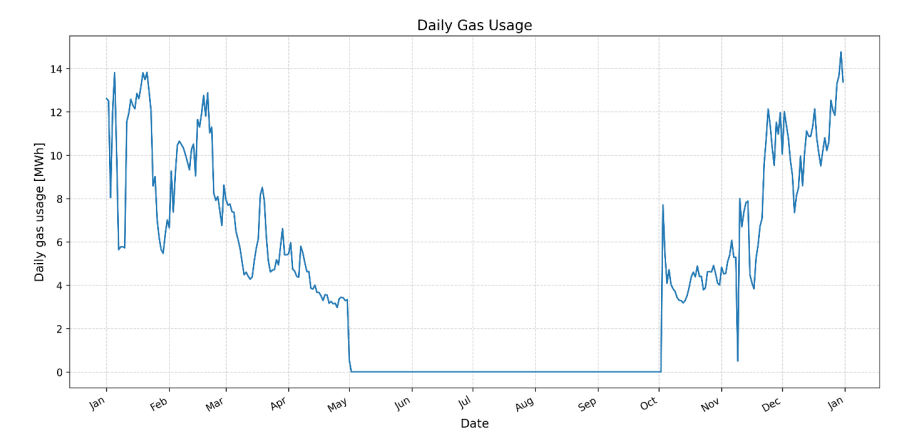


Figure 26 - Gas usage for heating - 2025.

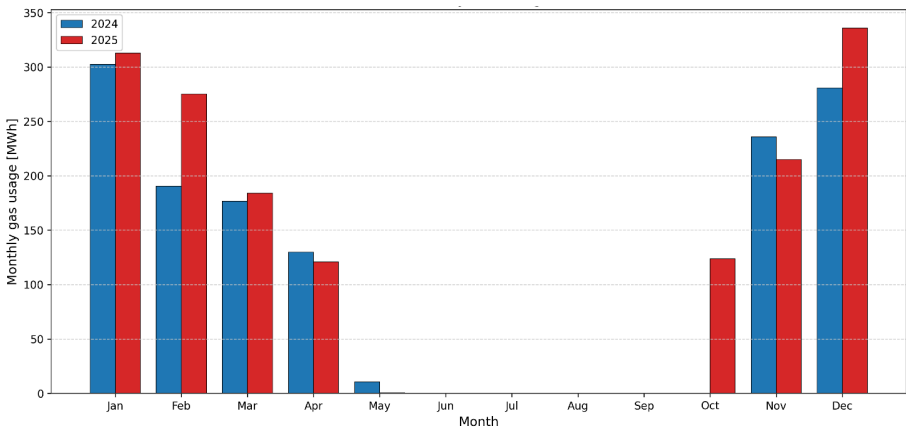


Figure 27 - Monthly gas usage

In Error! Reference source not found. input data for Pleaides is shown.



Table 5 - Input data for Pleiades

Zone No	Zone name	Heating/Cooling scenario	Internal gains	Occupancy	Ventilation
1	Baggage sorting	Set-point measurements Zone 1	40 W/m ²	0.08 occ/m ²	1 h ⁻¹
2	Departure terminal	Set-point measurements Zone 2	10 W/m ²	Daily occupants	1 h ⁻¹
3	Departure terminal	Set-point measurements Zone 3	10 W/m ²	Daily occupants	1 h ⁻¹
4	Baggage claim	Set-point measurements Zone 4	10 W/m ²	Daily occupants	1 h ⁻¹
5	Arrival waiting room	Set-point measurements Zone 5	10 W/m ²	Daily occupants	1 h ⁻¹
6	Departure terminal	Set-point measurements Zone 6	10 W/m ²	Daily occupants	1 h ⁻¹
7	Technical rooms	Set-point measurements Zone 7	40 W/m ²	0.08 occ/m ²	0.5 h ⁻¹
8	Shops, caffe bars and restaurants	Set-point measurements Zone 8	20 W/m ²	Daily occupants	1 h ⁻¹
9	Offices	Set-point measurements Zone 9	10 W/m ²	0.08 occ/m ²	0.5 h ⁻¹
10	Security and border check, check in	Set-point measurements Zone 10	10 W/m ²	Daily occupants	1 h ⁻¹
11	Technical rooms	Set-point measurements Zone 11	40 W/m ²	0.08 occ/m ²	0.5 h ⁻¹
12	Technical rooms	Set-point measurements Zone 12	40 W/m ²	0.08 occ/m ²	0.5 h ⁻¹
13	Unheated space	-	10 W/m ²		1 h ⁻¹
14	Unheated space	-	10 W/m ²		1 h ⁻¹
15	Unheated space	-	10 W/m ²		1 h ⁻¹
16	Unheated space	-	10 W/m ²		1 h ⁻¹

Daily occupants are number that was calculated from departed passengers divided by working hours and overall are for spaces where departed passengers can be found. Similarly for arrival spaces with included greeters which are 0.5 greeters per passenger but only for arrival space.

The overall infiltration rate through the building envelope was assumed to be 0.2 m³/h, reflecting the high airtightness of the curtain wall façade. Air exchange in the building is primarily provided by the mechanical ventilation systems.

3.3.3.2. Calculating Delivered Energy from Pleiades results



The dynamic simulation performed in the Pleiades environment provides hourly useful energy needs for space heating and cooling. To obtain the corresponding energy use by carrier, a post-processing calculation of delivered energy was performed in accordance with the Croatian regulatory framework for building energy performance assessment defined in the Technical Regulation on Rational Use of Energy and Thermal Protection in Buildings (Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama, NN 128/15, 70/18, 73/18, 86/18 and 102/20) and the associated EPB methodology for building energy calculations.

Within this framework, the useful energy need represents the thermal energy required to maintain indoor comfort conditions. Delivered energy is obtained by accounting for losses occurring in the technical systems responsible for energy generation, distribution, emission and control, thus representing the actual energy supplied by energy carriers such as natural gas or electricity.

Hourly useful heating and cooling needs obtained from the dynamic simulation were processed using a Python-based calculation routine developed for this study.

Heating is provided by a gas-fired heating system. The hourly delivered gas energy for heating was determined by dividing the simulated heating need by the overall system efficiency:

$$E_{H,del,gas,h} = \frac{Q_{H,nd,h}}{\eta_{H,gen} \cdot \eta_{H,dis} \cdot \eta_{H,em} \cdot \eta_{H,ctl}}$$

The following efficiency values were used:

- generation efficiency: $\eta_{H,gen} = 0.92$
- distribution efficiency: $\eta_{H,dis} = 0.95$
- emission efficiency: $\eta_{H,em} = 0.98$
- control efficiency: $\eta_{H,ctl} = 0.97$

Thus, the total heating system efficiency is:

$$\eta_{H,tot} = 0.92 \cdot 0.95 \cdot 0.98 \cdot 0.97 \approx 0.829$$

This means that the delivered gas energy is higher than the useful heating need due to losses occurring in heat generation, distribution, emission and control.



Cooling is provided by an electrically driven chiller. The hourly delivered electricity for cooling was calculated from the simulated cooling demand using the seasonal energy efficiency ratio (SEER/EER) and system efficiencies:

$$E_{C,del,el,h} = \frac{Q_{C,nd,h}}{EER_{seasonal} \cdot \eta_{C,dis} \cdot \eta_{C,em} \cdot \eta_{C,ctl}}$$

The following values were used:

- seasonal energy efficiency ratio: $EER_{seasonal} = 3.5$
- distribution efficiency: $\eta_{C,dis} = 1.0$
- emission efficiency: $\eta_{C,em} = 1.0$
- control efficiency: $\eta_{C,ctl} = 1.0$

Auxiliary electricity representing pumps, fans and control systems was included as a fixed share of the delivered heating and cooling energy:

$$E_{aux,el,h} = p_{aux} \cdot (E_{H,del,gas,h} + E_{C,del,el,h})$$

where the auxiliary fraction was taken as:

$$p_{aux} = 0.05$$

Annual delivered energy by carrier was obtained by aggregating the hourly values:

$$E_{del,gas} = \sum_h E_{H,del,gas,h}$$
$$E_{del,el} = \sum_h (E_{C,del,el,h} + E_{aux,el,h})$$

This procedure converts simulated useful thermal needs into delivered energy directly comparable with operational building performance. Since direct measurements of electricity used for cooling were not available, the calibration of the dynamic model was primarily performed against measured heating-related energy use. After achieving satisfactory agreement for the heating



demand, the calibrated model was used to estimate cooling demand and the corresponding electricity consumption through the conversion procedure described.

The delivered energy calculation therefore represents the link between the simulated thermal behavior of the building and the final performance indicators used for analysis and reporting in the replication case study.

3.3.3.3. Main challenges and constraints in calibrating the consumption profile for New Passenger Terminal in Zagreb Airport

Gas consumption and thermal energy consumption

- Heating for the New Passenger Terminal is produced in a dedicated boiler room that serves only this terminal building. As a result, the total natural gas consumption recorded for the boiler room can be directly associated with the energy use of the terminal, which simplifies the estimation of the total thermal energy demand of the building.
- However, the system does not include calorimeters or other sub-metering devices that would allow the distribution of thermal energy consumption to be measured at the level of individual systems or thermal zones. Consequently, it is not possible to distinguish the heating energy used in different parts of the building, which introduces uncertainty when calibrating the simulation model at the zone level.

Electricity consumption

- The main limitation in the calibration process relates to electricity consumption data. The terminal is supplied by a single electricity meter that records the total electrical consumption of the building. This value includes the electricity used by the air handling units (AHUs), chillers, lighting systems, office equipment, retail equipment, and all other electrical devices operating within the terminal.
- Because of this aggregated measurement, it is not possible to separate the electricity consumption associated with individual systems such as cooling equipment, ventilation systems, lighting, or miscellaneous electrical loads. This represents the main challenge when calibrating the dynamic simulation model, as the contribution of individual electricity consumers must be estimated based on assumptions and operational schedules rather than measured sub-metered data.



3.4. Results of dynamic thermal simulation

3.4.1. Zagreb Airport New Passenger Terminal

Dynamic thermal simulations were performed using the calibrated multizone model of the New Passenger Terminal developed in the Pleiades simulation environment. The simulations were conducted for a full reference year using hourly climatic data representative of the Zagreb region.

The objective of the simulation was to estimate the heating and cooling energy demand of the terminal and to evaluate the temporal variation of thermal loads under realistic operating conditions defined by occupancy schedules, internal heat gains, ventilation rates and HVAC system characteristics and temperature set point is measured temperature.

The results of the simulation provide insight into:

- the annual energy demand of the building,
- the seasonal variation of heating and cooling loads,
- the hourly power demand during representative periods of the year.

The obtained results were subsequently compared with measured energy consumption data to validate the simulation model and assess the accuracy of the calibration process.

Error! Reference source not found. presents the hourly heating and cooling energy demand. The results show a typical behavior like that observed in the Paris–Charles de Gaulle terminal case. The building exhibits relatively low heating demand, with a maximum heating capacity of approximately 1.3 MW, while the cooling demand is significantly higher, reaching a maximum required cooling capacity of about 2.4 MW.

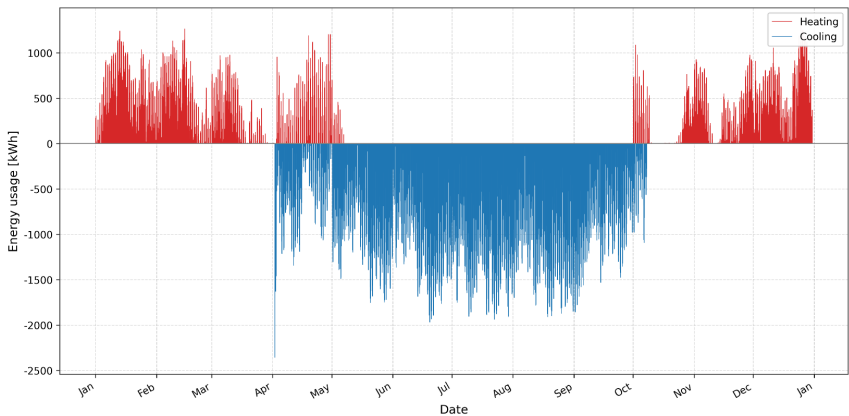


Figure 28 - Calculated hourly thermal energy usage

Error! Reference source not found. presents the monthly simulation results compared with the measured natural gas consumption, which was converted into heating energy. The comparison indicates that the model reproduces the measured energy use with reasonable accuracy. As shown in **Error! Reference source not found.**, the difference between measured and simulated heating energy amounts to approximately 11%, which is considered acceptable for the purposes of further analysis. A larger relative deviation is observed in May, where the percentage difference reaches 2220%. However, in absolute terms this corresponds to only 11 MWh and is therefore not significant in the annual energy balance. This discrepancy is likely related to differences in meteorological conditions during that month.

Error! Reference source not found. additionally shows that energy consumption varies significantly between different years. Considering that the simulation was performed using a typical meteorological year rather than the exact weather conditions of 2025 used for the comparison, the overall agreement between simulated and measured data can be considered satisfactory.

The calculated specific useful energy demand of the New Passenger Terminal in Zagreb amounts to 24.08 kWh/m² for space heating and 46.23 kWh/m² for space cooling.

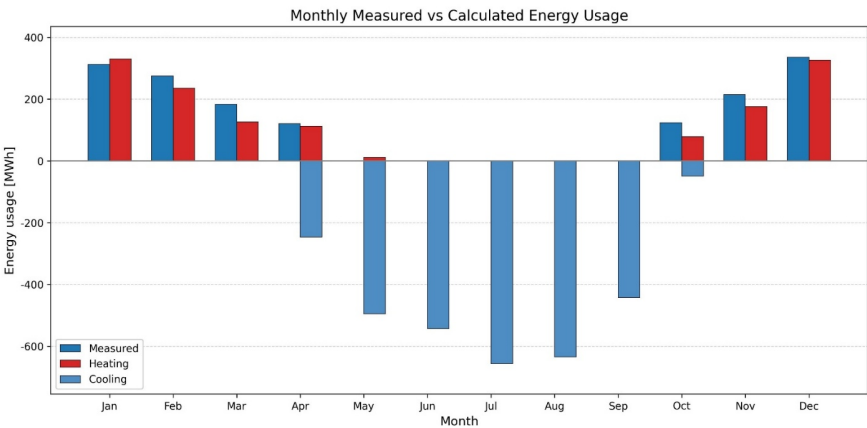


Figure 29 - Monthly calculated and measured energy use

Table 6 - Comparison of measured and calculated energy usage

Heating	Measured [MWh]	Calculated [MWh]	Difference [%]
January	312.6	330.5	+5.73
February	275.1	235.2	-14.50
March	183.9	126.1	-31.43
April	120.7	112.9	-6.46
May	0.5	11.6	+2220.00
June	0	0	n/a
July	0	0	n/a
August	0	0	n/a
September	0	0	n/a
October	123.7	78.0	-36.94
November	214.8	175.5	-18.29
December	335.9	326.6	-2.77
SUM	1,567	1,396.4	-10.89

Delivered energy for heating and electricity consumption for cooling were calculated using the national EPB calculation methodology. The results are presented in **Error! Reference source not found.** and **Error! Reference source not found.**

Higher deviations are observed in January and December; however, the overall difference between calculated and measured values is 1.89%. This level of accuracy indicates that the model provides sufficient accuracy for further analysis.

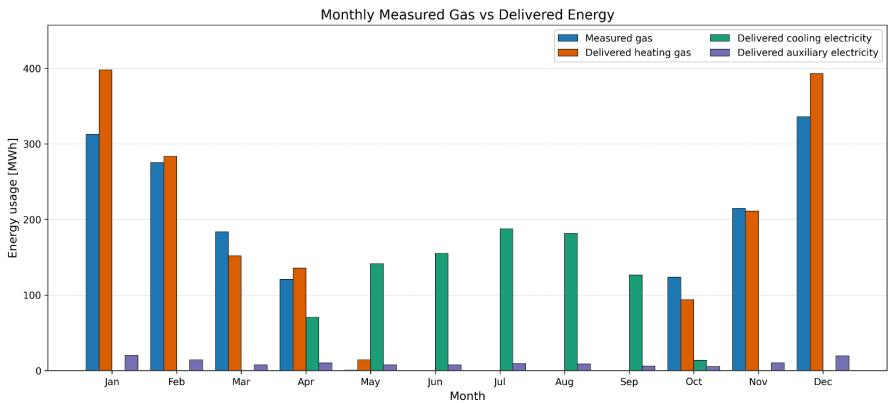


Figure 30 - Monthly measured and delivered energy

Table 7 - Measured and delivered energy for heating

Heating	Measured [MWh]	Calculated delivered [MWh]	Difference [%]
January	312.6	377.7	+20.89
February	275.1	269.3	-2.11
March	183.9	144.2	-21.59
April	120.7	129.0	+6.88
May	0.5	13.3	+2560
June	0	0	n/a
July	0	0	n/a
August	0	0	n/a
September	0	0	n/a
October	123.7	89.2	-27.89
November	214.8	200.6	-6.61

December	335.9	373.4	+11.16
SUM	1,567.1	1,596.7	1.85

Error! Reference source not found. and **Error! Reference source not found.** focus on cooling-related electricity consumption, which represents the primary energy source for cooling. Figure 31 shows the total measured electricity consumption together with the calculated electricity used by the chillers. The results indicate that electricity consumption during the summer months remains close to the base electricity demand observed in other months, with slightly lower values in May and September. Lower electricity consumption in May and September can be attributed to transitional seasonal conditions. During these months, outdoor temperatures are generally moderate, resulting in reduced cooling demand and lower operation of auxiliary systems associated with peak summer conditions. Chillers therefore operate at partial load, where their instantaneous efficiency (EER) is typically higher, leading to lower electricity consumption for the same cooling output. This effect is not explicitly represented in the model, as a constant seasonal efficiency (SEER) was applied for the cooling system. In addition, favourable outdoor conditions may improve the operation of air handling units, further reducing the electricity demand of the chiller system.

Table 8 - Measured and calculated energy needed for cooling

Electricity (cooling)	Measured [MWh]	Calculated energy needed for cooling [MWh]	Calculated delivered electric energy for cooling [MWh]
January	985.2	0	0
February	864.6	0	0
March	875.5	0	0
April	871.7	246.3	73.9
May	879.1	495.2	148.6
June	1,023.6	542.5	162.8
July	1,055.0	655.8	196.7
August	1,027.5	634.4	190.3
September	919.1	442.6	132.8
October	907.8	48.9	14.8
November	925.2	0	0

December	1,039.9	0	0
SUM	11,374.2	3,065.7	919.9

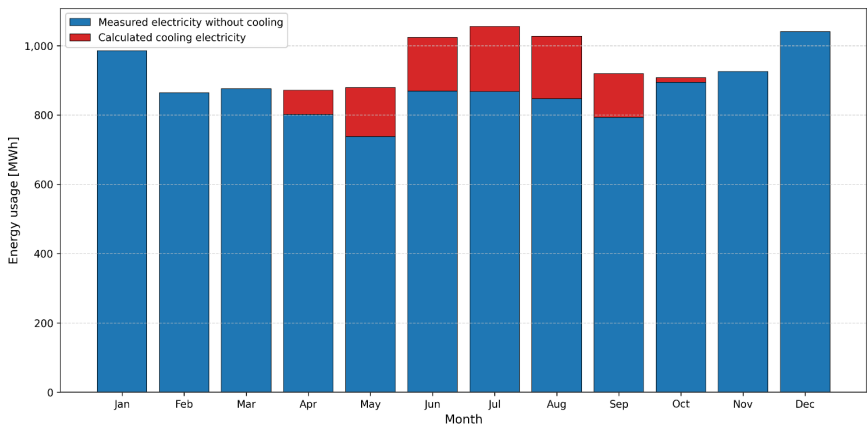


Figure 31 - Monthly electricity consumption including calculated cooling electricity

3.5. Results of the life cycle assessment

The main goal of LCA for this study is to determine the environmental impacts such as global warming potential and primary energy consumption of the existing Zagreb airport terminal, then compare the impacts of the existing buildings to the optimized proposals. The assessment was carried out using the Open LCA software, utilizing data from the ECOINVENT database (version 3.12, EN15804 unit processes).

3.5.1. Goal And Scope Definition

Life Cycle Assessment (LCA) was employed to evaluate the environmental impacts across the product stage of materials used in construction and energy in use stage.

The evaluation scope covers the entire life cycle which is assumed to be 50 years, consisting of construction stage, use stage renovation and the end-of-life stage. Therefore, calculation covered

following LCA modules: A1 raw material supply, A2 transport during product stage, A3 manufacturing of construction materials, A4 transport of construction materials, B6 operational energy usage and end of life stages C1 to C4.

The system boundaries considered the processes related to building operation, (e.g. district heating system using gas and light fuel oil for heating and sanitary hot water (DHW)) and all upstream processes related to the production of construction materials used.

The functional unit is 1 m² net floor area over one year, based on a life cycle of 50 years for the Zagreb new terminal building.

3.5.2. Inventory Analysis

The Life Cycle Inventory assessment (LCIA) phase involves data collection and the calculation procedure for the quantification of inputs and outputs of the product stage including modules A1 to A3 product stage, A4 transport of construction materials, B6 operational energy in use stage and C1-C4 end of life stage including deconstruction, transport, waste processing and disposal

Quantities of construction materials for LCA calculations were extracted from BIM / IFC model by creating a material take off schedule in Revit. The schedule was exported as an Excel spreadsheet, where all model materials grouped into seven 7 material groups. The amounts of materials used in construction with corresponding processes from ECOINVENT database (v 3.12) are shown in **Error! Reference source not found..** Chosen processes are the most similar ones for the construction materials used, with existing data such as input and output flows for the production in EU.

Table 9 - Construction materials, amounts and corresponding processes in ECOINVENT database

MATERIAL GROUP	MATERIAL TYPE	PROCESS (LCA) in ECOINVENT database	Amount	Unit
CONCRETE and REINFORCEMENT	Reinforced Concrete_C30/37	Concrete production. 30MPa. exposure classes XC3/XD2/XF1/XA1. with cement. unspecified	19,919	m³
	Reinforced Concrete_C25/30	Concrete production. 25MPa. for building construction. with cement. CEM II/A	4,385	m³



	Concrete - Cast-in-Place	Concrete production. 30MPa. exposure classes XC3/XD2/XF1/XA1. with cement. Unspecified	10	m ³
	Reinforcement	reinforcing steel production reinforcing steel EN15804GD. U	2,871,000	kg
ROCKWOOL	Rockwool insulation	stone wool production. packed	599,717	kg
DRYWALL BOARDS	Plasterbord	gypsum plasterboard production	942,668	kg
	Fibreboard	gypsum fibreboard production	274,608	kg
	Cement bord	particleboard production, cement bonded	27,413	kg
GLASS	Flat glass uncoated	flat glass production, uncoated flat glass, uncoated EN15804GD, U	1,042,350	kg
	Tempered flat glass	tempering. flat glass tempering. flat glass EN15804GD. U	214,800	kg
	Coated flat glass	flat glass production, coated	86,800	kg
STEEL	Steel construction elements (other than reinforcement)	sheet rolling, steel	10,251,472	kg
BRICK	Clay brick block	clay brick production, extruded	1,910,286	kg
	Aerated concrete block	autoclaved aerated concrete block production	14,070	kg
ALUMINIUM	Aluminium (roofing sheets, drywall profiles)	sheet rolling, aluminium	129,654	kg



Model graph modelled in Open LCA , presented in the **Error! Reference source not found.**, shows input flows for the A1-A3 phase with all construction materials of the terminal presented as a product systems. Graph is also showing as an example with the input (cement, gravel, sand, water, diesel, electricity, etc) and output flows (concrete, waste) to produce a concrete 25Mpa modelled in ECOINVENT .

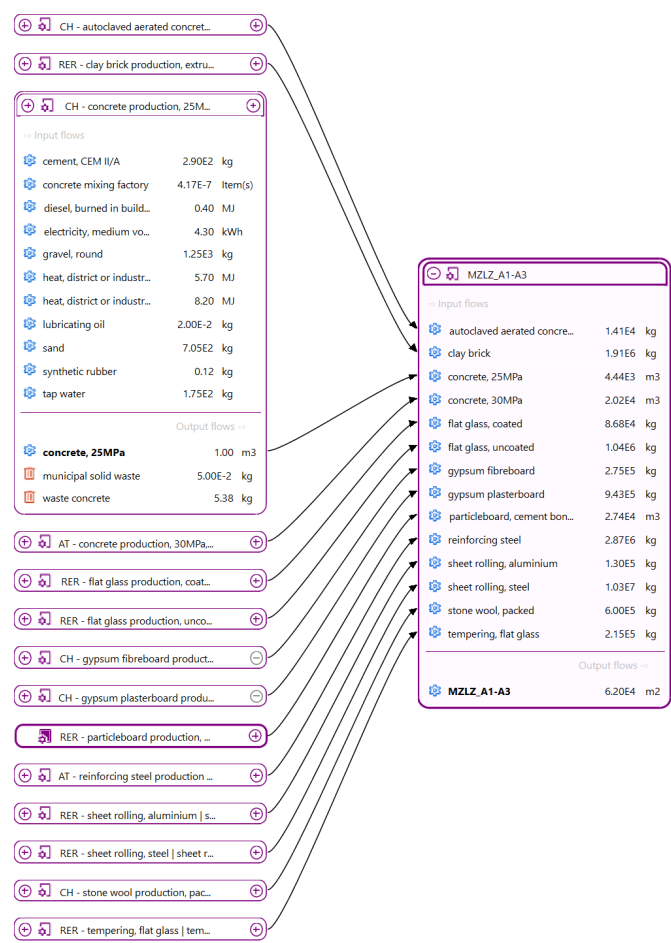


Figure 32 - Model graph for the A1-A3 construction of the terminal

Construction materials are assumed to be transported by truck over a distance of 100 km from factories. This process is a module A4 transportation, modelled as a transport of materials (total mass of 79125 t), with diesel lorries, > 32 tons, Euro 6, multiplied with distance in km, presented in **Error! Reference source not found..**

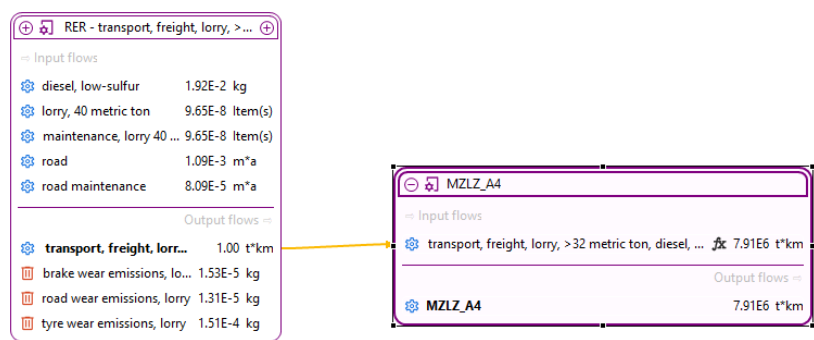


Figure 33 - Model graph for the A4 transport of construction materials

LCA calculation included energy use in the module B6 - operational energy. Input data is a life cycle energy consumption for 50-year period of building use, split into electricity, natural gas and light fuel oil consumption. Electricity is used for cooling, lighting and all electric equipment on terminal, while natural gas and light fuel oil are used for heating of the building and domestic hot water – DHW. **Error! Reference source not found.** shows energy consumption based on measured data in reference year 2025 and predicted energy consumption for the whole life cycle of 50 years.

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Table 10 - Annual and life cycle energy consumption for the terminal

ENERGY	Annual (2025)	LC 50 years	Unit
Gas	169,163	8,458,150	m3
	6,214,658	310,732,917	MJ
Light Fuel Oil	5,320	228,760	l

	195,354	9,767,720	MJ
Electricity	10,334	516,713	MWh
	37,203,386	1,860,169,306	MJ

Model graph modelled in Open LCA , presented in the **Error! Reference source not found.**, shows input flows for the B6 phase with all energy use of the terminal presented as a product system. Also, the graph shows which processes are inputs and outputs for the LCA. Operation energy use LCA phase covered direct impacts such as burning of gas and light fuel oil, and all upstream impacts in the life cycle of energy used including extraction and transport of raw materials, production of fuels, production and distribution of electricity to the final consumer.

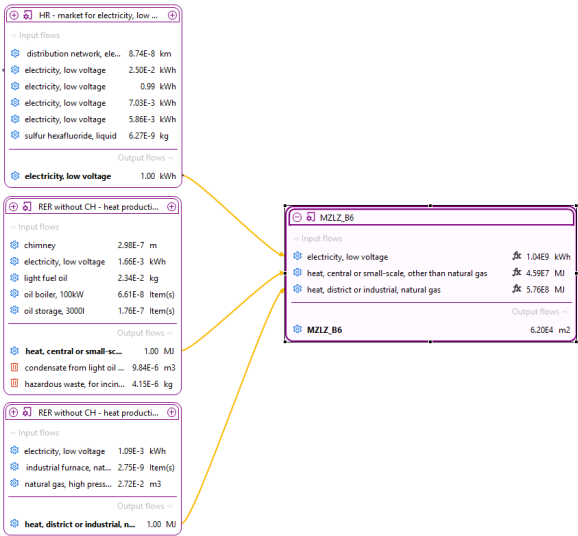


Figure 34 - Model graph for the B6 energy use of the terminal

The treatments of the construction materials at the end of life are recycling, landfilling and incineration. Calculation also included deconstruction and transport to the landfill and recycling

plants. The distance from the site to landfill plant in the deconstruction stage is 20 km. Aluminium and the steel from reinforcement and construction elements are supposed to be recycled at a recycling rate of 100% and used again, reducing the overall environmental impact. Concrete, bricks, glass and mineral wool are treated as inert materials and supposed to be landfilled. Plaster boards products are processed for final disposal to be incinerated and landfilled. **Error! Reference source not found.** shows the input flows - total mass of construction materials demolished and transported for recycling (aluminium and steel) or waste processing (other).

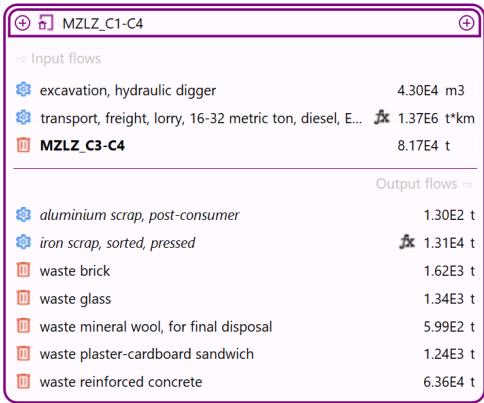


Figure 35 - Model graph for the module C1-C4 end of life

3.5.3. Life Cycle Impact Assessment

LCIA results are calculated according to inventory analysis presented previously.

The functional unit is 1 m² net floor area over one year, based on a building life cycle of 50 years. The relevant area is taken as the net usable floor area of the four levels of the new passenger terminal, obtained from a Revit schedule as the sum of the areas of all terminal rooms, amounting to 62,000 m². **Error! Reference source not found.** is showing LCIA results in 4 LCA modules.



Table 11 - LCA results in 13 impact categories (EN 15804:2019), and four modules of a terminal building life cycle

Impact category	Product stage (A1-A3)	Transport (A4)	Use stage (B6)	End of life (C1-C4)
Global Warming Potential - total (GWP-total) kg CO2 eq.	4.31E+00	2.60E-01	9.11E+01	7.11E-02
Global Warming Potential - fossil fuels (GWP-fossil) kg CO2 eq.	4.27E+00	2.60E-01	8.90E+01	7.05E-02
Global Warming Potential - biogenic (GWP-biogenic) kg CO2 eq.	4.28E-02	1.45E-04	2.11E+00	7.17E-04
Global Warming Potential - land use and land use change (GWP-luluc) kg CO2 eq.	2.30E-03	9.45E-05	2.95E-02	-1.25E-04
Depletion potential of the stratospheric ozone layer (ODP) - kg CFC-11 eq.	7.89E-08	6.13E-09	1.50E-06	1.61E-09
Acidification potential, Accumulated Exceedance (AP) mol H+ eq.	1.80E-02	6.13E-04	9.59E-01	2.45E-05
Eutrophication potential - freshwater (EP-freshwater) kg P eq.	1.13E-03	1.92E-05	1.02E-01	-5.95E-05
Eutrophication potential - marine (EP-marine) kg N eq.	3.98E-03	1.70E-04	9.38E-02	2.65E-04
Eutrophication potential - terrestrial (EP-terrestrial) mol N eq.	4.49E-02	1.83E-03	8.14E-01	2.83E-03
Photochemical Ozone Creation Potential (POCP) kg NMVOC eq.	1.39E-02	1.08E-03	2.77E-01	9.66E-04

Abiotic depletion potential - non-fossil resources (ADPE) kg Sb eq.	2.93E-05	7.83E-07	7.05E-04	-6.55E-06
Abiotic depletion potential - fossil resources (ADPF) MJ, net calorific value	4.14E+01	3.92E+00	1.33E+03	9.72E-01
Water (user) deprivation potential (WDP) m3 world eq. deprived	2.26E+00	2.26E-02	7.20E+01	-1.28E-02

Specifically, operational energy use in use stage B6 is the largest contributor to GWP total with 91.1 kg CO₂ per m2/ year, such as to other impact categories presented on **Error! Reference source not found..**

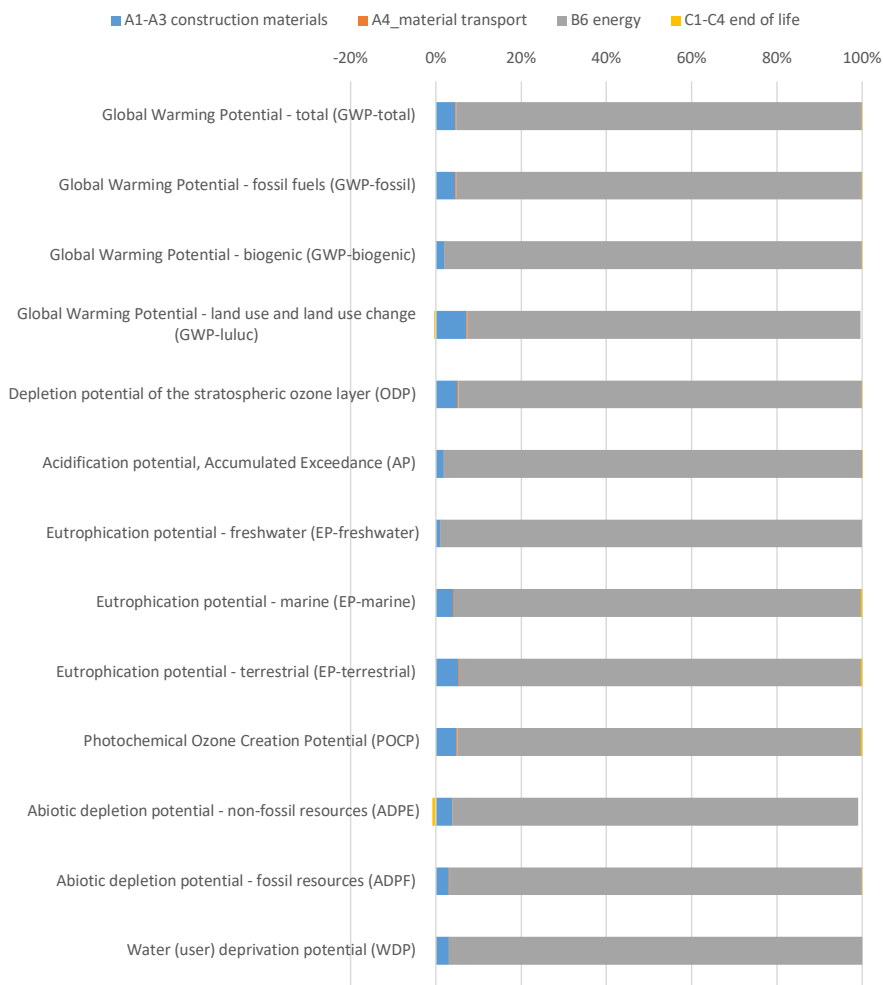


Figure 36 - Contribution of life cycle modules to 13 different environmental impact categories
Electricity consumption generates most of the GHG emissions in the use stage and is the largest

contributor to environmental impact in all modules. GHG emissions from use of gas and light fuel oil are both direct (due to fuel combustion) and indirect (upstream impacts of fuel production) as presented in the **Error! Reference source not found.**

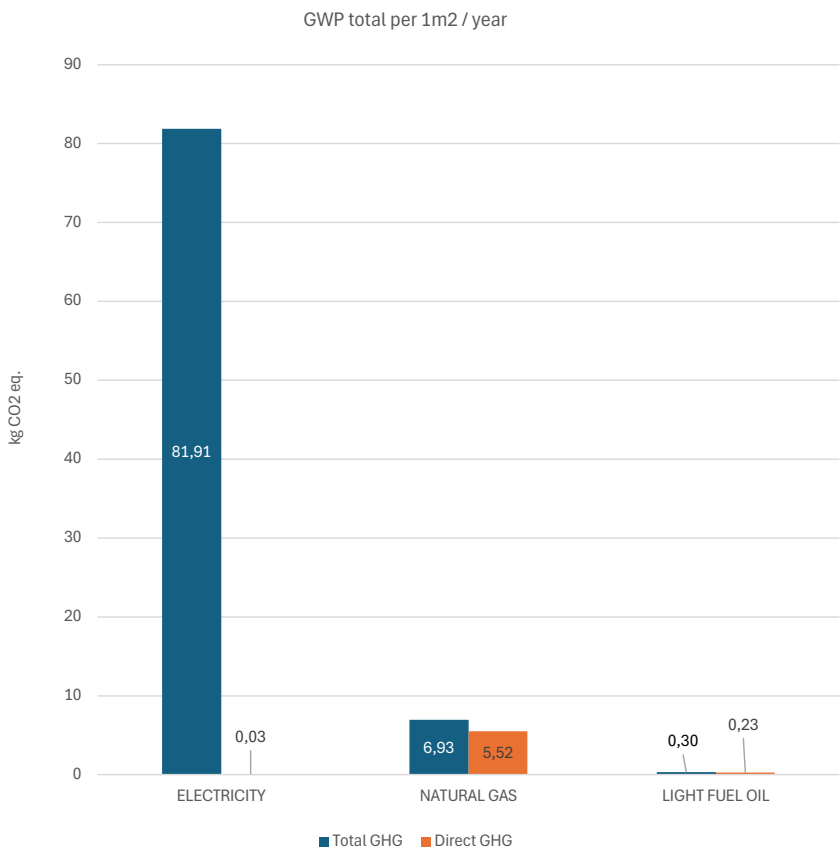


Figure 37 - GWP total for energy use (B6) per 1m2 per year

Environmental impacts, expressed as GWP total, embedded in the upstream product stage of construction material used in the terminal are largest for the concrete 48% and steel 33% (both reinforcement and construction steel) used in the construction.

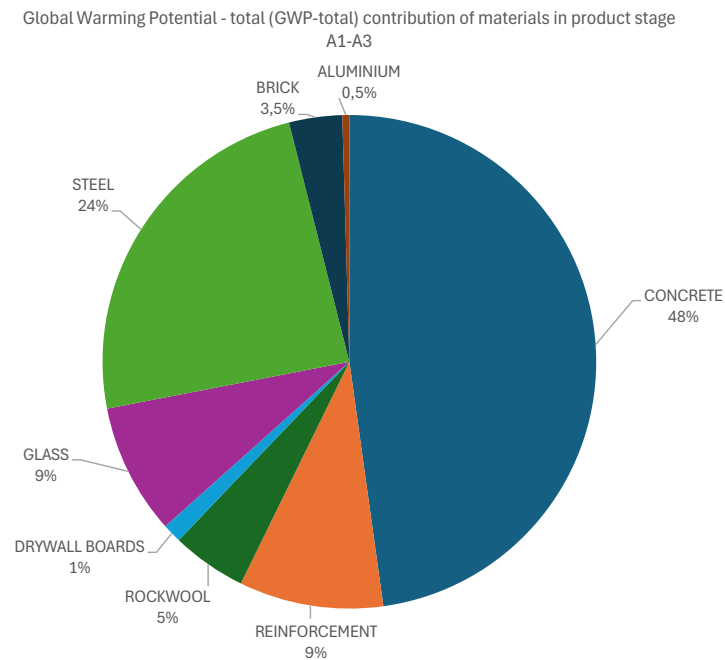


Figure 38 - Contribution of materials in product stage A1-A3 to GWP in tCO2 eq.

Finally, at the end-of-life cycle following processes are supposed to happen: deconstruction of building, transport of construction waste, recycling, landfilling and incineration of specific materials. The results of impact assessment of the end-of-life stage are presented in **Error! Reference source not found..**

Treatment of waste concrete generates the most of GWP total due to mass and energy intensive process, while recycled aluminium and steel is a GWP benefit in terms of avoided production of these materials.

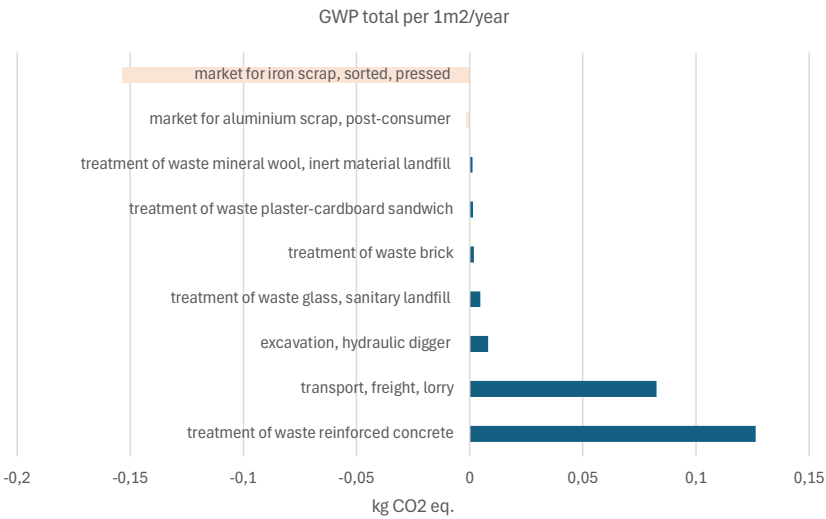


Figure 39 - GWP total for end-of-life cycle module

4. Recommendations For Energy Saving Measures

Since the building was completed in 2017 and already exhibits good thermal performance, further improvements of the building envelope would provide limited benefits and would likely not be cost effective. The following analysis focuses on potential measures for reducing cooling demand. Reducing heating demand would result in only minor savings compared to the required investment, making cooling the primary area for improvement.

Using the validated simulation model developed in Pleiades, several scenarios were analysed to evaluate possible strategies for reducing cooling energy demand. The analysed measures represent commonly applied approaches in practice.

4.1. Scenarios for improving energy efficiency

4.1.1. Summer Exterior Shading On South-East Curtain Walls

One potential measure to reduce cooling demand in buildings with large curtain wall surfaces is the implementation of automated external shading systems. Such systems follow the sun trajectory and are controlled to limit solar gains during summer while avoiding negative impacts on heating demand during winter. In this study, the proposed measure consists of installing automated external shading on the largest south-east oriented curtain wall surfaces, as illustrated in Figure 33. The corresponding implementation of this shading system within the Pleiades simulation model is shown in Figure 34.

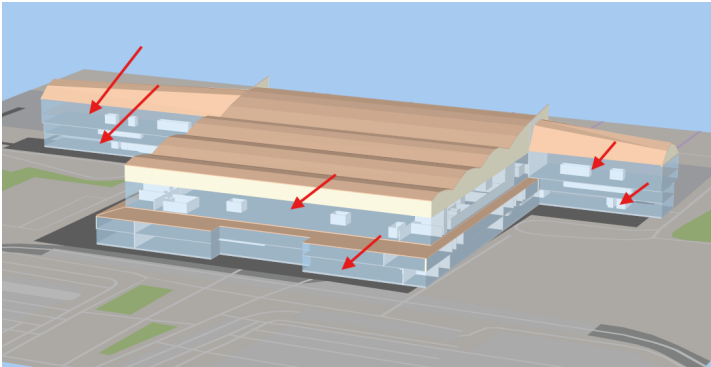


Figure 40 - Curtain wall with south-east orientation

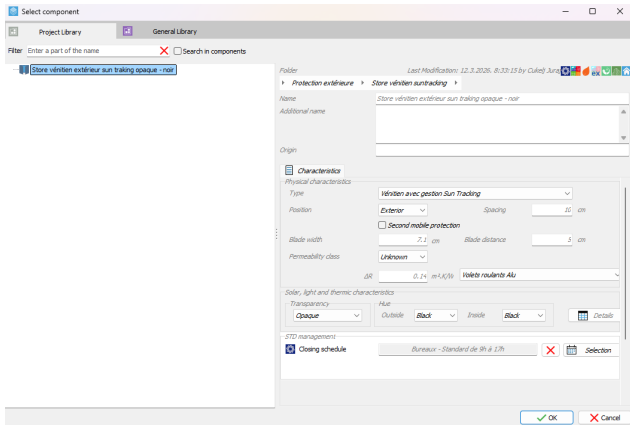


Figure 41 - Modelling dynamic shading in Pleiades

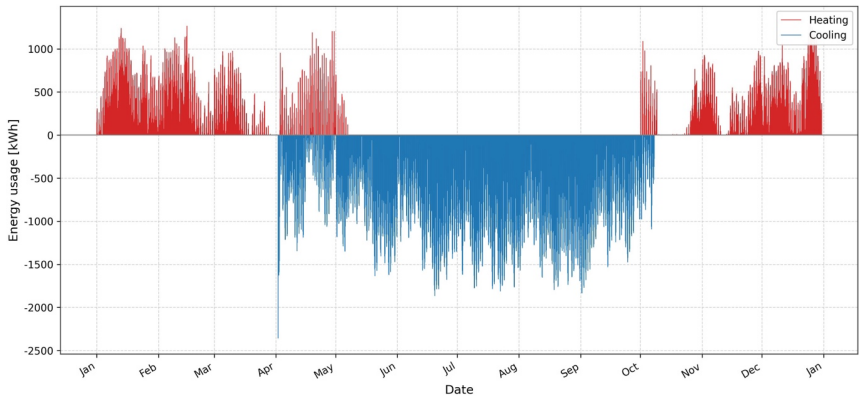


Figure 42 - Hourly energy usage with dynamic external shading

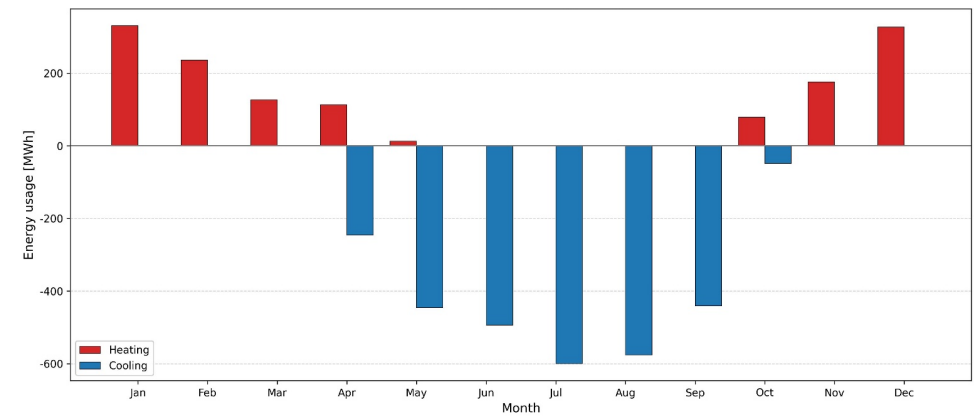


Figure 43 - Monthly energy usage with dynamic external shading

The results indicate a reduction in cooling energy demand, while heating energy consumption remains almost unchanged. This outcome is expected, as the shading system was modelled to operate only during the summer period.

4.1.2. Night Ventilation

Another approach is introduction of overnight increased air exchange to introduce free cooling effect, where outdoor colder air is ventilated through building to precool the building and therefore reduce total energy usage for cooling. In Pleiades that was made using ventilation schedule for summer months shown on Figure 37.

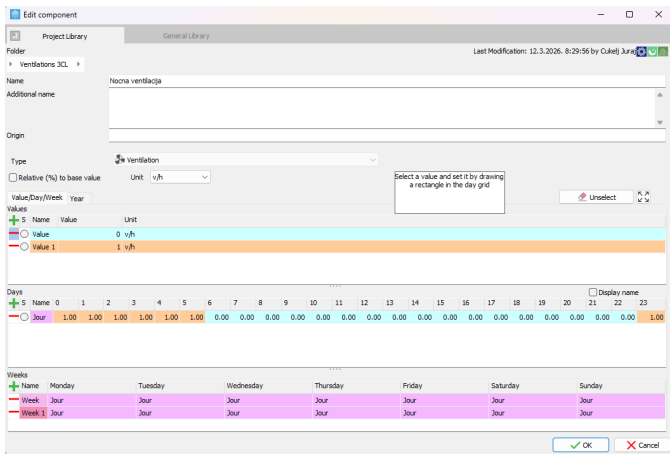


Figure 44 - Pleiades night ventilation modelling

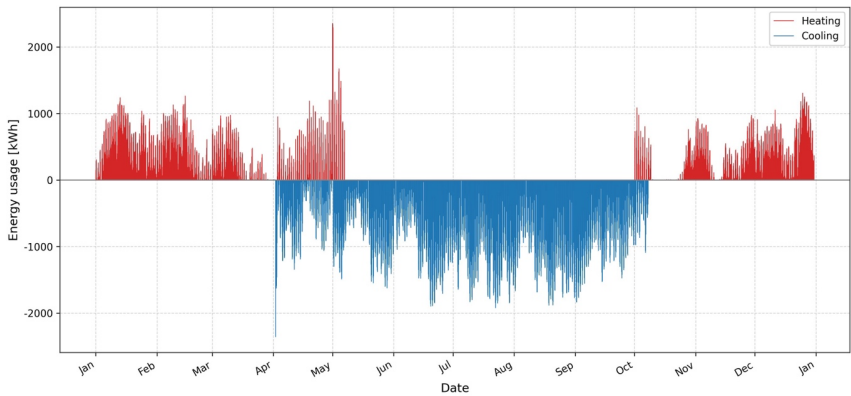


Figure 45 - Hourly energy usage with night ventilation

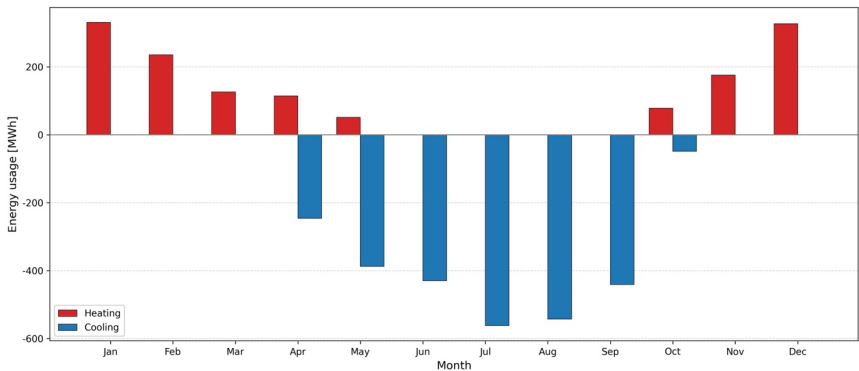


Figure 46 - Night ventilation monthly energy usage

The results indicate a slight increase in heating energy demand in May due to the operation of night ventilation during periods with lower outdoor temperatures, which increases heat losses in the early morning hours. At the same time, night ventilation effectively reduces cooling demand by removing accumulated heat from the building during the night. Detailed results are presented in Table 7. Overall, the scenario leads to a reduction in cooling energy consumption and a decrease in peak cooling power demand.

4.1.3. Night Ventilation And External Shading

Another approach is combining both strategies to reduce cooling needs even more.

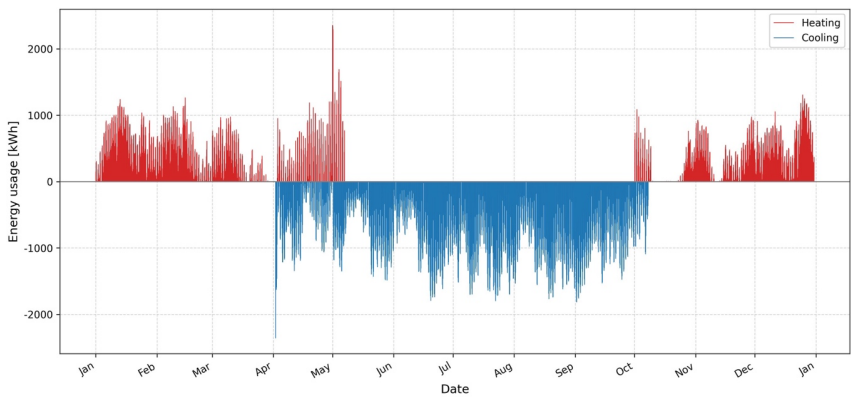


Figure 47 - Hourly energy usage for night ventilation and dynamic summer shading

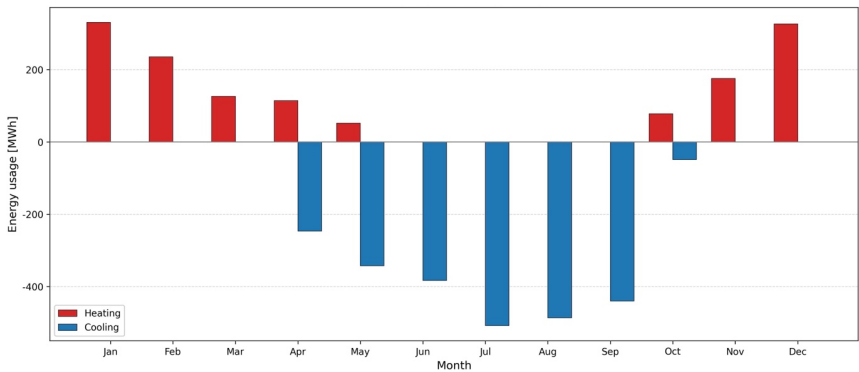


Figure 48 - Monthly energy usage with night ventilation and dynamic summer shading

The combined application of night ventilation and dynamic external shading results in a significant reduction of cooling demand during the summer period. Night ventilation removes accumulated heat from the building during nighttime hours, while the external shading system limits solar gains during periods of high solar radiation. The interaction of these two measures reduces both the total cooling energy demand and peak cooling loads compared to the individual scenarios.

4.1.4. Special Glazing On Southern Curtain Walls

Another potential measure is the installation of glazing with passive solar selective properties that reflect a larger portion of solar radiation when exposed to direct sunlight, while allowing higher solar transmittance under non direct radiation conditions. In this scenario, this kind of glazing is considered only for the south-east oriented curtain wall surfaces. The implementation of this glazing concept within the Pleiades model is illustrated in Figure 42.

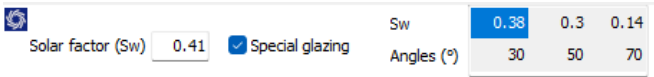


Figure 49 - Special glazing properties in Pleiades

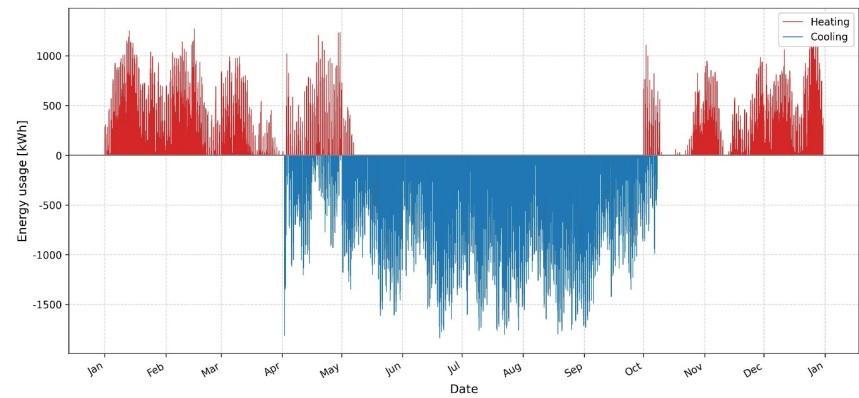


Figure 50 - Hourly energy usage with solar selective glazing

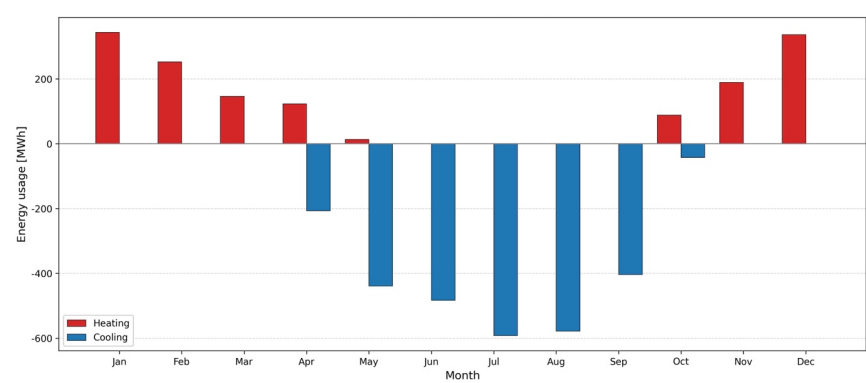


Figure 51 - Monthly energy usage with solar selective glazing

The solar-selective glazing is active throughout the entire year. As a result, it reduces solar gains not only during summer but also during winter months, which leads to a slight increase in heating energy demand. At the same time, the reduced solar gains significantly lower cooling energy demand during the summer period, which represents the primary expected effect of this measure.

4.2. Summary results of all proposed energy saving measures

Table 7 summarizes the results of the analyzed energy efficiency measures compared to the base scenario. The evaluated measures include night ventilation, dynamic external shading, the combination of dynamic shading with night ventilation, and the application of solar-selective glazing on the south-east curtain wall.

Night ventilation increases heating demand slightly during the transitional months due to additional heat losses during cooler night periods. The annual heating demand increases by 3%, while cooling demand is reduced by 13.3%. This indicates that night ventilation effectively removes accumulated heat during nighttime and lowers cooling requirements during summer operation.

Dynamic external shading shows only a minimal impact on heating demand (+0.1%) while reducing cooling demand by 6.96%. Since the shading is activated primarily during the summer period, solar gains in winter remain largely unaffected. This measure therefore reduces cooling demand without significantly influencing heating energy consumption.



The combined scenario of dynamic shading and night ventilation results in the largest reduction in cooling demand, with a decrease of 19.9% compared to the base case. Heating demand increases by 2.9%, which is primarily associated with the night ventilation component. This scenario also contributes to a reduction of peak cooling demand, indicating improved load management during summer operation.

The solar-selective glazing scenario applied to the south-east curtain wall reduces cooling demand by 10.44% but increases heating demand by 6.4%. This occurs because the glazing reduces solar gains throughout the year, including during winter months when solar radiation would otherwise contribute to passive heating.

Overall, the results show that strategies targeting solar gains and nighttime heat removal can significantly reduce cooling demand in buildings with large curtain wall areas. Among the analyzed measures, the combination of dynamic shading and night ventilation provides the highest cooling energy savings, while dynamic shading alone offers a balanced solution with minimal impact on heating demand.



Table 12 - Possible energy savings measures

Energy usage [MWh]	Base		Night ventilation		Dynamic shading		Dynamic shading and night ventilation		Special glazing wall curtain	
January	330.5	-	330.5	-	330.5	-	330.5	-	343.2	-
February	235.2	-	235.5	-	235.2	-	235.5	-	242.3	-
March	126.1	-	126.1	-	126.1	-	125.1	-	146.7	-
April	112.9	-246.3	114.6	-246.3	112.9	-246.3	114.6	-246.3	122.8	-206.4
May	11.6	-495.2	50.9	-387.5	12.8	-445.9	52.1	-342.3	13.0	-439.0
June	-	-542.5	-	-429.9	-	-493.7	-	-383.3	-	-483.0
July	-	-655.8	-	-562.3	-	-600.3	-	-508.0	-	-592.2
August	-	-634.4	-	-543.2	-	-575.9	-	-486.1	-	-578.2
September	-	-442.6	-	-441.2	-	-441.3	-	-439.9	-	-404.1
October	78.0	-48.9	78.0	-48.9	78.0	-48.9	78.0	-48.9	88.2	-42.7
November	175.5	-	175.5	-	175.5	-	175.4	-	189.4	-
December	326.6	-	326.6	-	326.6	-	326.6	-	336.3	-
Max. Value	330.5	-655.8	330.5	-562.3	330.5	-600.3	330.5	-508.0	343.2	-592.2
SUM	1,396.4	3,065.7	1,437.7	2,659.3	1,397.6	2,852.3	1,437.8	2,454.8	1,492.3	2,745.6
Difference	-	-	+41.3	-406.4	+1.2	-213.4	+41.4	-610.9	+95.9	-320.1
% Difference			+3%	-13.3%	+0.1%	-6.96%	+2.9	-19.9%	+6.4	-10.44%



* Positive values represent heating energy consumption while negative values correspond to cooling energy demand

4.3. Environmental impacts of potential energy savings measures

Environmental impact of measures is based on energy savings in 4 scenarios compared to baseline as previously presented. According to modeled energy consumption in the baseline year, energy for the heating is generated with gas (97%) and light fuel oil (3%) while cooling energy is produced exclusively with electricity.

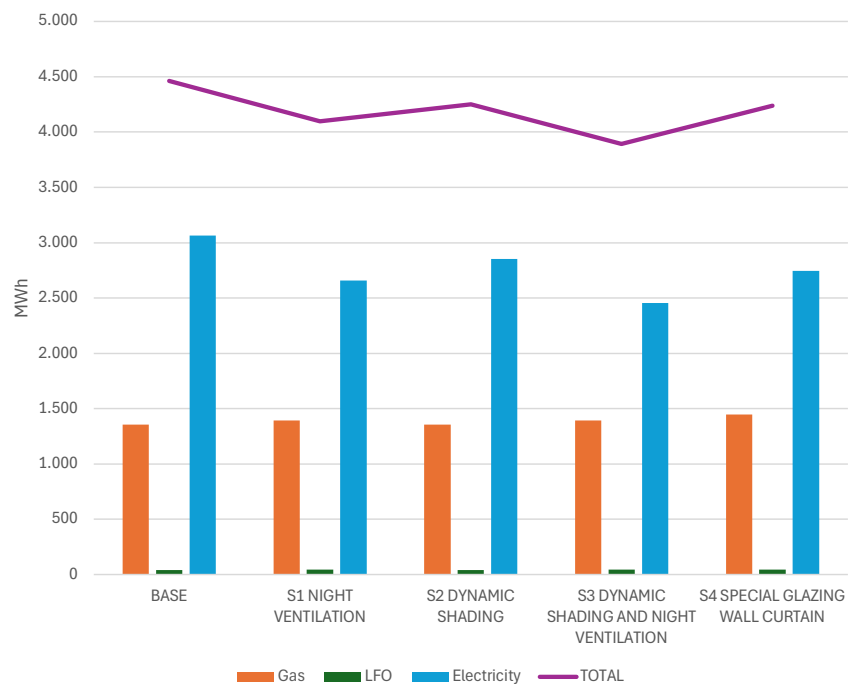


Figure 52 - Annual energy usage for the heating and cooling in baseline and 4 energy saving scenarios

The **Error! Reference source not found.** below shows the life-cycle environmental impacts of the Baseline, Scenario 1, Scenario 2, Scenario 3 and Scenario 4 . Impacts are calculated for the total



energy consumption including heating and cooling for the 1 m2 net area building in one year period.



Table 13 - LCA of the baseline and 4 energy saving scenarios

Impact category	Heating, cooling_base	Heating, cooling S1	Heating, cooling S2	Heating, cooling S3	Heating, cooling S4
Global Warming Potential - total (GWP-total) kg CO2 eq.	30.56	27.42	28.83	25.77	28.35
Global Warming Potential - fossil fuels (GWP-fossil) kg CO2 eq.	29.92	26.87	28.24	25.26	27.78
Global Warming Potential - biogenic (GWP-biogenic) kg CO2 eq.	0.63	0.54	0.58	0.50	0.56
Global Warming Potential - land use and land use change (GWP-luluc) kg CO2 eq.	9.02E-03	7.89E-03	8.42E-03	7.31E-03	8.15E-03
Depletion potential of the stratospheric ozone layer (ODP) - kg CFC-11 eq.	6.06E-07	5.67E-07	5.82E-07	5.44E-07	5.87E-07
Acidification potential, Accumulated Exceedance (AP) mol H+ eq.	0.29	0.25	0.27	0.23	0.26
Eutrophication potential - freshwater (EP-freshwater) kg P eq.	0.03	0.03	0.03	0.02	0.03
Eutrophication potential - marine (EP-marine) kg N eq.	0.03	0.03	0.03	0.02	0.03
Eutrophication potential - terrestrial (EP-terrestrial) mol N eq.	0.25	0.22	0.24	0.21	0.23
Photochemical Ozone Creation Potential (POCP) kg NMVOC eq.	0.09	0.08	0.08	0.07	0.08

Abiotic depletion potential - non-fossil resources (ADPE) kg Sb eq.	2.11E-04	1.83E-04	1.96E-04	1.70E-04	1.89E-04
Abiotic depletion potential - fossil resources (ADPF) MJ, net calorific value	451.63	406.72	426.70	382.76	420.45
Water (user) deprivation potential (WDP) m3 world eq. deprived	21.44	18.62	19.96	17.20	19.22

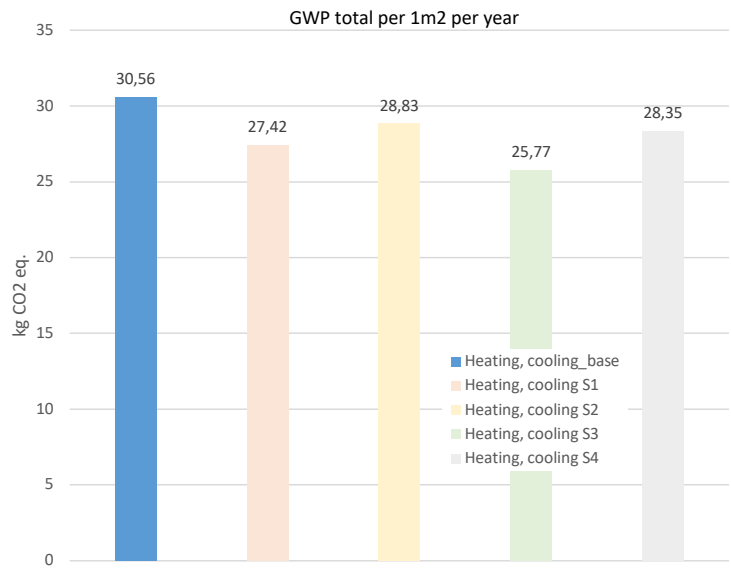


Figure 53 - GWP total per 1m2 per year for baseline and 4 energy saving scenarios

The most perspective scenario from the climate aspect is S3 with dynamic shading and night ventilation reducing the GWP total for 16% compared to baseline. Since the scenario 3 is a measure aiming to reduce cooling needs for 19.9%, GHG emission reduction is mainly contributed to the savings of electricity used for the cooling purposes, while heating demand increases only by 2.9%.



5. Conclusion And Outlook

5.1. Regarding the replicability

The replication case study for improving energy usage was carried out at Zagreb Franjo Tuđman Airport, located in Zagreb, Croatia. The terminal building was constructed between 2013 and 2017. The objective of this sub-task was to replicate the innovative methodology proposed in Deliverable D4.5, and to evaluate its applicability to the Zagreb Airport terminal building.

The replication case study consisted of four main steps.

- I. Step 1 involved analysing the proposed methodology and adapting it to the Zagreb Airport case study, while integrating the lessons learned during the development of the methodology by the Paris team (D4.5, 2025).
- II. Step 2 consisted of performing an hourly energy assessment and calibrating the building energy model using the Pleiades simulation software.
- III. Step 3 involved assessing the environmental impacts of the terminal building, including both the embodied impacts of construction materials and the operational impacts related to energy consumption for heating and cooling, using Life Cycle Assessment (LCA)
- IV. Step 4 involved analyzing different scenarios for improvement of current energy usage for heating and cooling, and assessing potential environmental gains.

The terminal building in Zagreb was modelled using a simplified modelling approach, which enabled the application of the same workflow, including thermal simulation, model calibration using available energy consumption data, optimisation of renovation measures, and environmental performance evaluation through life cycle assessment. The replication confirmed that the methodology is adaptable to different airport contexts and building configurations.

The successful application of the methodology to the Zagreb terminal building demonstrates its robustness and suitability for replication in other airport renovation projects, including the planned application to Cluj Airport. The results confirm that the methodology can support decision-making by providing reliable estimates of energy performance, environmental impacts, and greenhouse gas emission reductions associated with renovation strategies.

5.2. Regarding the dynamic multizone simulation

A dynamic multizone energy model of the Zagreb Airport terminal was successfully developed and calibrated using the Pleiades simulation environment. The model includes sixteen thermal zones representing the main



functional areas of the building and incorporates hourly climatic data based on the Croatian national methodology.

The development of the simulation model required a multi-step workflow starting from the available Building Information Model (BIM). The building geometry was first prepared in Autodesk Revit, after which the model was exported to IFC format and subsequently imported into the Pleiades simulation environment. This process required numerous iterations and manual adjustments to correctly translate the architectural BIM model into a thermally consistent simulation model. Attention was required to correctly define building envelope elements, thermal zones, and construction layers.

Although the preparation and conversion of the BIM model proved to be time consuming and technically challenging, the experience gained during this process represents an important methodological outcome of the project. The established workflow for transferring BIM geometry from Revit to Pleiades provides a practical approach that can be reused in future studies and similar building energy modelling projects.

The calibration process was performed using measured natural gas consumption for heating and total electricity consumption for the terminal building. The comparison between simulated and measured heating energy consumption shows an overall deviation of approximately 11%, while the difference in delivered energy calculations is approximately 1.89%. Considering the limitations related to available monitoring data and the use of a typical meteorological year, this level of deviation is within the acceptable range for calibrated building energy models reported in literature, typically $\pm 10\text{--}15\%$ for monthly calibration when detailed submetering data are not available.

The calibrated model provides a reliable representation of the thermal behaviour of the terminal building and enables the evaluation of different operational energy reduction strategies.

The results confirm that dynamic simulation is an effective tool for analysing energy performance in large and complex airport buildings where internal loads, solar gains and operational schedules strongly influence energy demand. Furthermore, the developed modelling workflow and calibrated simulation model provide a valuable foundation for future analyses of energy efficiency measures, operational optimisation, and investment planning.

5.3. Regarding the Life Cycle Assessment approach

Life Cycle Impact Assessment results were calculated based on the inventory analysis, mostly as an output from BIM model. The functional unit was defined as 1 m^2 of net floor area per year over a 50-year building life cycle, for a total net floor area of $62,000 \text{ m}^2$.



The results show that operational energy use (module B6) is the largest contributor to global warming potential (GWP), mainly due to electricity consumption, which represents the highest environmental impact across all modules. In the product stage, the main contributors to embodied emissions are concrete (48%) and steel (33%). At the end-of-life stage, waste concrete treatment generates the highest GWP due to the large material mass and energy-intensive processing, while recycling of aluminum and steel provides environmental benefits by avoiding the production of primary materials.

5.4. Regarding the optimization approach

The analysis of operational energy reduction strategies confirms that cooling demand represents the dominant component of the terminal's energy consumption. The building is characterized by extensive curtain wall surfaces and high internal gains associated with passenger activities, equipment operation and lighting loads.

Among the analyzed measures, the combined strategy of dynamic external shading and night ventilation provides the highest reduction in cooling demand, achieving a decrease of approximately 19.9% compared to the base case. Dynamic shading alone also provides a measurable reduction in cooling demand while maintaining nearly unchanged heating energy consumption. Night ventilation contributes additional reductions by removing accumulated heat from the building mass during night hours. This scenario is also the most perspective scenario from the climate aspect, with the 16% reduction in GWP total compared to baseline.

The use of solar-selective glazing reduces cooling demand but simultaneously increases heating demand due to reduced solar gains during winter periods. Consequently, this measure requires careful evaluation with respect to the climatic context and the overall energy balance of the building.

Beyond the evaluation of individual measures, the development of a calibrated dynamic multizone simulation model represents a key outcome of this study. The validated model provides a reliable digital representation of the building's thermal behavior and enables systematic evaluation of future energy efficiency measures.

Such a modelling framework is essential for supporting investment planning and decision-making processes. By combining simulation results with real energy prices and investment costs, the model can be used to perform objective economic analyses, including return of investment (ROI) and payback period calculations. This enables building owners and operators to quantify the financial impact of proposed energy efficiency measures and to priorities investments that provide the highest energy and economic benefits.



Therefore, the calibrated simulation model not only supports the assessment of current operational strategies but also provides a robust tool for future optimization of airport terminal energy performance.

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