



D.4.6: Report on replication made on Innovative Lighting and Energy and CO2 efficiency in existing airport Terminals – PART 2: Energy and CO2 efficiency in Cluj-Napoca's Arrivals Terminal

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Table of Contents

1. EXECUTIVE SUMMARY.....	8
1.1. INTRODUCTION.....	8
1.2. BRIEF DESCRIPTION OF THE REPLICATION CASE STUDY	8
1.3. LIMITS OF THE REPLICATION CASE STUDY	9
2. REPLICATION OF PROPOSED METHODOLOGY.....	10
2.1. DATA COLLECTION	10
2.1.1. BUILDING INFORMATION MODEL.....	10
2.1.2. OCCUPANCY SCENARIOS	10
2.1.3. CLIMATE DATA	10
2.2. ENERGY SIMULATION	10
2.3. LIFE CYCLE ASSESSMENT	11
2.4. OPTIMISATION	12
3. RESULTS FOR THE PARTIAL REPLICATION EX-POST CASE STUDY.....	14
3.1. PRESENTATION OF THE CASE STUDY	14
3.2. DATA COLLECTION	16
3.2.1. BUILDING DIGITAL MODEL.....	16
3.2.2. OCCUPANCY SCENARIOS	16
3.2.3. CLIMATE DATA	18
3.2.4. EQUIPMENT DATA COLLECTION & HOURS OF OPERATION	18
3.3. ELABORATION OF DIGITAL MODEL	20
3.4. CONFIGURATION OF THE DYNAMIC THERMAL SIMULATION	22
3.4.1. HOURLY CLIMATIC DATA	22
3.4.2. ZONE DEFINITION	25
3.4.3. OCCUPANCY SCENARIO	25
3.5. RESULTS OF DYNAMIC THERMAL SIMULATION	34



3.5.1. CLUJ-NAPOCA AIRPORT ARRIVALS TERMINAL 34

3.6. RESULTS OF THE LIFE CYCLE ASSESSMENT 37

3.7. OPTIMISATION RESULTS 52

4. CONCLUSION AND OUTLOOK 70

REFERENCES 72

List of tables

Table 1 - Passenger monthly and daily flow history for one year 17

Table 2 - Technical specifications of Air Handling Units for Arrivals Terminal..... 19

Table 3 - Data collection for Gross Floor Area (GFA) of buildings at facility level..... 30

Table 4 - Data collection regarding methane gas consumption at the facility level 31

Table 5 - Data collection regarding electricity consumption at building level 31

Table 6 - Initial input data regarding the occupancy scenario & lighting..... 32

Table 7 - Initial input data regarding the currently in operation HVAC equipment..... 33

Table 8 - Input data for the calibrated model based on monitored and collected real data 33

Table 9 - Annual final energy consumptions Dynamic Model vs. Measurements..... 33

Table 10 - The environmental impacts (per m² and per year) of Arrivals Terminal..... 41

Table 11 - Optimal Designs for minimum Net Site Energy and investment optimization objectives 59

Table 12 - Changes in life-cycle stages 68

List of figures

Figure 1 - Blueprints of the airport terminals..... 16

Figure 2 - Hourly climate data in Design Builder (TMY)..... 18

Figure 3 - 3D geometrical model in Design Builder..... 20

Figure 4 - Basement zoning..... 21

Figure 5 - Ground floor zoning 21



Figure 6 - 1 st Floor and Mezzanine zoning	22
Figure 7 - Meteorological file in Design Builder	23
Figure 8 - Hourly weather data in Cluj-Napoca (TMY)	24
Figure 9 - Climate datasets extract in Cluj-Napoca AMY 2021 vs. TMY	25
Figure 10 - Thermal energy consumption measurements for the year 2021 in Arrivals Terminal.....	26
Figure 11 - Electricity consumption measurements in Arrivals terminal	27
Figure 12 - Monthly electricity consumption measurements in Arrivals terminal	27
Figure 13 - Annual energy consumption for Arrivals Terminal	28
Figure 14 - Thermal energy consumption comparison in CLJ Arrivals terminal (AMY 2021)	28
Figure 15 - Electricity consumption comparison in CLJ Arrivals terminal	29
Figure 16 - Measurements by category of consumers in BMS – Arrivals Terminal	32
Figure 17 - Thermal power for heating & DHW and cooling demand in the simulation of CLJ terminal	34
Figure 18 - Hourly thermal energy consumption for heating and DHW	35
Figure 19 - Hourly electrical energy consumption for cooling	35
Figure 20 - Hourly thermal and electrical power in the simulation of CLJ terminal	36
Figure 21 - Interface of transport settings in One Click LCA	38
Figure 22 - Interface of service life and end-of-life settings in One Click LCA	39
Figure 23 - Interface of energy settings in One Click LCA	40
Figure 24 - LCA stages and system boundaries for buildings (EN 15978)	41
Figure 25 - Global warming potential total kgCO ₂ e by Life-cycle stages	43
Figure 26 - Global warming potential total kgCO ₂ e by resource type and subtype	44
Figure 27 - Contribution of life cycle stages to different environmental impact indicators	45
Figure 28 - The building's annual impacts over its lifespan	46
Figure 29 - Interface of Design Builder for setting the optimization objectives	53
Figure 30 - Interface of Design Builder for setting shading solutions	54
Figure 31 - Interface of Design Builder for setting the population size and generations	54
Figure 32 - Interface of Design Builder with optimal designs found in the search space	55
Figure 33 - Optimisation results based on criteria heating load and investment	55
Figure 34 - Interface of Design Builder for setting the design variables	57
Figure 35 - Optimisation results based on criteria net site energy and investment	58
Figure 36 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1 ...	61
Figure 37 - Global Warming Potential total, kg CO ₂ e - Life-cycle stages for Baseline vs Scenario 1	62

Figure 38 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1 vs Scenario 2	63
Figure 39 - Global Warming Potential total, kg CO ₂ e - Life-cycle stages for Baseline vs Scenario 1 vs Scenario 2	64
Figure 40 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1 vs Scenario 2 vs Scenario 3	65
Figure 41 - Global Warming Potential total, kg CO ₂ e - Life-cycle stages for Baseline vs Scenario 1 vs Scenario 2 vs Scenario 3	67



1. Executive summary

1.1. Introduction

The replication case study is applied to the Arrivals Terminal of the Cluj-Napoca Airport, located in Romania. The building body was built in 2008.

The objectives of sub-task WP4.1.3b are to partially replicate the innovative methodology proposed within the deliverable *D4.5. Report including a methodology proposal for design and conception of refurbished airport Terminals*, to address energy and CO₂ efficiency improvement in existing airport Terminals.

The replication case study consists of:

- Step 1: analysis of the proposed methodology and its application for the Cluj-Napoca Airport Arrivals Terminal. Also, a specific approach is to use the lessons learned in developing the methodology by the Paris' team (ARMINES & ADP).
- Step 2: hourly energy assessment, model calibration and optimization using evolutive algorithms (NSGA II) of the terminal, by using the software DESIGN BUILDER - version 7.3 (solver Energy Plus – version 9.4).
- Step 3: Life Cycle Assessment (LCA), for the Arrival Terminal of the International Avram Iancu Airport Cluj. The assessment evaluates the environmental impacts of the terminal building over its entire 50-year lifespan, covering the construction, use, renovation, and deconstruction stages. The LCA was performed using One Click LCA software with the ecoinvent database (version 3.11).

1.2. Brief description of the replication case study

The methodology was analyzed, and an implementation method was identified for the Cluj-Napoca airport. The proposed methodology includes modelling, energy simulation, life cycle assessment, and optimization.

As regarding the modelling, the BIM model was identified as being laborious and with a significantly negative impact on the computational effort in the actual hourly energy simulation, so the .dwg format was used directly to create the digital model (characterized by geometry, physical properties of materials etc.).



Dynamic simulation results aim to be compared with energy consumption measurements, in order to calibrate the model, with the final scope of better controlling the energy saving predictions obtained through the use of the optimization module.

1.3. Limits of the replication case study

In regard to the calibration process, limited measurement data is available. The thermal energy required for heating and Domestic Hot Water (DHW) is produced for the entire airport into a building adjacent to the airport and there is no available separate thermal metering, on building bodies.

For the electrical energy consumed by the Arrivals Terminal, measurements were available. The electrical consumers monitored are the equipment for: mechanical ventilation, cooling, and miscellaneous indoor equipment used for the current activity of the terminal. Nevertheless, there are consumers which are not monitored separately through BMS, of which the most important is the lighting as category of consumer.

Other limits, in relation to the Paris-Charles de Gaulle airport (CDG) model, refer to the zoning approach. The approach used for Cluj-Napoca airport Arrivals Terminal considered grouping large zones by categories of main functions. Increasing the number of calculation zones is expected to lead to a higher accuracy of the simulation but would also significantly increase the computational effort (simulation time and required computational memory). In addition, this aspect becomes important, considering that the calibrated model is used in the optimization process, and the computational effort of the optimization directly depends on the calibrated hourly dynamic model, which is considered as a reference in the energy saving analysis. In the end, the energy and CO₂ efficiency of the terminal is the fundamental objective of this model. Therefore, the Cluj-Napoca's replication model proposes a balance of resources in relation to the considered objectives, of dynamic energy modelling and calibration model development, to be further used for computationally intensive optimizations processes.

Several limitations affect the interpretation of the LCA results. Some material and system data rely on generic ecoinvent processes rather than manufacturer-specific datasets, which introduces uncertainty in the exact embodied impacts. Furthermore, the use of the 2023 Romanian grid mix by One Click LCA means that future renewable energy deployment will shift these results over time, as Romania's electricity emission factor has already declined in recent years due to increasing wind and solar shares in the mix and is expected to decrease further with the planned expansion of renewable capacity.. Finally, results are influenced using standard component lifespans and European recycling benchmarks, both of which may differ from actual maintenance schedules and local waste management practices.



2. Replication of proposed methodology

Below is a brief analysis of what was done for the partial replication case study at Cluj-Napoca airport in relation to what was proposed in *D4.5: Report including a methodology proposal for design and conception of refurbished airport Terminals*.

2.1. Data collection

2.1.1. Building information model

The major difficulties of the French team regarding the generation of the BIM model and its import into the energy simulation software represented lessons learned, so that at the time of starting the replication case study for Cluj-Napoca's airport, it was opted to use floor plans to define the geometric model in the energy simulation software. This decision was also made due to the time gap between the activity of the two teams (more than a year), practically the experience learned at Paris airport case study allowing the focus on the dynamic energy simulation and further steps, in the case of the replication case study in Cluj.

2.1.2. Occupancy scenarios

Data was collected or estimated regarding the use of the different premises, in the form of hourly or daily scenarios specifying overtime:

- 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,
- The opening of doors and other possible elements (opening patterns, required time for opening and closing of the automated doors etc.).

2.1.3. Climate data

An actual year file was used for Cluj-Napoca airport coordinates (latitude 46,78, longitude 23,69), extracted from Copernicus platform (ERA5 hourly data on single levels) [1]. The climate dataset includes hourly values for external ambient air temperature, global horizontal solar radiation, diffuse horizontal and direct normal solar radiation, relative humidity, wind speed etc.

2.2. Energy simulation

The dynamic building energy simulation was undertaken by using EnergyPlus solver – v9.4, including the Design Builder interface – v7.3.



The results in terms of energy consumption were compared with BMS electricity consumption measurements and methane gas measurements (invoices).

The calibration of the model was undertaken by considering input parameters with high uncertainty, such as the miscellaneous equipment used indoor within the passenger area (e.g., coffee machines & electric ovens in the restaurant open area etc.), which uses electrical energy in operation and also represents internal gains to the building balance. This approach reflects measured but unmonitored electricity consumption by consumer categories.

As regarding the air change rate, as another input parameter with high uncertainty, the curtain walls for the Cluj-Napoca terminal are immovable and the opening & closing of the automated doors were considered in the energy simulation by analysing the patterns of their usage. Air infiltrations driven by wind and stack effects were considered in conjunction with the actual technical condition of the terminal (good airtightness). For the automated access doors patterns of their usage were identified, based on the passenger history and the time required to open/close the main automated doors (5 sec to open / 5 sec fully open / 5 sec to close).

Further, different scenarios were defined, and the effect of their implementation was quantified by using the calibrated model.

2.3. Life cycle assessment

LCA is applied in this study to quantify the environmental impacts associated with the Arrival Terminal over its entire life cycle, and to compare the performance of the baseline and optimized scenario. The assessment is performed with One Click LCA, using the ecoinvent database as background life cycle inventory (LCI).

The principle of the approach is to account for all relevant upstream and downstream processes linked to the building: extraction and processing of raw materials, manufacturing of construction products, transport to the construction site, construction works, building operation (energy and water use), maintenance and replacements, as well as end-of-life processes and possible recycling or recovery routes. This ensures that the comparison between scenarios captures both the embodied impacts of construction and the operational impacts over the use phase.

Material quantities for the different construction and renovation stages are obtained from the building model and bills of quantities and are then mapped to corresponding LCI datasets in ecoinvent (e.g. concrete, steel, insulation materials, glazing systems). Transport distances from production sites to the airport are defined according to typical supply chains for the main material families and technical systems and are parameterised in the LCA model for both initial construction and subsequent replacements.



To avoid impact transfer, LCA is not limited to greenhouse gas (GHG) emissions but covers a broader set of impact indicators, such as climate change, cumulative primary energy use, abiotic resource depletion, water use, waste generation, damage to ecosystem quality and damage to human health, following commonly used characterisation methods. This multi-criteria perspective is essential to ensure that measures reducing operational energy or emissions do not lead to disproportionate increases in other environmental burdens.

Finally, the results are reported per impact category and life cycle stage, to support the identification of the most contributing processes and the evaluation of improvement potential in future design or renovation projects.

2.4. Optimisation

An optimization approach was considered by using Design Builder's integrated optimization module.

The optimization process of the hourly dynamic model consists of definition of optimization objectives, definition of design variables, definition of design constraints and conduct multi-objective optimization.

Below is a brief description on what is implemented within the module – source: https://designbuilder.co.uk/helpv7.0/Content/OptimisationBackground.htm?utm_source=copilot.com.

DesignBuilder uses a Genetic Algorithm (GA) based on the NSGA-II, developed by Deb et al. [2]. This is widely used as a "fast and elitist multiobjective" method providing a good trade-off between a well converged and a well distributed solution set. NSGA-II uses the non-dominated sorting method, which is proven to be highly effective in ranking competing objectives. One deficiency of the original NSGA2 is that it does not provide a way for handling constraints efficiently. This is addressed in JEA using the stochastic ranking method. It works as follows:

1. First, the population is randomly initialised.
2. The design variants (chromosomes) are sorted and put into fronts based on Pareto non-dominated sets. Within a Pareto front, the chromosomes are ranked based on Euclidean distances between solutions or I-dist (the term used in NSGA-II). Generally, solutions which are far away (not crowded) from other solutions are given a higher preference in the selection process to help create a diverse solution set and avoid crowding.
3. The most suitable design variables are picked from the current population and put into a mating pool.
4. In the mating pool, tournament selection, crossover, and mating is carried out.
5. The mating pool and current population is combined. The resulting set is sorted, and the best chromosomes are passed into the new population.



6. Go to step 2 unless convergence has been reached.
7. The solution set is the highest ranked Pareto non-dominated set from all populations.



3. Results for the partial replication ex-post case study

3.1. Presentation of the case study

The case study is the Arrivals Terminal of the Cluj-Napoca Airport, located in Romania.



Photo. West and South façade



Photo. North façade



Photo. Non-circulating terrace floor

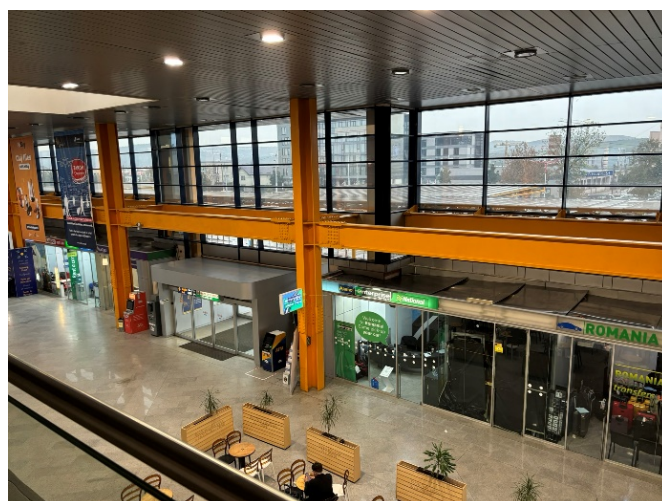


Photo. Main arrivals hall

Below is a brief description of the terminal's technical characteristics studied.

Construction year	2008
Gross Area Gross volume	10602 m ² 56700 m ³
Technical data Building envelope	Exterior walls - metal panels thermally insulated with 15 cm PUR, $U = 0,236 \text{ W/m}^2 \cdot \text{K}$ Curtain walls (double glazed & Aluminum frames with thermal break), $U = 1,98 \text{ W/m}^2 \cdot \text{K}$ Skylights made of three-chamber cellular polycarbonate, $U = 3,00 \text{ W/m}^2 \cdot \text{K}$ Terrace floor with 25 cm mineral wool thermal insulation (renovated in 2019), $U = 0,154 \text{ W/m}^2 \cdot \text{K}$



HVAC, DHW & lighting systems	Heating – 3 x gas boiler Buderus Logano SK 72, heating capacity 3 x 1320 kW (centralized production in an adjacent technical building, for all the buildings of the airport) Cooling – 1 x chiller CGAN 212, cooling capacity 389 kW Mechanical ventilation – 5 x AHU with heat recovery, mixing chambers and heating&cooling batteries Domestic Hot Water – 1 x boiler Buderus Logano SK 625, thermal capacity 530 kW (centralized production for all buildings) Lighting – mainly LED technology (years 2022-2023); Pel $\approx$ 45 kW
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3.2. Data collection

3.2.1. Building digital model

AutoCAD file format (.dwg files) were requested from the airport representatives, in order to develop the digital model for the energy simulation. Plans for each level of the terminal were received, as well as a global plan for the airport with the thermal distribution networks of the thermal agent, from the Thermal Power Plant to each building body.

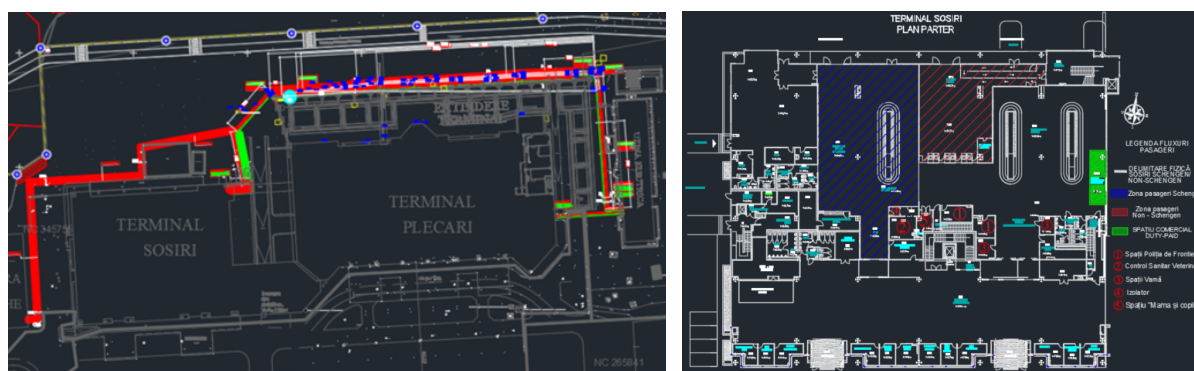


Figure 1 - Blueprints of the airport terminals

3.2.2. Occupancy scenarios

Data collected refer to:

- **the number of persons:**
 - o **passenger daily & monthly flow history;**
 - o **number of staff members and their working schedules - for continuously (24 h/day) / discontinuously (8 h/day) provided services;**



- the number of employees of companies operating within the terminal perimeter.
- the set-point temperature (heating and air conditioning);
- internal heat gains linked to electricity consumption (based on BMS monitoring results);
- the air flows supplied and extracted by mechanical ventilation;
- the opening of doors and other possible elements.

Table 1 - *Passenger monthly and daily flow history for one year*

Crt. No.	Month	Monthly Traffic of Disembarked Passengers on AICJ	Daily Average of Passengers Disembarked on AICJ
1	Sept. 23	150.856	5.029
2	Oct. 23	144.686	4.667
3	Nov. 23	109.161	3.639
4	Dec. 23	121.714	3.926
5	Jan. 24	92.367	2.980
6	Feb. 24	99.359	3.426
7	Mar. 24	113.925	3.675
8	Apr. 24	120.522	4.017
9	May 24	136.385	4.400
10	Jun. 24	145.393	4.846
11	Jul. 24	177.179	5.715
12	Aug. 24	172.200	5.555

In addition, an average of 1.000 passengers/month can be added to these passenger averages, this category including relatives of passengers expected at the airport, as well as employees of companies operating within the airport perimeter and working within the Cluj Airport Arrivals Terminal.

No. of airport employees and their work schedule



There are 360 employees in total, for the whole airport, of which 130 people with 8 hours work shift and 230 people with 12 hours work shift. For the Arrivals terminal in the offices area there are 109 employees with 8-hour shift.

3.2.3. Climate data

A typical year for Cluj-Napoca airport location was initially considered, from the database of software DESIGN BUILDER. Values refer to hourly ambient air temperatures (outside dry-bulb temperature and outside dew-point temperature), direct normal solar radiation and diffuse horizontal radiation etc.



Figure 2 - Hourly climate data in Design Builder (TMY)

However, for better accuracy in the calibration process, an Actual Meteorological Year (AMY) was used for the year 2021, for the airport coordinates (latitude 46,78, longitude 23,69), extracted from the Copernicus platform (ERA5 hourly data on single levels) [1] and was introduced in Design Builder as .epw file.

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 below.



Table 2 - Technical specifications of Air Handling Units for Arrivals Terminal

Name	Service area	No.	Type	Supplied Flow	Evacuated Flow	El. battery	Water batteries		Heat recovery
				[m3/h]	[m3/h]	Heating	Heating	Cooling	
		[-]				[kW]	[kW]	[kW]	[%]
AHU-1	Offices area - 1st floor	1	VTS AHU 5700	5700	5700	90	30	14,8	74
AHU-2	Offices area	1	TRANE	12500	7700	0	104	70	83
AHU-3.1	Main public hall	1	TRANE	21500	19000	0	258	150	65
AHU-3.2	Main public hall	1	TRANE	21500	19000	0	258	150	65
AHU-4	International arrivals area	1	TRANE	18000	16000	0	165	113	64
AHU-5	Domestic arrivals area	1	TRANE	12000	10500	0	115	75	58
				91200	77900	90	930	572,8	



3.3. Elaboration of digital model

The modelling was undertaken based on AutoCAD files, which were provided by the airport representatives. The 3D digital model was developed in the software Design Builder.

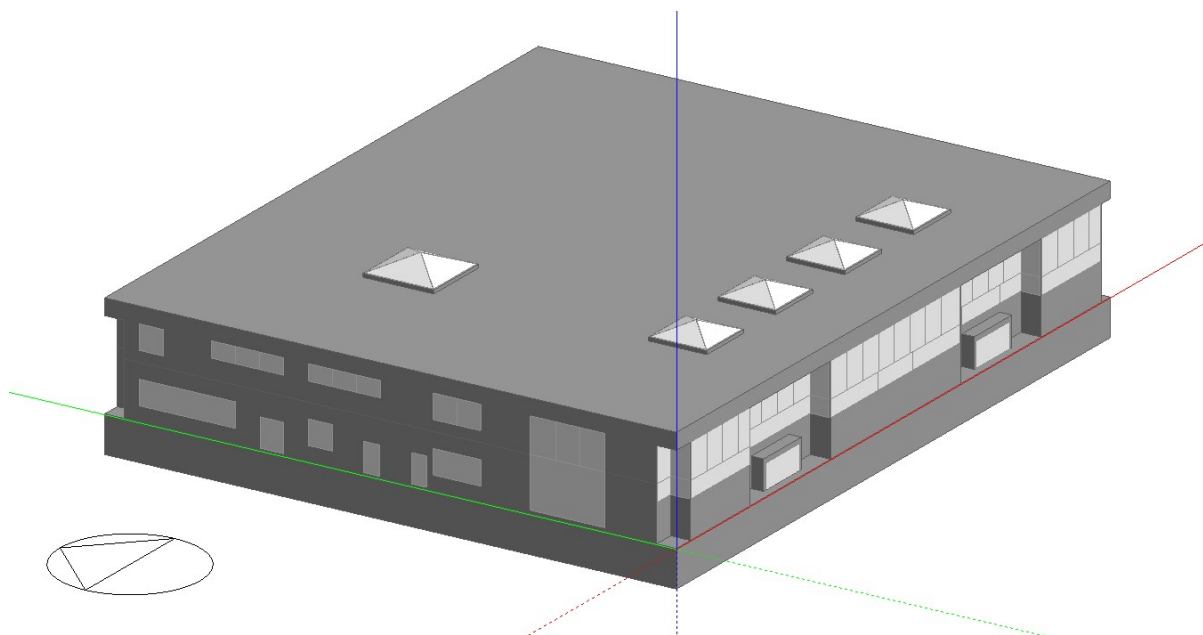


Figure 3 - 3D geometrical model in Design Builder

Multiple zones were considered in relation to a similar activity for a specific zone. One effect on the modeling was that not all interior walls were drawn, but only those that separate different calculation zones within the 3D model.

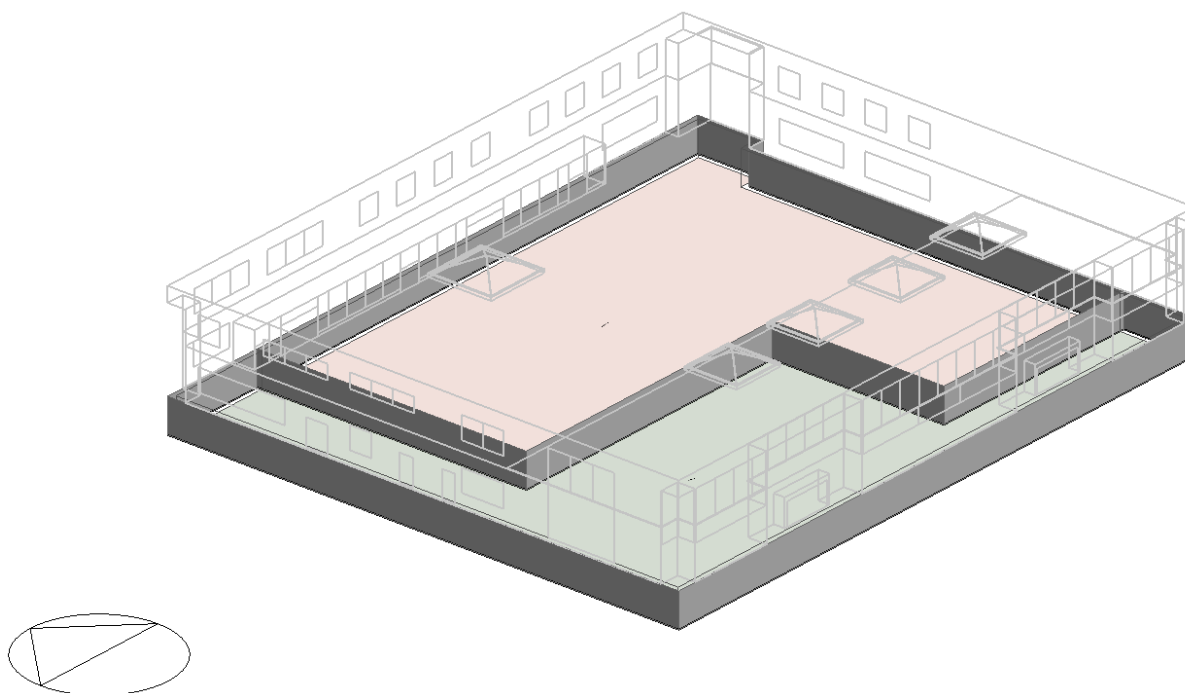


Figure 4 - Basement zoning

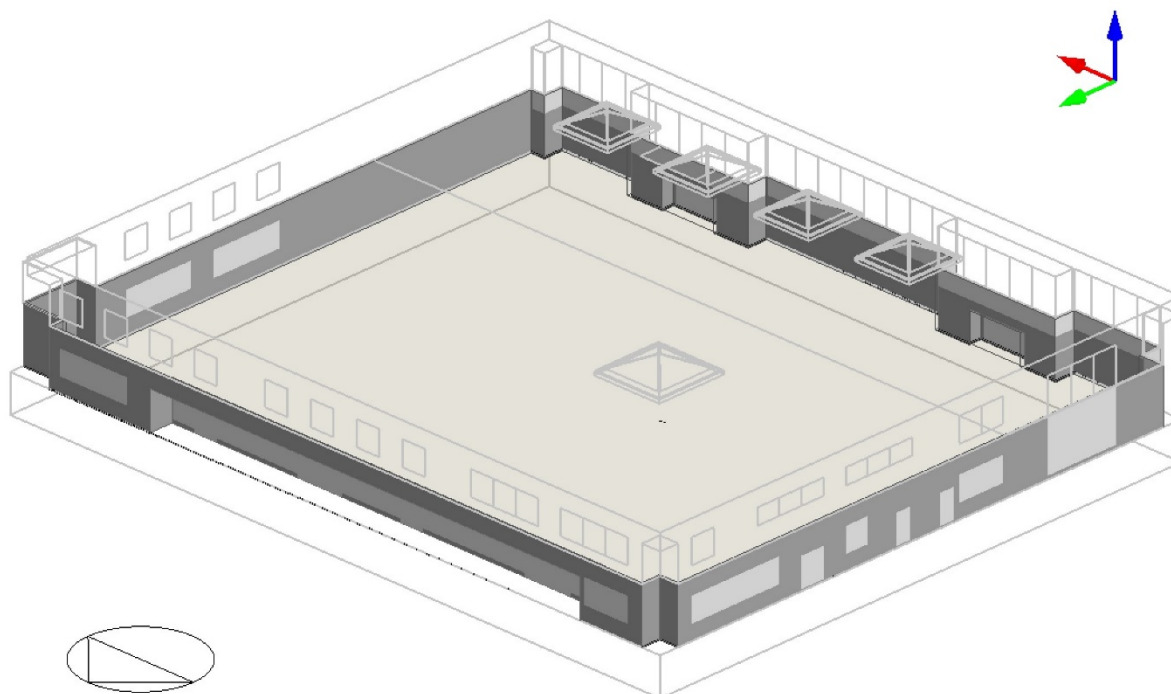


Figure 5 - Ground floor zoning

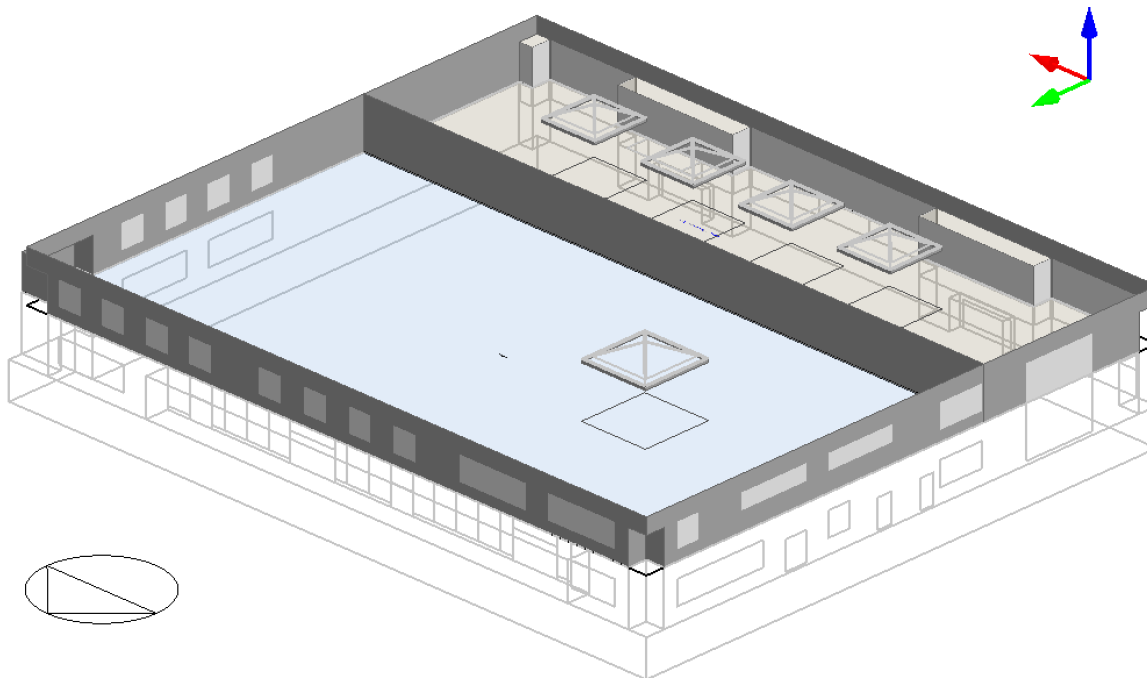


Figure 6 - 1st Floor and Mezzanine zoning

3.4. Configuration of the dynamic thermal simulation

3.4.1. Hourly climatic data

DesignBuilder uses **Climate Analytics**, a comprehensive set of global climate data, to simulate the performance of buildings. This data is available in **EPW format (EnergyPlus Weather File)**.

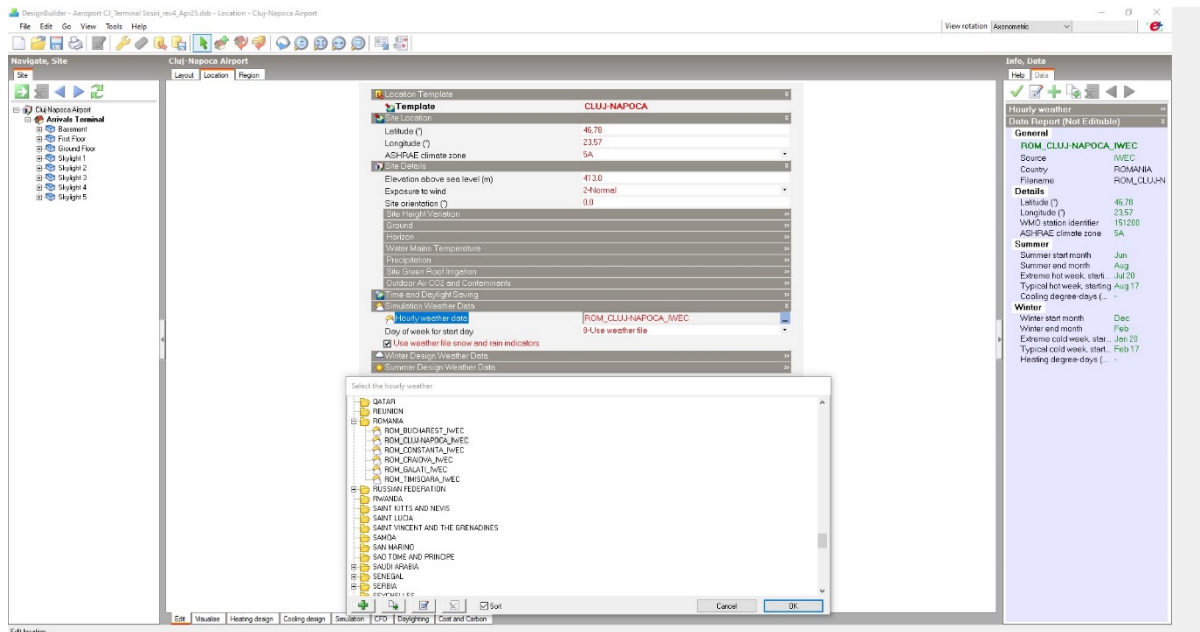
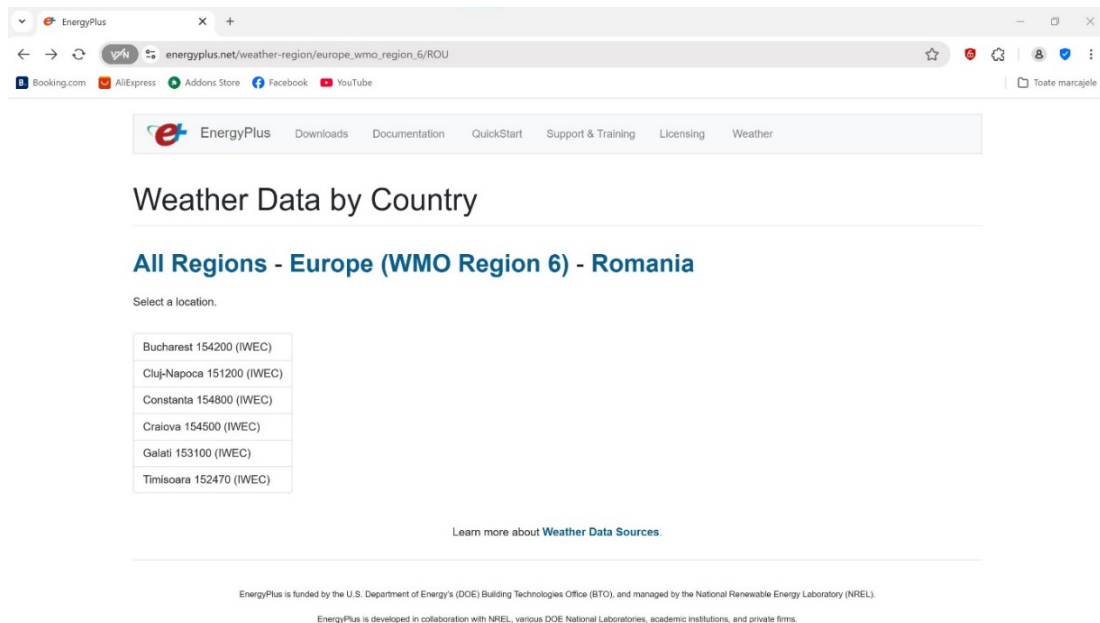


Figure 7 - Meteorological file in Design Builder

Typical years are used for general purpose energy and environmental simulations and for compliance and certification work. They are representative of long-term weather compiled from 20-30 years of data and match the long-term data from a particular location. Typical weather files use “real” data but may not be a contiguous year. Data is made up of months from multiple years across two or more decades.

IWEC is a typical year format available through Climate Analytics and which was used for the location of Cluj-Napoca Airport.



However, for better accuracy in the calibration process, an Actual Meteorological Year (AMY) was used for the year 2021, for the airport coordinates (latitude 46,78, longitude 23,69), extracted from the Copernicus platform (ERA5 hourly data on single levels) [1].



Figure 8 - Hourly weather data in Cluj-Napoca (TMY)

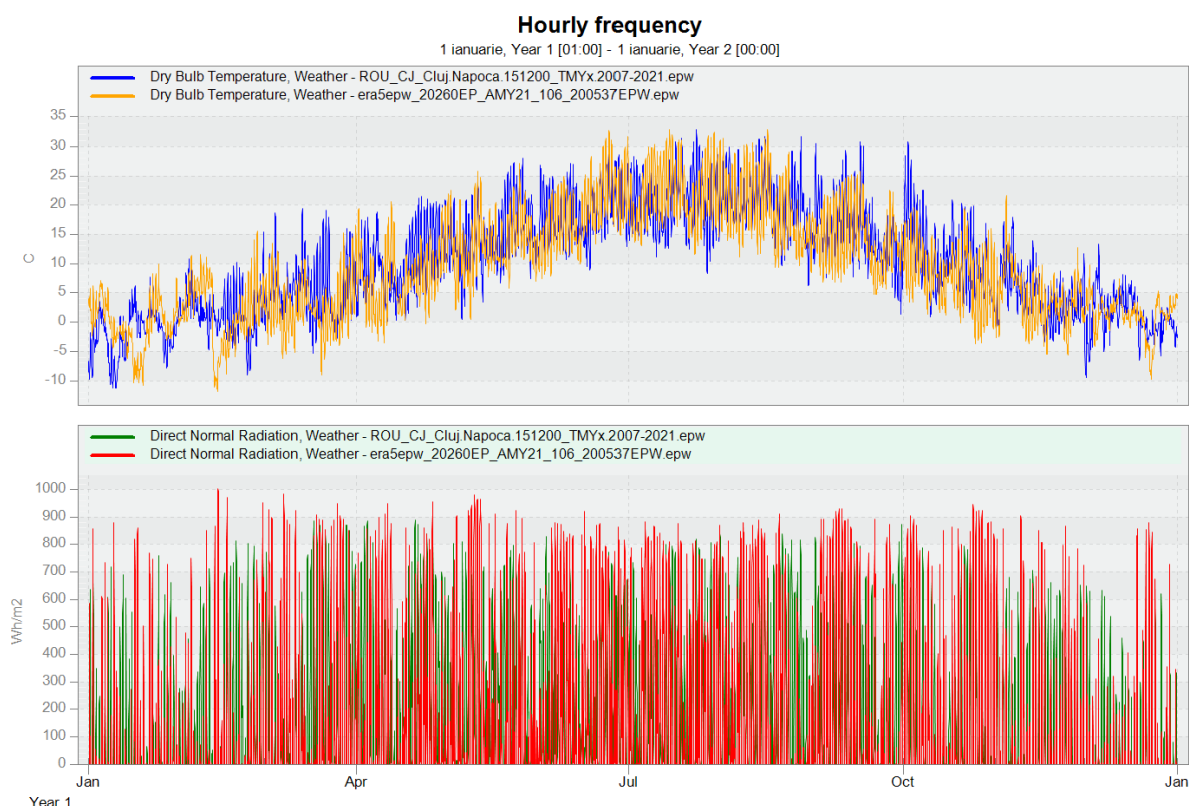


Figure 9 - Climate datasets extract in Cluj-Napoca AMY 2021 vs. TMY

3.4.2. Zone definition

The model was divided into multiple zones, considering the following principles:

- The zones are divided based on levels and use;
- The adjacent rooms are grouped into one zone if they have similar use and similar occupancy scenarios;
- The open floors of a mezzanine level are combined with the zones of the level below.

3.4.3. Occupancy scenario

3.4.3.1. Scenario calibration

Regarding the scenario used for each calculation zone the calibration approach was considered. Therefore, methane gas and electricity consumptions were collected for the Arrivals Terminal, for several years, and also an analysis of these consumptions was undertaken.

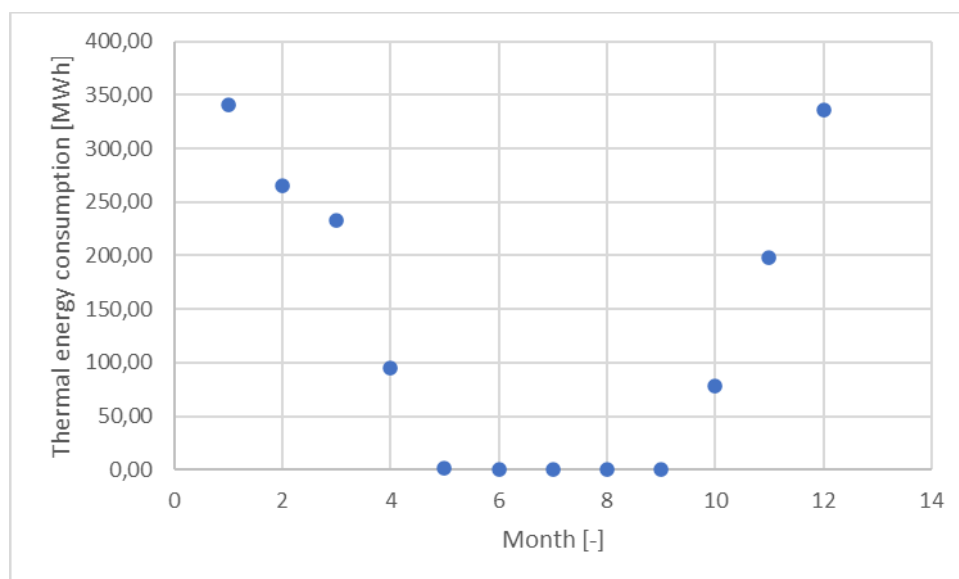


Figure 10 - Thermal energy consumption measurements for the year 2021 in Arrivals Terminal

Electricity consumption for multiple years was provided by the airport representatives. The values refer both to total electricity consumption at the terminal level, and to consumption by several categories of consumers within the terminal. However, as can be seen from the graph below, the electricity consumption of the consumer categories for which detailed consumption history exists is relatively small compared to the total electricity consumption recorded at the terminal level. This particular identified aspect was used as a key factor in calibrating the dynamic hourly model.

The electricity consumption for Arrivals Terminal used for the calibration is 111,0 kWh/m².year, which is the recorded value for the year 2024.

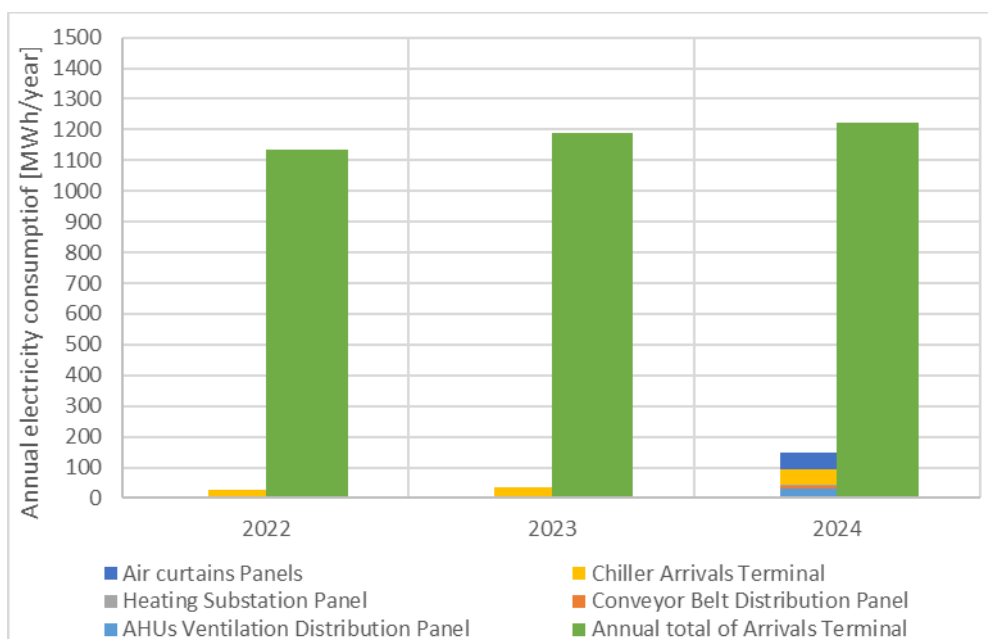


Figure 11 - Electricity consumption measurements in Arrivals terminal

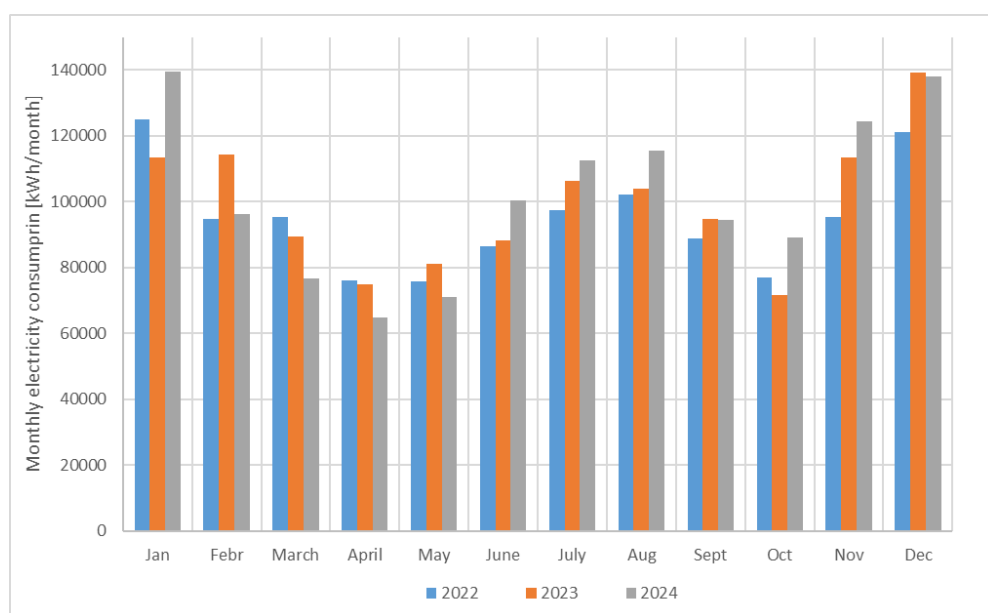


Figure 12 - Monthly electricity consumption measurements in Arrivals terminal

The results of the calibration process are presented below for the thermal energy consumption and electricity consumption, both measured and simulated values.



The thermal energy consumption relates with the heating and domestic hot water services, while electricity consumption relates with mechanical ventilation, cooling, and lighting – as building services, as well as the process electricity consumption within the terminal (office equipment, conveyor belts, miscellaneous equipment etc.).

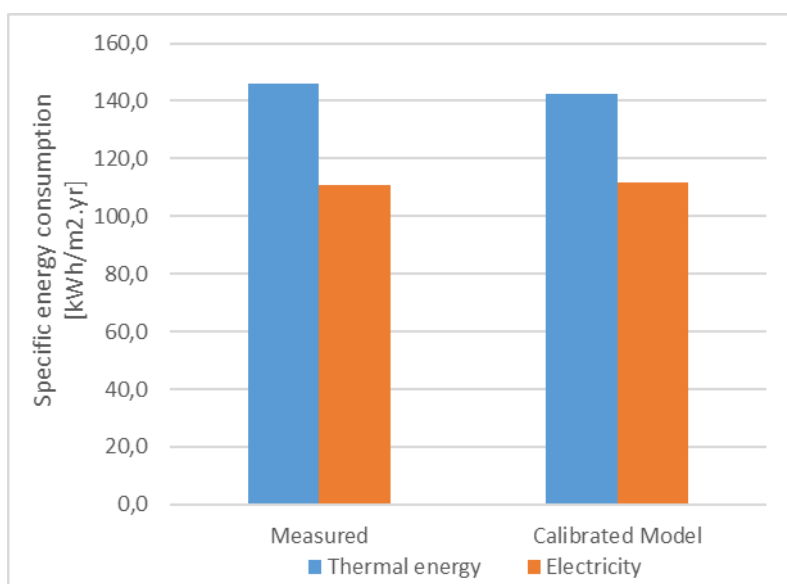


Figure 13 - Annual energy consumption for Arrivals Terminal

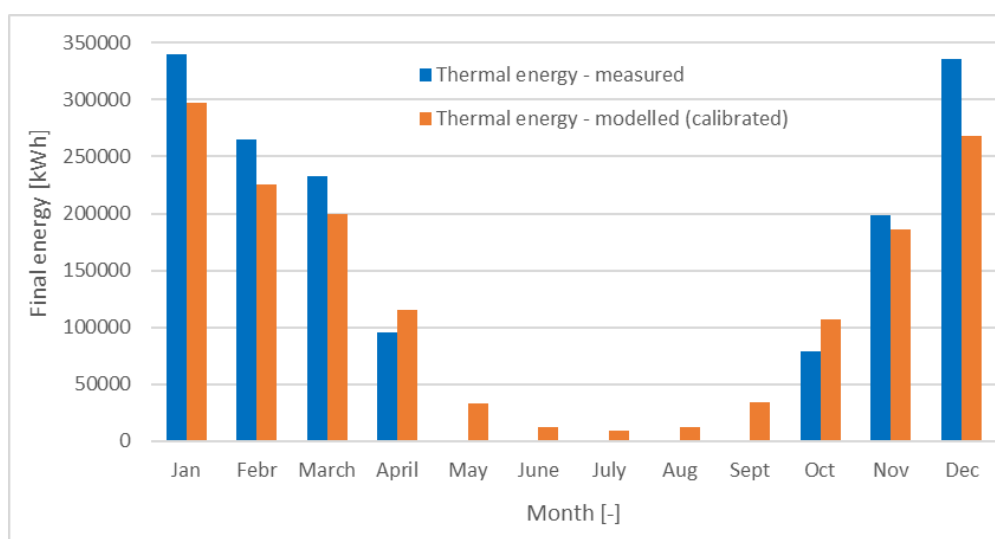


Figure 14 - Thermal energy consumption comparison in CLJ Arrivals terminal (AMY 2021)

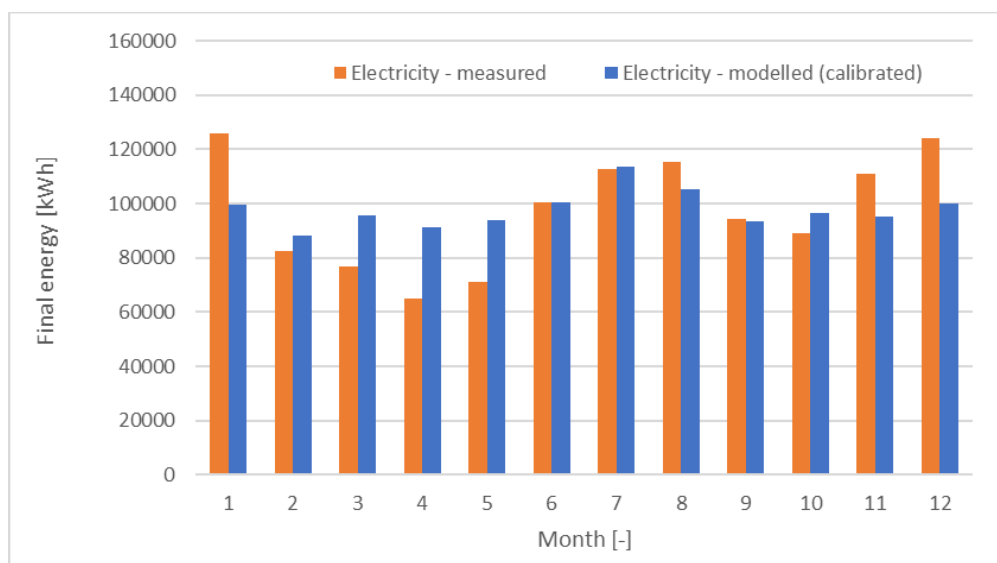


Figure 15 - Electricity consumption comparison in CLJ Arrivals terminal

3.4.3.2. Main challenges and constraints in calibrating the consumption profile for the Arrivals Terminal in Cluj-Napoca

Methane gas consumption and thermal energy consumption

- Heating and hot water for consumption is provided by the thermal power plant, which serves the following buildings and building bodies: Arrivals Terminal body and Departures Terminal body – together as 1st building, Electrical Power Plant & Thermal Power Plant – as 2nd building (these two buildings are representing the so-called *New Airport*), respectively another distinct building, the so-called *Old Airport* – as 3rd building, currently used as a restaurant for the airport employees. For all these buildings there is a single methane gas meter - the C3 meter. There is no other type of metering (e.g., flow meters), which would separate methane gas consumption at the building level.
- In 2024, the Departures Terminal was extended, from a Gross Surface of 14420 sqm to a Gross Surface of 21621 sqm. This aspect implies that, for the calibration, methane gas consumption history can be taken into account up to and including 2023.

Electricity consumption

- Electricity consumption was extracted from the BMS for the interval 2022-2024, exclusively for the Arrivals Terminal and by consumer categories. However, following the analysis of the data provided, it was found that for the years 2022-2023 reported data for certain consumer categories were missing due to technical issues within the BMS's server.



Thus, the consumptions of electricity monitored in the Arrivals Terminal in 2024 are considered as representative data.

- Also, it is identified that the several consumer categories are missing, of which the most important is the lighting.

3.4.3.3. Real consumption history analysis and numerical model calibration

In order to break down the consumption of methane gas recorded by the C3 meter and, subsequently, of thermal energy, a centralization of the surfaces of the buildings served by the heating plant was carried out – as can be seen in the table below.

Table 3 - Data collection for Gross Floor Area (GFA) of buildings at facility level

Airport building assembly centralizer	After extension	Before extension	Details	GFA weights before extension [%]
	GFA [m2]	GFA [m2]		
New Airport buildings			Heating and DHW source provided by the thermal power plant - only one methane gas meter - C3	
Arrivals Terminal	10602	10602		36,4
Departures Terminal	21621,4	14419,5		49,5
Electrical and Thermal Power plant	798	798		2,7
Old Airport building	3296,5	3297		11,3
<i>Handling building</i>			<i>Has another heating source and separate methane gas meter-C2</i>	
Total Gross Floor Area [m2]	36317,87	29116		100

For the breakdown of methane gas consumption, the weights of the building Gross Floor Areas in the building complex served by the same meter were considered. It was taken into account that the largest share (85,9%) within the assembly is attributed to the two active terminals, which have similar destination and operating conditions.

Thus, the breakdown of the methane gas history, in conjunction with the GFA of each building / building body of the assembly, was considered. In addition, it is emphasized that the share of other buildings in the metered assembly that do not have the current terminal destination is rather reduced (14,1%), which is expected to introduce rather a limited error. The GFA-weighted apportionment introduces unquantified uncertainty regarding the thermal energy consumption and input data for calibration, being a clear limitation of the data available in situ for the current application. To eliminate this error source, it is strongly recommended to use the building's own consumption history, recorded by a thermal energy meter located at the building under analysis (in case of future replications in real buildings).

The table below presents the methane gas consumption for several years, received from the airport representatives. It is noted that only for the year 2021 there is a breakdown of the two



meters in the data received. At the same time, the year 2020 is excluded considering the COVID pandemic. Thus, the value recorded by the C3 meter in the year 2021 remains as a reference value, for methane gas consumption.

Table 4 - Data collection regarding methane gas consumption at the facility level

Real consumption of methane gas at the Cluj-Napoca airport	2019 [m3]	2020 [m3]	2021 [m3]
C3 - methane gas meter			402776
<i>C2 -methane gas meter</i>			<i>31531</i>
Total [m3]	414933	404693	434307
Total [kWh]	4377543,2	4269511,2	4581939
Total [MWh]	4377,5	4269,5	4581,9

As regarding the electricity consumption, data monitored through BMS was received – as can be seen in the table below, and as it was justified previously, the year 2024 is considered as representative.

Table 5 - Data collection regarding electricity consumption at building level

Real electricity consumption at the ARRIVALS TERMINAL	2022 [kWh]	2023 [kWh]	2024 [kWh]
Total electricity consumption from BMS monitoring	1135312	1191019	1222697

Thus, it was found that the total reported consumption is much higher than the sum of the consumption by consumer category, as can be seen in the table below.

This may be due to:

- 1) there are types of consumers for which no reporting was carried out at all in some years, for example: HVAC and air curtains in 2022 and 2023 have a 0 kWh report, although they most likely operated under normal conditions. This was due to technical issues of the BMS's server.
- 2) there are other consumers compared to what actually monitored, such as the lighting as a category of consumer of electrical consumption.

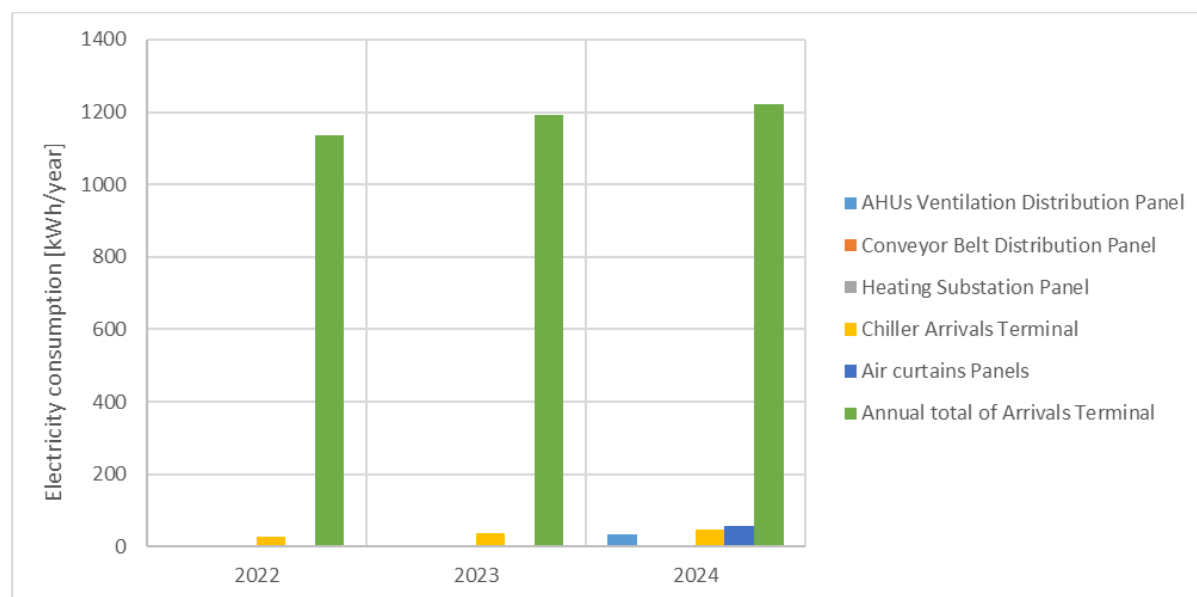


Figure 16 - Measurements by category of consumers in BMS – Arrivals Terminal

Initial scenarios in Design Builder calculated model

As regarding the **initial** input data, this is presented as following, considering specific inputs for the main categories of input data: Activity, Construction, Openings, Lighting and HVAC, for each calculation zone.

Table 6 - Initial input data regarding the occupancy scenario & lighting

Input data type	Activity					Lighting
Calculation Zones	Occupancy	DHW	Heating Setpoint	Cooling Setpoint	Process equipment	Power density
	[people/m2]	[l/m2-day]	[oC]	[oC]	[W/m2]	[W/m2]
Zone 1. Passenger Terminal	0,3414	0,75	20	25	-	4,2
Zone 2. Office Area	0,1226	0,197	20	25	12,7	4,7
Zone 3. Luggage Area	0,1185	0,00	20	25	-	3,2
Zone 4. Other areas	0,0000	0,3	20	25	-	3,2



Table 7 - Initial input data regarding the currently in operation HVAC equipment

Input data type	HVAC						
Calculation Zones	Heating - η	Cooling - ESEER	DHW - η	Nat Vent	Mech Vent	Heat Recov	Fans Energ
	[-]	[-]	[-]	[ac/h]	[m3/s]	[-]	[W/m2]
Zone 1. Passenger Terminal	0,85	3,00	0,85	-	20,28	0,63	14,14
Zone 2. Office Area	0,85	3,00	0,85	-	5	0,7	5,32
Zone 3. Luggage Area	0,85	-	0,85	5,00	-	-	0,00
Zone 4. Other areas	0,85	-	0,85	0,6	-	-	0,00

Adjusted scenarios in Design Builder calibrated model

In order to calibrate the model all collected data and measurements were used. Thus, in the following table are presented the precalculated input values for the main variables, considering the real consumption profile of the terminal.

Table 8 - Input data for the calibrated model based on monitored and collected real data

Input data type	Adjusted Activity					
Calculation Zones	Occupancy	DHW	Heating Setpoint	Cooling Setpoint	Process equipment	Miscellaneous equipment
	[people/m2]	[l/m2-day]	[oC]	[oC]	[W/m2]	[W/m2]
Zone 1. Passenger Terminal	0,057	0,75	21	25	0,18	8,00
Zone 2. Office Area	0,041	0,197	22	25	12,7	-
Zone 3. Luggage Area	0,000	0,00	20	25	-	-
Zone 4. Other areas	0,000	0,3	20	25	-	-

After the adjustments with the real collected data, the results are as follows.

Table 9 - Annual final energy consumptions Dynamic Model vs. Measurements

Final energy (FE) consumption	Preliminary Model	Calibrated Model	Measured	Abs. Err.	Relative Err.	RMSE (monthly)
	[kWh/m2.yr]	[kWh/m2.yr]	[kWh/m2.yr]	[kWh/m2.yr]	[%]	[kWh/m2.yr]
Thermal energy	102,6	142,57	145,9	3,4	2,3	3,13
Electricity	89,6	111,56	111,0	0,6	0,5	1,57
Total	192,2	254,1	256,9	2,8	1,1	-

A detailed description of the calibration methodology used for the Arrivals Terminal of the Cluj-Napoca International Airport is presented as an APPENDIX, published as Open Access article in the scientific journal *Buildings* - DOI: [10.3390/buildings16061195](https://doi.org/10.3390/buildings16061195).



3.5. Results of dynamic thermal simulation

3.5.1. Cluj-napoca airport arrivals terminal

The heating & DHW and cooling thermal powers are shown in the figure below. These are the values for the heating & DHW and cooling **thermal energy demand, without the heat losses associated with emission, distribution, transportation, and generation subsystems**. The maximum heating power (thermal power) is 847 kW and the maximum cooling power (thermal power) is 368 kW.

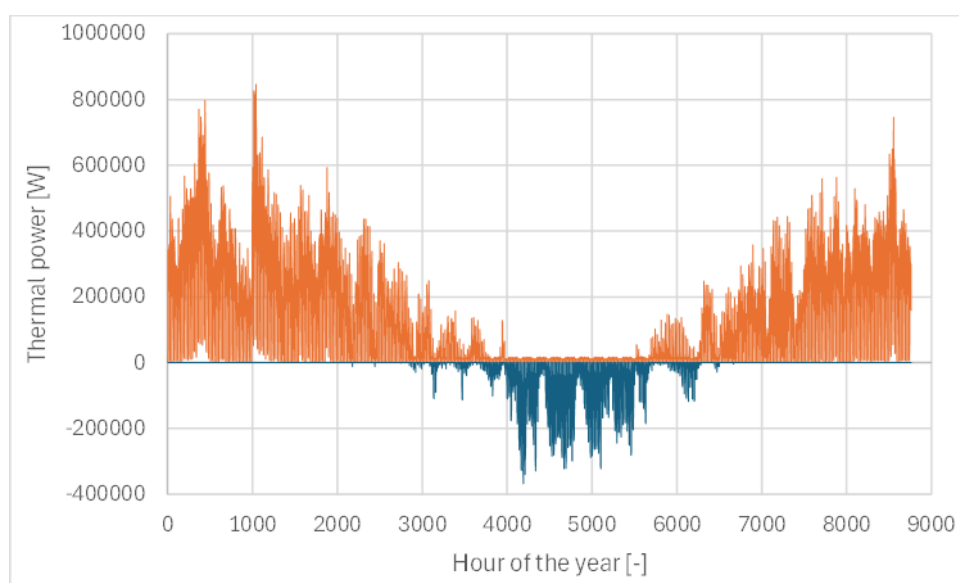


Figure 17 - Thermal power for heating & DHW and cooling demand in the simulation of CLJ terminal

Furthermore, the thermal powers (for heating & DHW) and the electrical powers (for cooling), associated with the final energy consumptions, are presented in the figures below. These are the values for the heating hourly energy consumption and for the cooling hourly electrical energy consumption, **with the heat losses associated with emission, distribution, transportation, and generation subsystems**. The maximum heating power (thermal power associated with final energy) is 1024 kW, and the maximum cooling power (electrical power associated with final energy) is 123 kW.

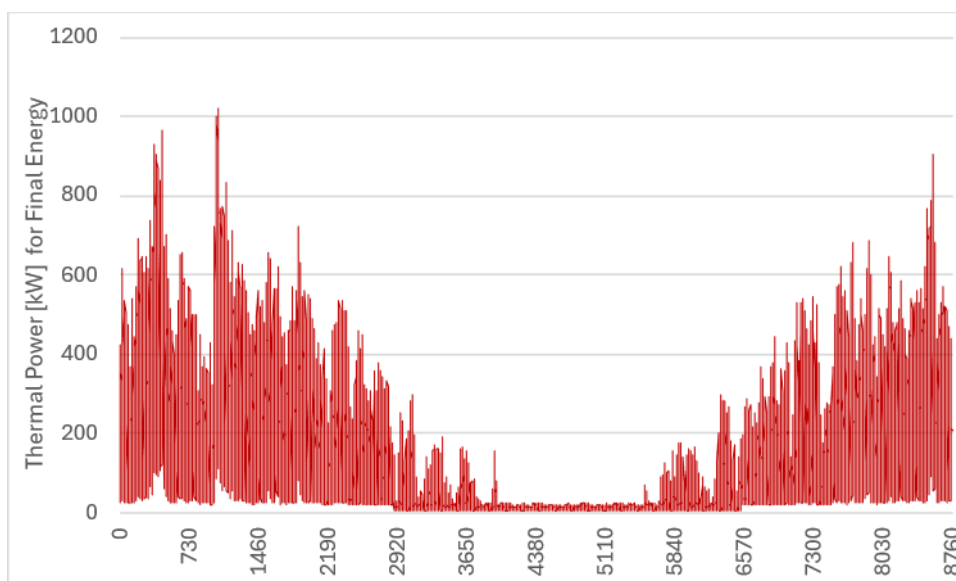


Figure 18 - Hourly thermal energy consumption for heating and DHW

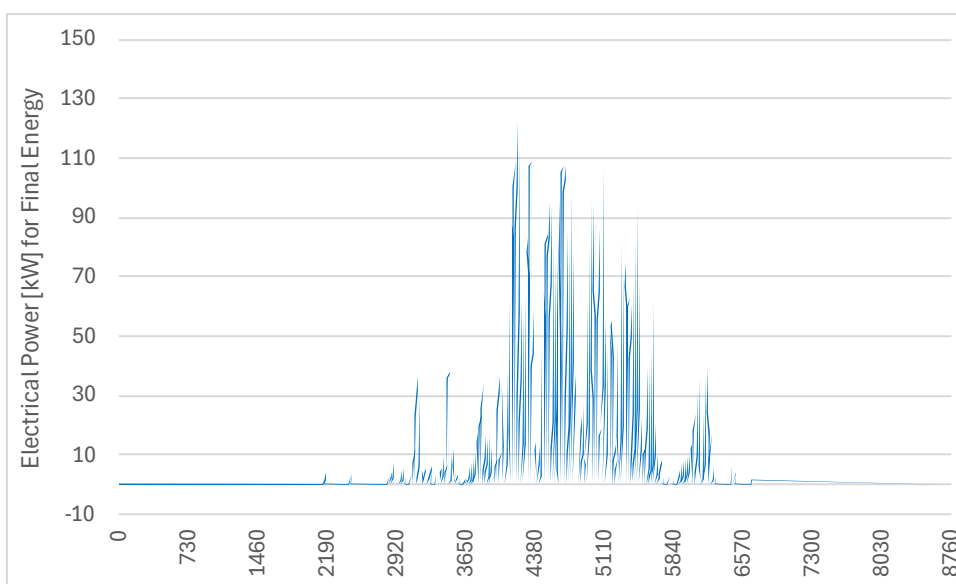


Figure 19 - Hourly electrical energy consumption for cooling

In addition, for this case study the evaluation of all energy consumers (both thermal energy and electricity) was undertaken, and the results are presented below.

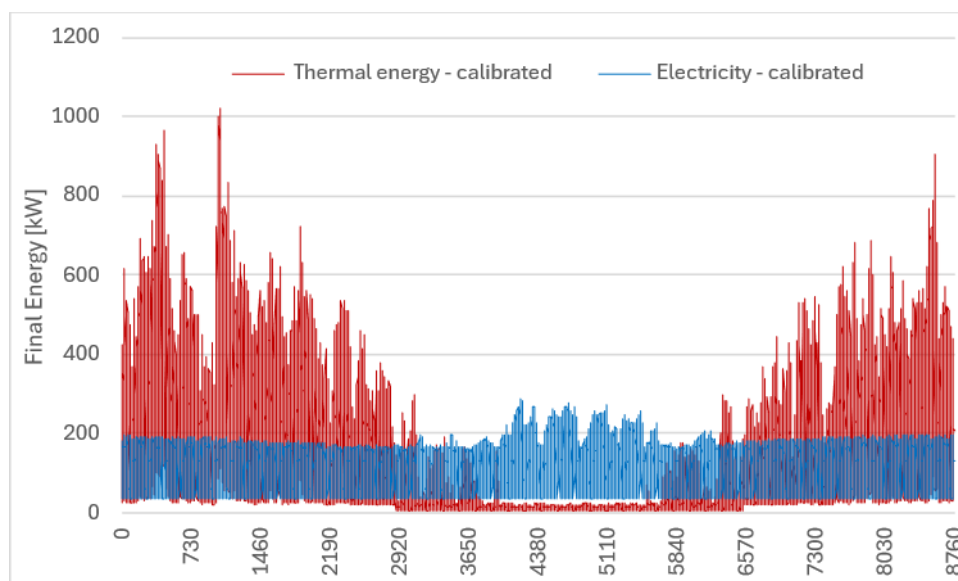


Figure 20 - Hourly thermal and electrical power in the simulation of CLJ terminal



3.6. Results of the life cycle assessment

3.6.1. Goal and scope definition

The goal of the LCA is to quantify the life-cycle environmental impacts associated with the Arrival Terminal of Cluj-Napoca International Airport and to compare the performance of a baseline configuration with an optimized scenario that includes energy and envelope improvements. The assessment supports design and renovation decisions by identifying the main impact drivers over the building's lifetime and by evaluating whether optimization measures reduce overall burdens rather than shifting them between life cycle stages or impact categories. The functional unit is the service provided by the Arrival Terminal over a 50-year reference study period, reported as total impacts for the building and as aggregated stage results according to EN15804+A2 life cycle modules (A1–A5, B1–B7, C1–C4, D). EN15804+A2 extends the indicator set and requires separate reporting of GWP total, GWP fossil, GWP biogenic, GWP from land-use and land-use change, as well as more detailed resource use and emissions indicators, leading to a richer but more complex result profile.

System boundaries follow a cradle-to-grave approach and include production of construction materials (A1–A3), transport to site (A4), construction and installation processes including site waste (A5), use stage processes such as energy and water consumption and material replacements (B4–B7), deconstruction and end-of-life treatment (C1–C4), as well as potential benefits and loads beyond the system boundary (Module D) from recycling and material recovery.

The LCA is performed with One Click LCA, using ecoinvent (version 3.11) as background life cycle inventory and implementing EN15804+A2 indicator set to allow consistency with European building assessment practice and comparability with previous airport terminal studies. The scope covers the building foundation, structure, envelope, internal partitions, floor and ceiling finishes, technical systems, and associated replacements; user equipment and passenger transport to and from the airport are excluded, in line with the reference study for the Paris terminals. Results are reported per life cycle module and aggregated for the main impact indicators, including Global Warming Potential (GWP), primary energy demand, water use, waste generation and damage indicators where applicable, to support a multi-criteria evaluation of the refurbishment options.

3.6.2. Inventory analysis

The life cycle inventory compiles all relevant input and output flows associated with the Arrival Terminal. For the product stage (A1–A3), material quantities from the building model and bills of quantities are mapped to ecoinvent datasets for concrete, reinforcing steel, masonry, insulation



materials, glazing systems, internal partitions and finishes. Transport to the site (Module A4) is modeled using standard delivery distances and specialized vehicles. Specifically, a 100 km transport distance is assumed for steel fibers and profiles, while insulation materials are modeled at 200 km. Ready-mix concrete is assigned a shorter distance of 20 km to account for the use of specialized concrete mixer trucks. These distances are integrated into the One Click LCA software for analysis, as illustrated in the figure below.

The screenshot shows the One Click LCA software interface. The top navigation bar includes 'One Click LCA', 'Projects', 'Materials Compass', and 'Sustainability Tools' (marked as NEW). The user is logged in as 'Tania Rus'. The main interface shows a project path: 'Return to project' > 'AIAIC' > 'Level(s) life-cycle ...' > 'Baseline'. On the left, a sidebar lists building materials categories: 'Foundation and sub-surf...', 'External walls and facade', 'Columns and load-beari...', 'Internal and non-bearing...', 'Floors and horizontal ele...', 'Other materials', 'Doors and windows', 'Finishes', 'External areas', and 'Building systems'. The main area is titled 'Foundation and sub-surface' and shows a table of resources with their transport settings.

Resource Name	Transport 1 distance, ...	Transport 1 Method
☐ XPS insulation panels, L=0.035 W/mK, R=2.85 m2K/W, 100 mm, 3.8 kg/m2, 38 kg/m3, compr...	200	Trailer combination, 40 ton capacity, 100% fill rate (+A18
☐ Modified bitumen waterproofing membrane, 3.54 mm, 4.25 kg/m2, 1200 kg/m3 (One Click LCA)	100	Trailer combination, 40 ton capacity, 100% fill rate (+A18
☐ Ready-mix concrete, C20/25, 2335 kg/m3 (ROMCIM ROMANIA)	20	Concrete mixer truck, appr. 8 m3, 100% fill rate (+A1&A2
☐ Steel fibres for concrete reinforcement, manufacturers average, 7850 kg/m3, FMH, FMC, FM...	100	Trailer combination, 40 ton capacity, 100% fill rate (+A18
☐ Ready-mix concrete, C8/10, 2214 kg/m3 (STRABAG S.R.L.)	20	Concrete mixer truck, appr. 8 m3, 100% fill rate (+A1&A2

Figure 21 - Interface of transport settings in One Click LCA

The environmental impacts of the construction and installation processes (A5) cover material wastage, site operations, and waste management. These impacts are driven primarily by material wastage, followed by contributions from biogenic packaging waste. Within the use stage, the impacts of repair (B3) are considered negligible. However, material replacement and refurbishment (B4–B5) represent a significant portion of the inventory, with most of these emissions stemming from the production of replacement materials rather than the subsequent waste processing. Operational energy consumption (B6) is the most substantial contributor to the overall life cycle inventory. Finally, the impact of water use (B7) accounts for the supply and treatment of potable water throughout the project's 50-year service life. End-of-life processes (C1–C4) include deconstruction and demolition, waste transport, waste processing, and final disposal. Beyond-the-system-boundary benefits (Module D) are included to represent avoided burdens from recycling and material recovery.

The building's elements lifespans are modeled based on intervals like those established for the Charles de Gaulle airport, assuming a 10-year cycle for finishes, 20 years for equipment, and 30 years for windows and doors. The building structure itself is assigned to a 50-year lifespan. To



maintain the facility's integrity over this period, all materials and equipment are systematically replaced at the end of their service lives during the renovation stage.

The end-of-life treatment for materials is modeled through a combination of recycling, incineration, and landfilling. High recovery rates are assumed for metals and steel (90%), with a slightly lower proportion of glass (80%) also directed toward recycling. In contrast, specific components like aluminum double-glazing windows are assigned to a partial recycling rate (50%). Synthetic materials, such as polystyrene, is designated for incineration, while all remaining materials are assumed to be landfilled. For the deconstruction stage, a standard transport distance of 10 km is applied for the movement of waste from the site to the landfill facility. The service life specifications and end-of-life processing methods for each building element are detailed in the figure below.

Resource Name	Service Life years	EOL Process
PVC door, 42.4 kg/m ² (OKNOPLAST Sp. z o.o.)	30	Glass-containing product recycling (80 % glass)
Aluminium doors, 49.2 kg/m ² (OKNOPLAST Sp. z o.o.)	30	Aluminium recycling
Aluminium framed sliding glass door, double glazed, 3 x 2.18 m, 40.86 kg/m ² , S600 (3 m x 2, ...)	30	Glass-containing product recycling (80 % glass)
Aluminium framed entrance glass door, double glazed, 1.23 x 2.18 m, 31.41 kg/m ² , SUPRE...	30	Glass-containing product recycling (80 % glass)
Wooden doorleaf, 0.838x1.981 m, 8.8 kg/m ² (JELD-WEN)	30	Wood-containing product incineration (80% wood)
Fire and smoke resistant galvanized steel profile door, 1230x2180 mm, 85.34 kg/m ² , SP700 (...)	30	Metal-containing product recycling (90 % metal)
Galvanized steel door, 40.04 kg/m ² , SMU101/201 (Tammer OU)	30	Metal-containing product recycling (90 % metal)

Figure 22 - Interface of service life and end-of-life settings in One Click LCA

Operational energy demand is categorized into four primary uses: heating, cooling, Domestic Hot Water (DHW), and specific electricity for lighting and ventilation. Heating and DHW are supplied by the airport's dedicated thermal plant, which operates on 100% natural gas. For the Arrival Terminal of the airport, natural gas consumption is estimated at 30% of the total utility usage, due to the lack of sub-metering. Cooling is provided by electric chillers. All electrical energy is sourced from the national utility grid. These parameters are configured within the software interface as shown below.

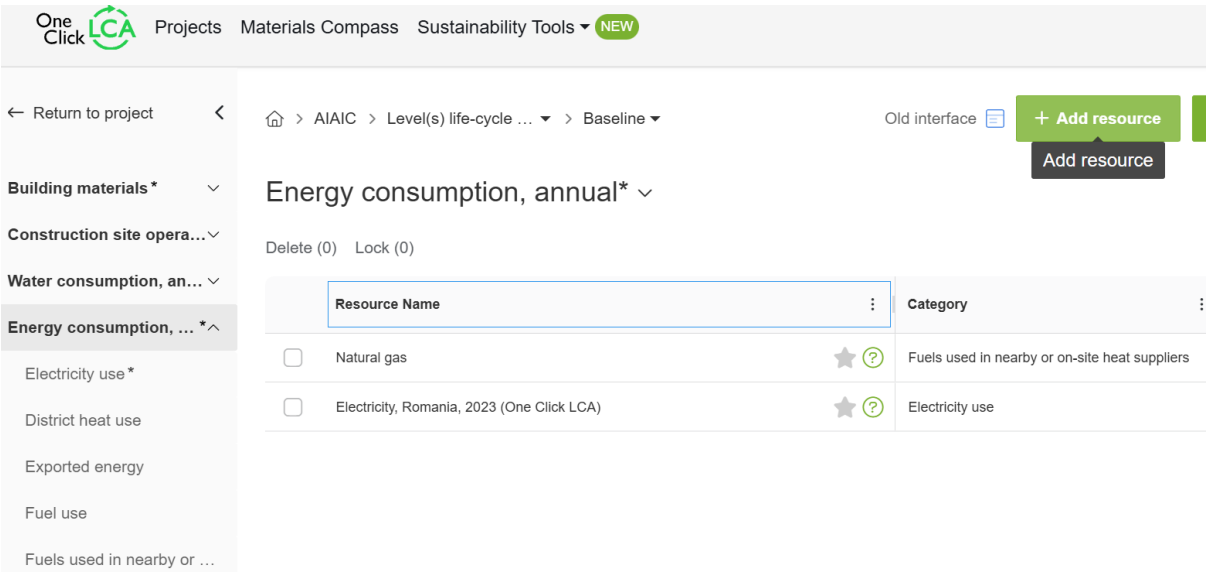


Figure 23 - Interface of energy settings in One Click LCA

3.6.3. Impact assessment

To achieve a holistic view of the building's carbon footprint, the analysis covers all four primary stages: Product, Construction, Use, and End of Life. Within the Use Stage, the assessment distinguishes between embodied impacts (such as maintenance and repairs) and Operational Impacts (B6–B7), which account for the energy and water consumed during the building’s occupancy. Finally, by including Stage D, the report highlights 'Circular Economy' benefits, demonstrating how recovered materials can offset the environmental costs of future projects.

The following provides a comprehensive breakdown of the LCA framework for buildings, specifically aligned with the EN 15978 standard. It illustrates how environmental impacts are categorized across the entire lifespan of a structure, ranging from raw material extraction to the potential for circularity after demolition.

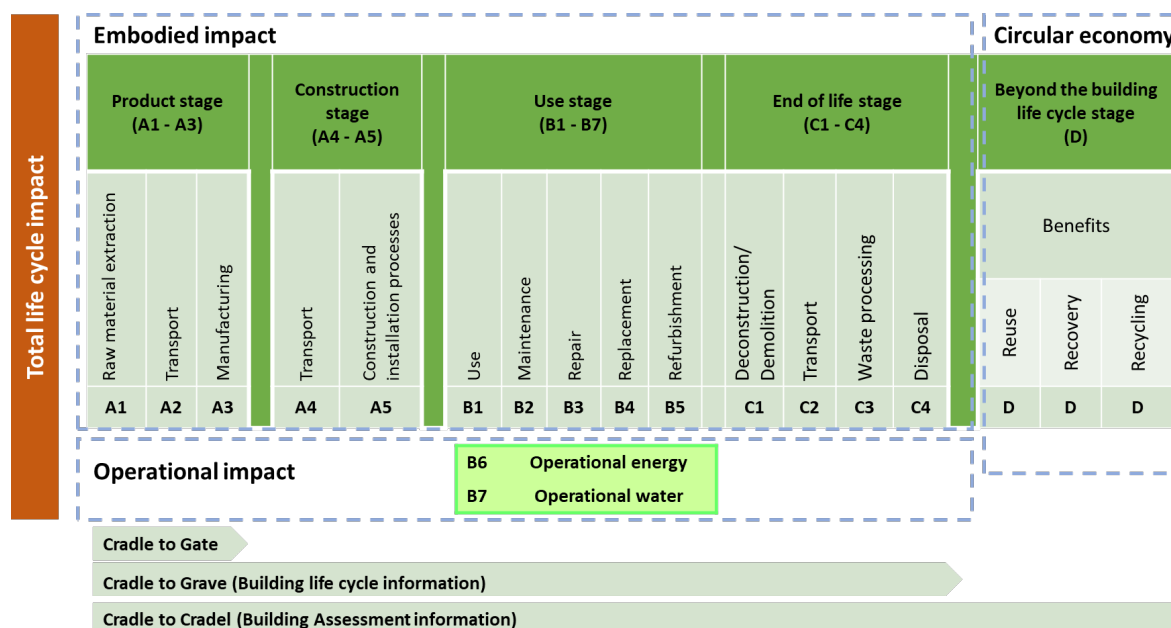


Figure 24 - LCA stages and system boundaries for buildings (EN 15978)

Table 10 - The environmental impacts (per m² and per year) of Arrivals Terminal

Indicator	Results category					
	Product stage (A1 - A3)	Construction stage (A4 - A5)	Use stage (B1 - B7)	End-of-life (C1 - C4)	Benefits (D)	Total
Global Warming Potential total kg CO ₂ e (GWP – total)	7.07E+00	5.23E-01	8.22E+01	6.37E-01	-2.92E+00	8.75E+01
Global Warming Potential fossil kg CO ₂ e (GWP – fossil)	7.12E+00	4.34E-01	8.21E+01	6.27E-01	-2.89E+00	8.74E+01
Global Warming Potential biogenic kg CO ₂ e (GWP – biogenic)	-6.44E-02	8.88E-02	0.00E+00	1.00E-02	-1.64E-02	1.80E-02
Global Warming Potential, LULUC kg CO ₂ e (GWP – LULUC)	1.11E-02	5.64E-04	8.62E-02	1.21E-04	-7.28E-03	9.07E-02
Depletion potential of the stratospheric ozone layer kg CFC11e (ODP-A2)	7.77E-07	6.65E-08	7.91E-06	9.94E-08	-1.05E-07	8.75E-06
Acidification potential,	3.06E-02	1.49E-03	2.78E-01	1.72E-03	-7.52E-03	3.04E-01



accumulated exceedance mol H+ eq. (AP-A2)						
Eutrophication freshwater kg P eq. (EP-P)	1.30E-01	4.30E-03	7.19E-03	3.29E-05	-5.01E-04	1.41E-01
Eutrophication aquatic marine kg N eq. (EP-M)	5.66E-03	2.54E-04	4.70E-02	4.95E-04	-1.30E-03	5.22E-02
Eutrophication terrestrial mol N eq. (EP-T)	7.26E-02	3.27E-03	4.83E-01	5.43E-03	-1.21E-02	5.52E-01
Formation potential of tropospheric ozone kg NMVOC eq. (POCP-A2)	2.13E-02	1.01E-03	1.49E-01	1.63E-03	-5.83E-03	1.67E-01
Abiotic depletion potential (ADP-elements) for non-fossil resources (+A2) kg Sbe (ADPE+A2)	9.53E-05	3.84E-04	4.92E-04	2.19E-03	7.29E-07	3.17E-03
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ (ADPF+A2)	8.42E+01	6.09E+00	1.10E+03	1.07E+01	-2.38E+01	1.18E+03
Water use m ³ deprived	3.93E+01	1.02E+00	3.90E+03	2.78E-01	-6.64E+00	3.94E+03

The following descriptions provide an overview of the environmental impact indicators shown in the life-cycle results, which measure the various ways a project affects the natural world beyond simple carbon emissions.

Global Warming Potential measures the amount of heat trapped in the atmosphere by greenhouse gases relative to carbon dioxide. GWP-total is the sum of all greenhouse gas effects throughout the project's life. GWP-fossil specifically tracks emissions from burning fossil fuels, which accounts for most of this project's impact, particularly during the B6 Energy stage. GWP-biogenic accounts for carbon released or sequestered by biological materials like wood; notably, this project shows negative values in the A1-A3 stage, indicating carbon is stored in the materials. GWP-LULUC measures emissions resulting from land use and land-use changes, such as deforestation for mining or construction.

Depletion potential of the stratospheric ozone layer (ODP-A2) measures the potential for chemical emissions to break down the ozone layer, which protects the Earth from ultraviolet radiation. This



impact is almost entirely driven by the B6 Energy stage in the data provided in the table. Acidification potential (AP-A2) quantifies the increase in acidity within soil and water systems, which can damage forests and aquatic life. Formation potential of tropospheric ozone (POCP-A2) measures the creation of ground-level smog, which affects human respiratory health and plant growth. Both indicators show that operational energy is the primary source of these pollutants.

Eutrophication measures the excessive enrichment of ecosystems with nutrients like nitrogen and phosphorus, which leads to oxygen depletion in water. Eutrophication freshwater (EP-P) focuses on phosphorus and is unique in this data because it is dominated by the A1-A3 Materials stage rather than energy. Eutrophication aquatic marine (EP-M) and terrestrial (EP-T) measure nitrogen-based enrichment in oceans and on land, respectively, and are both primarily influenced by the project's energy consumption.

Abiotic depletion potential (ADPE +A2) tracks the exhaustion of non-fossil resources, such as minerals and elements. This indicator shows a diverse spread of impact, with C2 Waste transport and A1-A3 Materials playing significant roles. Abiotic depletion potential (ADPF+A2) measures the consumption of fossil fuel energy resources, which is predictably dominated by the B6 Energy phase. Finally, Water use measures the volume of water deprived from local environments, which in this case is almost entirely attributed to the energy production required for operations.

Global Warming Potential total kg CO2e - Life-cycle stages

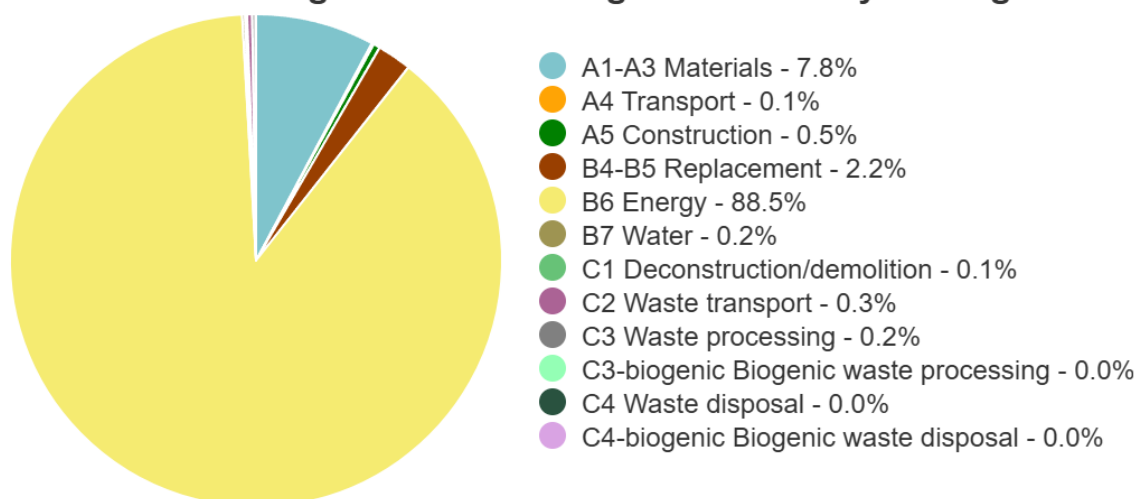


Figure 25 - Global warming potential total kgCO₂e by Life-cycle stages

According to the above figure, the vast majority of the GWP is concentrated in the B6 Energy stage, which accounts for 88.5% of the total kg CO₂e. This suggests that the operational phase is



far more significant than the initial construction or eventual demolition. The embodied carbon within the materials themselves, represented by stages A1 through A3, contributes 7.8% to the total, while replacement and maintenance during the B4 and B5 stages adds another 2.2%. All other factors, including transportation, construction site activities, and various end-of-life waste processes, represent negligible amounts, with each contributing less than 1% to the overall footprint.

Bubble chart, total life-cycle impact by resource type and subtype, Global Warming Potential total

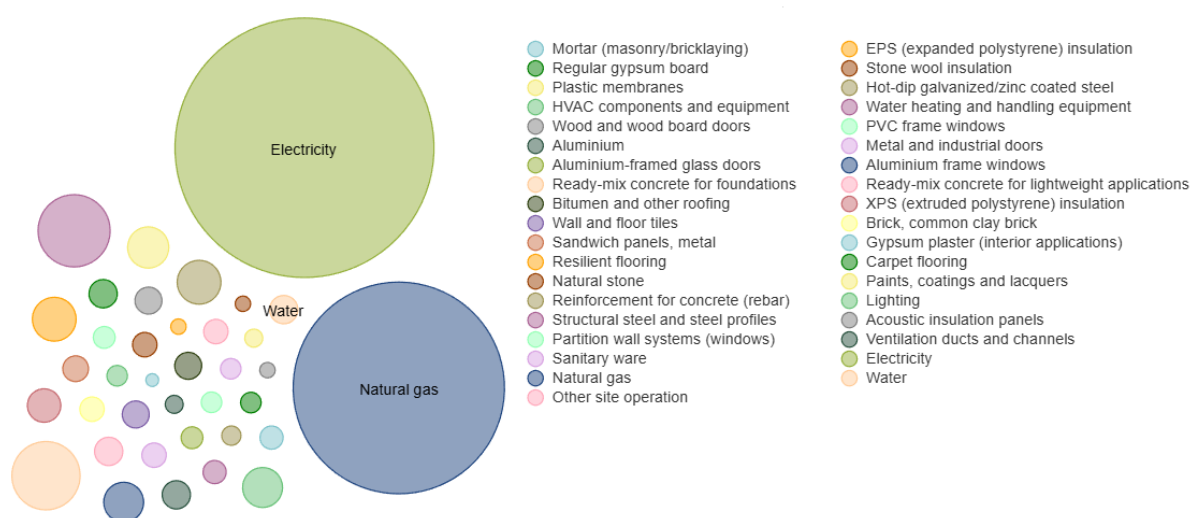


Figure 26 - Global warming potential total kgCO₂e by resource type and subtype

The above figure clarifies the results by identifying the specific resources responsible for the GWP total kgCO₂e emissions. In alignment with the high energy impact noted in the pie chart, the bubble chart shows that Electricity is the largest contributor to the life cycle's GWP. Natural Gas follows as the second most significant driver of emissions. While utilities dominate the chart, certain physical materials also show notable impacts, specifically structural steel, various types of insulation like EPS and XPS, and concrete. Other components like water heating equipment and plastic membranes have moderate footprints, but they remain secondary to the massive environmental cost associated with the building's energy consumption.

The following Sankey diagram presents in a different manner that GWP originates from the B6 Energy lifecycle stage. These emissions flow are electricity use and fuels used on-site, which ultimately translate into Electricity and Natural gas as the dominant resource contributors. In contrast, other categories such as A1–A3 Materials, Water, and Structural steel represent a much smaller fraction of the total environmental impact.



Sankey diagram, Global Warming Potential total

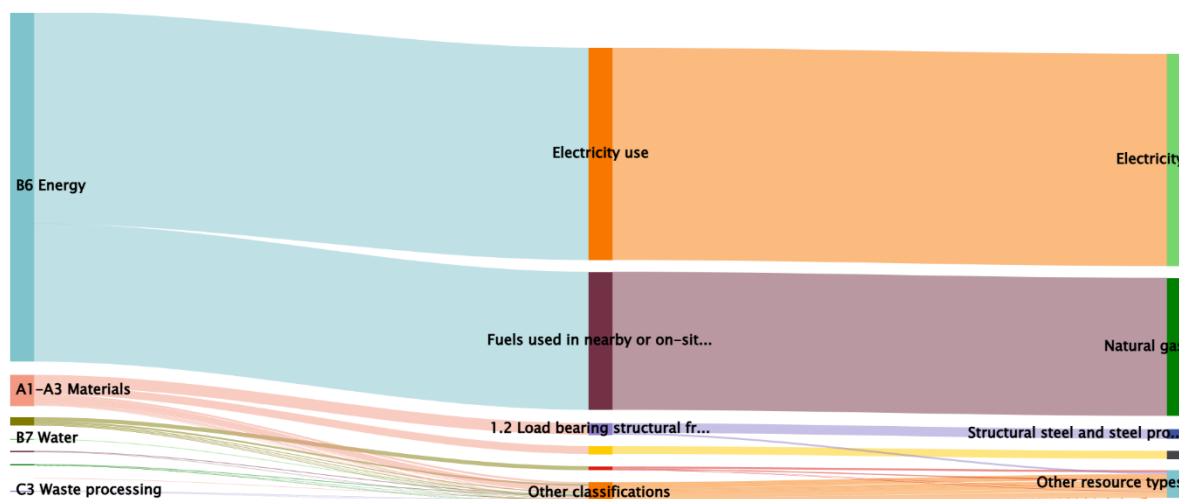


Figure: Sankey diagram of GWP

Life-cycle impacts by stage as stacked columns

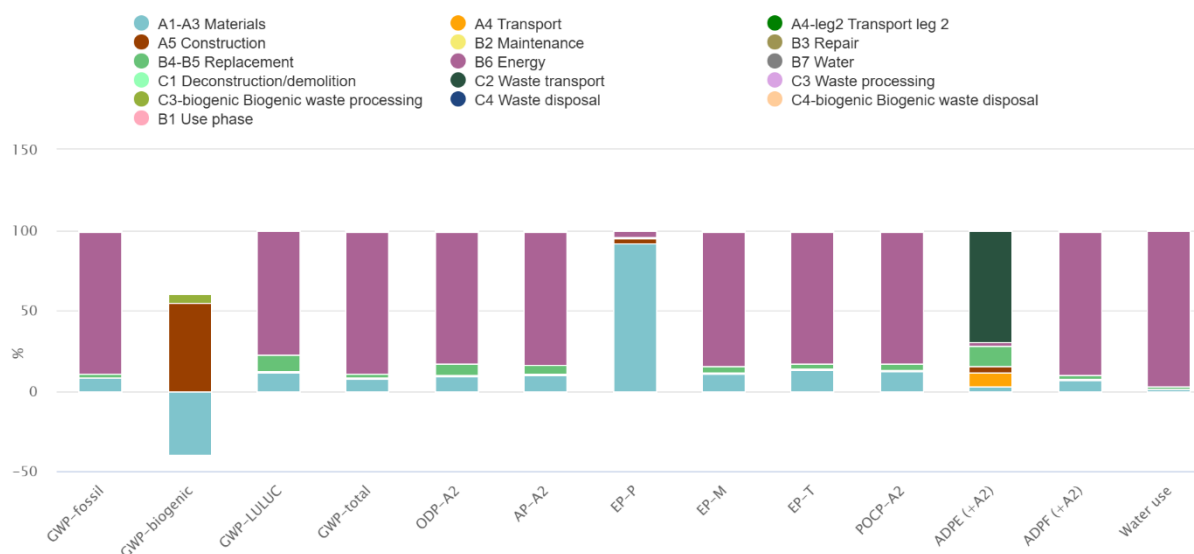


Figure 27 - Contribution of life cycle stages to different environmental impact indicators

The stacked column chart details the environmental impacts across various life-cycle stages for several categories beyond just global warming. Across most categories, including GWP-total, ODP-A2, and AP-A2, the B6 stage is the primary driver of impact. For instance, in the GWP-total category, the B6 stage accounts for 88.47% of the total, contributing 4,210.3 t CO₂e. Similarly, in the ODP-A2 category, the B6 stage represents 81.56% of the impact, totaling 3.8 kg CFC11e. This trend is further reflected in the EP-T category, where the B6 stage accounts for 81.36% of the



total impact. This energy use consistently overshadows the materials and construction phases, such as A1–A3, which contributes 12.86% to terrestrial eutrophication.

The GWP-biogenic category stands out as a unique outlier, showing a significant negative impact of -39.47% (-33,882.13 kg CO₂e) from A1-A3, which indicates carbon sequestration or storage within the materials themselves. This negative value is offset by stage A5, which contributes the largest positive biogenic impact of 54.4% in that specific column. Another notable variation appears in the EP-P category, where the A1-A3 stage accounts for nearly the entire impact, leaving the B6 Energy stage with a negligible share.

Resource-specific categories like ADPE (+A2) demonstrate a much more diverse distribution of impact. In this category, C2 becomes the major contributor at 69.18%, while B4-B5 contributes 13.04% and A4 adds 8.74%. Similarly, the Water use category is almost entirely dominated by the energy stage, reflecting the high-water intensity of energy production or operational requirements. Overall, while materials and waste processes occasionally dominate specific niche indicators, such as B4–B5 contributing 3.82% to terrestrial eutrophication, the operational energy consumed during the B6 phase remains the most significant environmental burden across most of the assessed life-cycle metrics.

Visualisation of the annual impacts

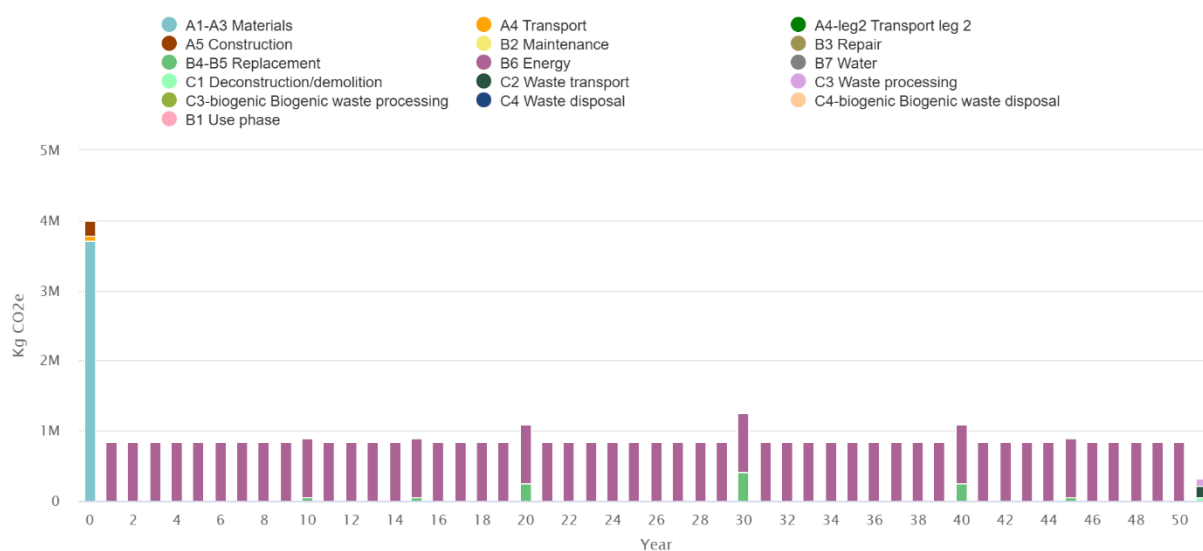


Figure 28 - The building's annual impacts over its lifespan

The annual impact visualization reveals that the highest carbon spike occurs at year 0, primarily driven by A1-A3 at 3,717.4 t CO₂e as the building is constructed. Following this initial peak, the building maintains a steady baseline of annual emissions attributed to B6 Energy, which totals



4,210.3 t CO₂e over the 50 years period. Periodic spikes in impact are visible throughout the timeline; for example, at year 20, a significant spike is recorded with 250.6 t CO₂e attributed to the B4-B5 Replacement stage and 842.06 t CO₂e from energy use. These correspond to the renewal of building components. The timeline concludes at year 51 with impacts associated with the end-of-life phase, including 57.16 t CO₂e for deconstruction, 159.15 t CO₂e for waste transport, and 113.4 t CO₂e for waste processing.

3.6.4. Interpretation

While it is possible to compare the environmental impact indicators of the studied Arrival Terminal to reference benchmarks, established standards are currently limited to residential buildings, offices, and schools. The LCA of the Arrival Terminal yielded a GWP total value of 81.1 kgCO₂/m²*year. When compared to the office building benchmark from the MC-001 Romanian standard [3], this performance aligns with pollution level E. The Use Stage (B1-B7) accounts for over 90% of the building's total CO₂ emissions. This suggests that energy consumption during operation (heating, cooling, lighting, and ventilation) is the primary driver of the terminal's environmental impact, rather than the materials used for construction. The "Embedded Carbon" (Product + Construction stages) represents about 8.3% of the total lifecycle impact. While material selection is important, the data indicates that the most effective way to reduce the terminal's carbon footprint is to optimize its operational energy systems.

The tables below detail the environmental impacts per square meter for four distinct functional zones: the check-in area, waiting lounge, retail spaces, and offices. The scope of this assessment covers the building envelope materials, building services and operational usage; internal equipment, such as computers and servers, is excluded from the system boundaries.

Impact indicators per m²/year, check-in zone

Indicator	Results category					
	Product stage (A1 - A3)	Construction stage (A4 - A5)	Use stage (B1 - B7)	End-of-life (C1 - C4)	Benefits (D)	Total
Global Warming Potential total kg CO ₂ e (GWP – total)	1.87E+01	1.38E+00	2.17E+02	1.68E+00	-7.71E+00	2.31E+02
Global Warming Potential fossil kg CO ₂ e (GWP – fossil)	1.88E+01	1.15E+00	2.17E+02	1.66E+00	-7.65E+00	2.31E+02
Global Warming Potential biogenic kg CO ₂ e (GWP – biogenic)	-1.70E-01	2.35E-01	0.00E+00	2.65E-02	-4.34E-02	4.75E-02



Global Warming Potential, LULUC kg CO ₂ e (GWP – LULUC)	2.93E-02	1.49E-03	2.28E-01	3.21E-04	-1.92E-02	2.40E-01
Depletion potential of the stratospheric ozone layer kg CFC11e (ODP-A2)	2.05E-06	1.76E-07	2.09E-05	2.63E-07	-2.76E-07	2.31E-05
Acidification potential, accumulated exceedance mol H ⁺ eq. (AP-A2)	8.09E-02	3.94E-03	7.35E-01	4.55E-03	-1.99E-02	8.05E-01
Eutrophication freshwater kg P eq. (EP-P)	3.44E-01	1.14E-02	1.90E-02	8.70E-05	-1.32E-03	3.73E-01
Eutrophication aquatic marine kg N eq. (EP-M)	1.50E-02	6.72E-04	1.24E-01	1.31E-03	-3.43E-03	1.38E-01
Eutrophication terrestrial mol N eq. (EP-T)	1.92E-01	8.64E-03	1.28E+00	1.44E-02	-3.21E-02	1.46E+00
Formation potential of tropospheric ozone kg NMVOC eq. (POCP-A2)	5.63E-02	2.67E-03	3.93E-01	4.30E-03	-1.54E-02	4.41E-01
Abiotic depletion potential (ADP-elements) for non-fossil resources (+A2) kg Sbe (ADPE+A2)	2.52E-04	1.02E-03	1.30E-03	5.80E-03	1.93E-06	8.36E-03
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ (ADPF+A2)	2.22E+02	1.61E+01	2.91E+03	2.84E+01	-6.28E+01	3.12E+03
Water use m ³ deprived	1.04E+02	2.71E+00	1.03E+04	7.34E-01	-1.75E+01	1.04E+04

Impact indicators per m²/year, waiting area

Indicator	Results category					
	Product stage (A1 - A3)	Construction stage (A4 – A5)	Use stage (B1 – B7)	End-of-life (C1 – C4)	Benefits (D)	Total
Global Warming Potential total kg CO ₂ e (GWP – total)	4.31E+01	3.19E+00	5.02E+02	3.89E+00	-1.78E+01	5.34E+02



Global Warming Potential fossil kg CO ₂ e (GWP – fossil)	4.34E+01	2.65E+00	5.01E+02	3.83E+00	-1.76E+01	5.33E+02
Global Warming Potential biogenic kg CO ₂ e (GWP – biogenic)	-3.93E-01	5.41E-01	0.00E+00	6.11E-02	-1.00E-01	1.10E-01
Global Warming Potential, LULUC kg CO ₂ e (GWP – LULUC)	6.77E-02	3.44E-03	5.26E-01	7.41E-04	-4.44E-02	5.53E-01
Depletion potential of the stratospheric ozone layer kg CFC11e (ODP-A2)	4.74E-06	4.06E-07	4.83E-05	6.06E-07	-6.38E-07	5.34E-05
Acidification potential, accumulated exceedance mol H ⁺ eq. (AP-A2)	1.87E-01	9.10E-03	1.70E+00	1.05E-02	-4.59E-02	1.86E+00
Eutrophication freshwater kg P eq. (EP-P)	7.93E-01	2.62E-02	4.38E-02	2.01E-04	-3.05E-03	8.60E-01
Eutrophication aquatic marine kg N eq. (EP-M)	3.45E-02	1.55E-03	2.87E-01	3.02E-03	-7.92E-03	3.18E-01
Eutrophication terrestrial mol N eq. (EP-T)	4.43E-01	1.99E-02	2.95E+00	3.31E-02	-7.41E-02	3.37E+00
Formation potential of tropospheric ozone kg NMVOC eq. (POCP-A2)	1.30E-01	6.17E-03	9.07E-01	9.92E-03	-3.56E-02	1.02E+00
Abiotic depletion potential (ADP-elements) for non-fossil resources (+A2) kg Sbe (ADPE+A2)	5.81E-04	2.34E-03	3.00E-03	1.34E-02	4.45E-06	1.93E-02
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ (ADPF+A2)	5.13E+02	3.72E+01	6.72E+03	6.55E+01	-1.45E+02	7.19E+03
Water use m ³ deprived	2.40E+02	6.25E+00	2.38E+04	1.69E+00	-4.05E+01	2.40E+04

Impact indicators per m²/year, retail spaces

Indicator	Results category					
	Product stage (A1 - A3)	Construction stage (A4 – A5)	Use stage (B1 – B7)	End-of-life (C1 – C4)	Benefits (D)	Total
Global Warming Potential total kg CO ₂ e (GWP – total)	3.41E+01	2.53E+00	3.97E+02	3.08E+00	-1.41E+01	4.23E+02



Global Warming Potential fossil kg CO ₂ e (GWP – fossil)	3.44E+01	2.09E+00	3.97E+02	3.03E+00	-1.40E+01	4.22E+02
Global Warming Potential biogenic kg CO ₂ e (GWP – biogenic)	-3.11E-01	4.29E-01	0.00E+00	4.84E-02	-7.93E-02	8.68E-02
Global Warming Potential, LULUC kg CO ₂ e (GWP – LULUC)	5.36E-02	2.72E-03	4.16E-01	5.86E-04	-3.52E-02	4.38E-01
Depletion potential of the stratospheric ozone layer kg CFC11e (ODP-A2)	3.75E-06	3.21E-07	3.82E-05	4.80E-07	-5.05E-07	4.23E-05
Acidification potential, accumulated exceedance mol H ⁺ eq. (AP-A2)	1.48E-01	7.20E-03	1.34E+00	8.31E-03	-3.63E-02	1.47E+00
Eutrophication freshwater kg P eq. (EP-P)	6.28E-01	2.08E-02	3.47E-02	1.59E-04	-2.42E-03	6.81E-01
Eutrophication aquatic marine kg N eq. (EP-M)	2.73E-02	1.23E-03	2.27E-01	2.39E-03	-6.27E-03	2.52E-01
Eutrophication terrestrial mol N eq. (EP-T)	3.51E-01	1.58E-02	2.33E+00	2.62E-02	-5.86E-02	2.67E+00
Formation potential of tropospheric ozone kg NMVOC eq. (POCP-A2)	1.03E-01	4.89E-03	7.18E-01	7.86E-03	-2.82E-02	8.06E-01
Abiotic depletion potential (ADP-elements) for non-fossil resources (+A2) kg Sbe (ADPE+A2)	4.60E-04	1.86E-03	2.37E-03	1.06E-02	3.52E-06	1.53E-02
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ (ADPF+A2)	4.07E+02	2.94E+01	5.32E+03	5.18E+01	-1.15E+02	5.69E+03
Water use m ³ deprived	1.90E+02	4.95E+00	1.88E+04	1.34E+00	-3.21E+01	1.90E+04

Impact indicators per m²/year, office area

Indicator	Results category					
	Product stage (A1 - A3)	Construction stage (A4 – A5)	Use stage (B1 – B7)	End-of-life (C1 – C4)	Benefits (D)	Total
Global Warming Potential total kg CO ₂ e (GWP – total)	2.82E+01	2.09E+00	3.28E+02	2.54E+00	-1.16E+01	3.49E+02



Global Warming Potential fossil kg CO ₂ e (GWP – fossil)	2.84E+01	1.73E+00	3.28E+02	2.50E+00	-1.15E+01	3.49E+02
Global Warming Potential biogenic kg CO ₂ e (GWP – biogenic)	-2.57E-01	3.54E-01	0.00E+00	3.99E-02	-6.55E-02	7.17E-02
Global Warming Potential, LULUC kg CO ₂ e (GWP – LULUC)	4.43E-02	2.25E-03	3.44E-01	4.84E-04	-2.91E-02	3.62E-01
Depletion potential of the stratospheric ozone layer kg CFC11e (ODP-A2)	3.10E-06	2.65E-07	3.16E-05	3.97E-07	-4.17E-07	3.49E-05
Acidification potential, accumulated exceedance mol H ⁺ eq. (AP-A2)	1.22E-01	5.95E-03	1.11E+00	6.86E-03	-3.00E-02	1.21E+00
Eutrophication freshwater kg P eq. (EP-P)	5.19E-01	1.72E-02	2.87E-02	1.31E-04	-2.00E-03	5.63E-01
Eutrophication aquatic marine kg N eq. (EP-M)	2.26E-02	1.02E-03	1.88E-01	1.98E-03	-5.18E-03	2.08E-01
Eutrophication terrestrial mol N eq. (EP-T)	2.90E-01	1.30E-02	1.93E+00	2.17E-02	-4.84E-02	2.20E+00
Formation potential of tropospheric ozone kg NMVOC eq. (POCP-A2)	8.50E-02	4.04E-03	5.93E-01	6.49E-03	-2.33E-02	6.65E-01
Abiotic depletion potential (ADP-elements) for non-fossil resources (+A2) kg Sbe (ADPE+A2)	3.80E-04	1.53E-03	1.96E-03	8.75E-03	2.91E-06	1.26E-02
Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ (ADPF+A2)	3.36E+02	2.43E+01	4.40E+03	4.28E+01	-9.49E+01	4.70E+03
Water use m ³ deprived	1.57E+02	4.09E+00	1.56E+04	1.11E+00	-2.65E+01	1.57E+04



3.7. Optimisation results

The optimization was performed by using the optimization tool integrated in Design Builder. The optimization is based on genetic algorithms and offers the possibility to provide the best designs options.

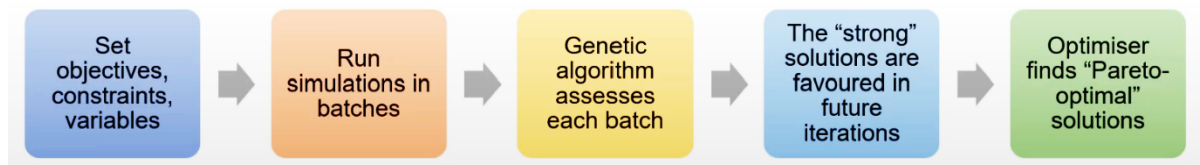


Figure: Optimization process. Source: <https://designbuilder.co.uk/training/webinars>

The optimization process was undertaken starting from the calibrated model and considering this model as reference. One simulation for the calibrated model takes around 19 minutes (processor Intel(R) Core(TM) i9-8950HK CPU @ 2.90GHz, RAM 16,0 GB, storage 932 GB).

The optimization considered two main approaches, followed by simulations:

- the first approach is similar to that from followed methodology, which actually is not suitable for Cluj-Napoca's case study, in terms of technical meaning;
- the second approach is tailored for the actual technical condition of the Cluj-Napoca Arrivals Terminal.

First approach optimization

The set of objectives that were defined following deliverable D4.5, the two objectives being the minimization of the Heating load [kWh] and the minimization of the required investment - CAPEX [eur].

However, this approach is not suitable for Cluj-Napoca Arrivals Terminal, because the building is already well insulated (15 cm insulation thickness in the walls and 25 cm insulation thickness for the roof). In addition, the roof thermal insulation and waterproofing have been redone in the recent years (2019).

Also, the parametrization of the thicknesses of the thermal insulation as input for the optimization, with a step of 1 cm, it is not technically realistic, because the thermal insulation materials available on the market are cut to standard thicknesses, leading to artificial design variables for the optimization process and unnecessary computational resources usage.



Thus, in addition to the two objectives, were used two design variables, with a relevant technical meaning in relation to the “Heating load objective” (design variables that may significantly influence this particular objective). These are the glazings and the shading solutions.

For the first approach there were considered 2 varying parameters, with 12 options for the glazing types (2 double and 10 triple glazed solutions), and with 16 options for the shading solutions. The prices used for double and triple glazings are 450 €/m² and 615 €/m².

The interfaces of Design Builder optimization module settings are shown in the figures below.

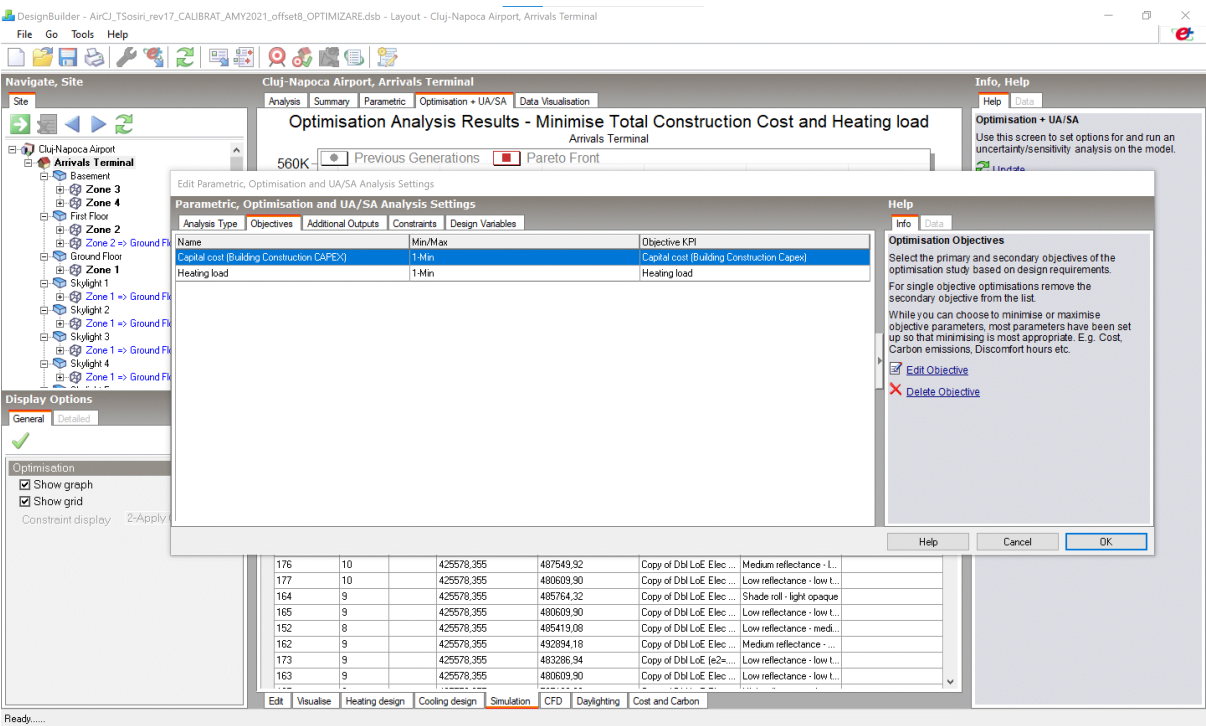


Figure 29 - Interface of Design Builder for setting the optimization objectives

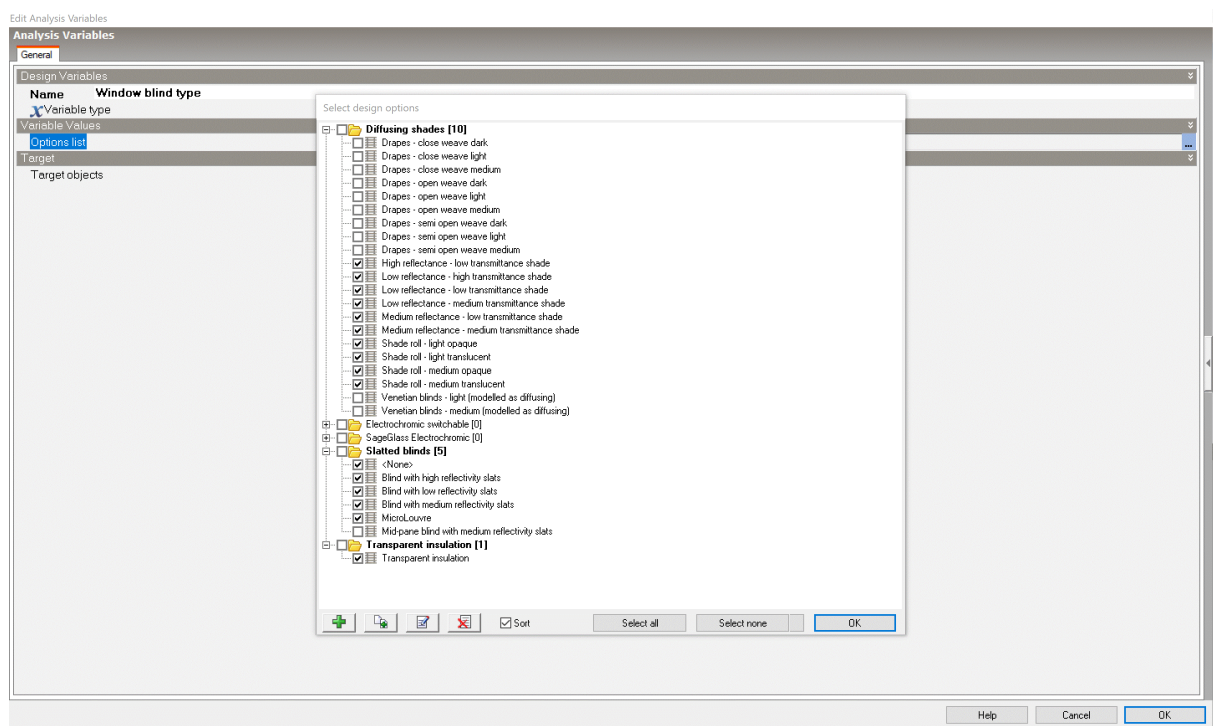


Figure 30 - Interface of Design Builder for setting shading solutions

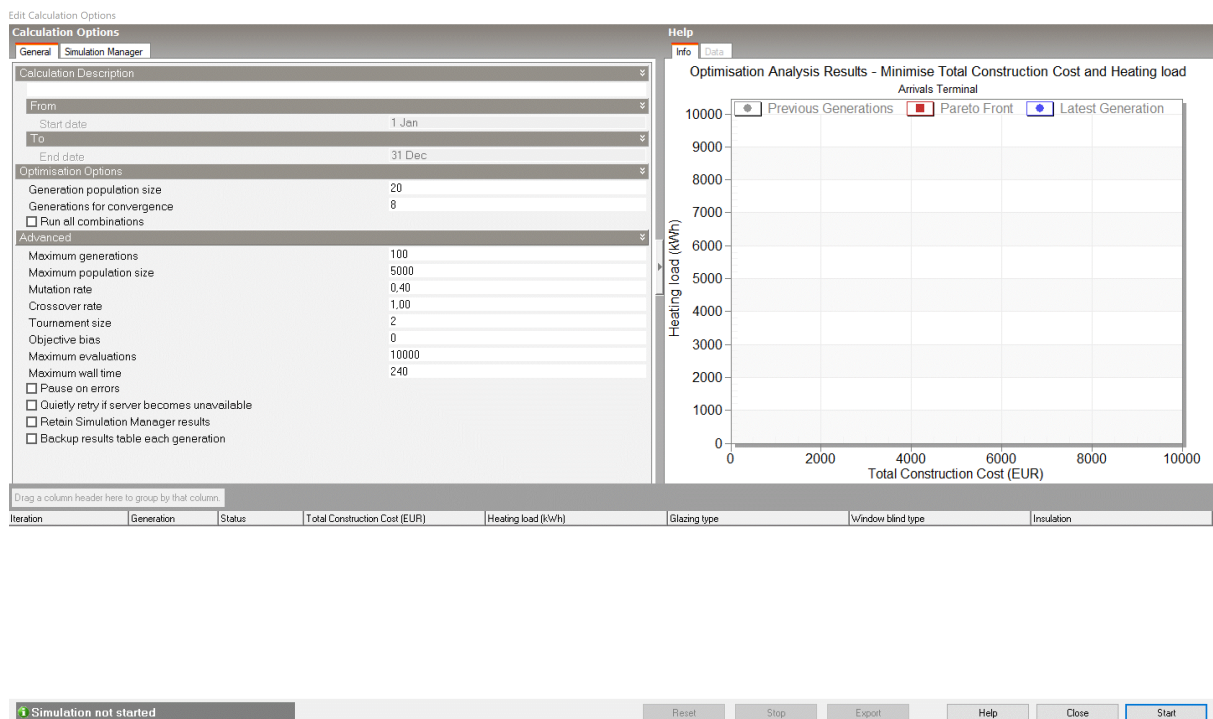


Figure 31 - Interface of Design Builder for setting the population size and generations

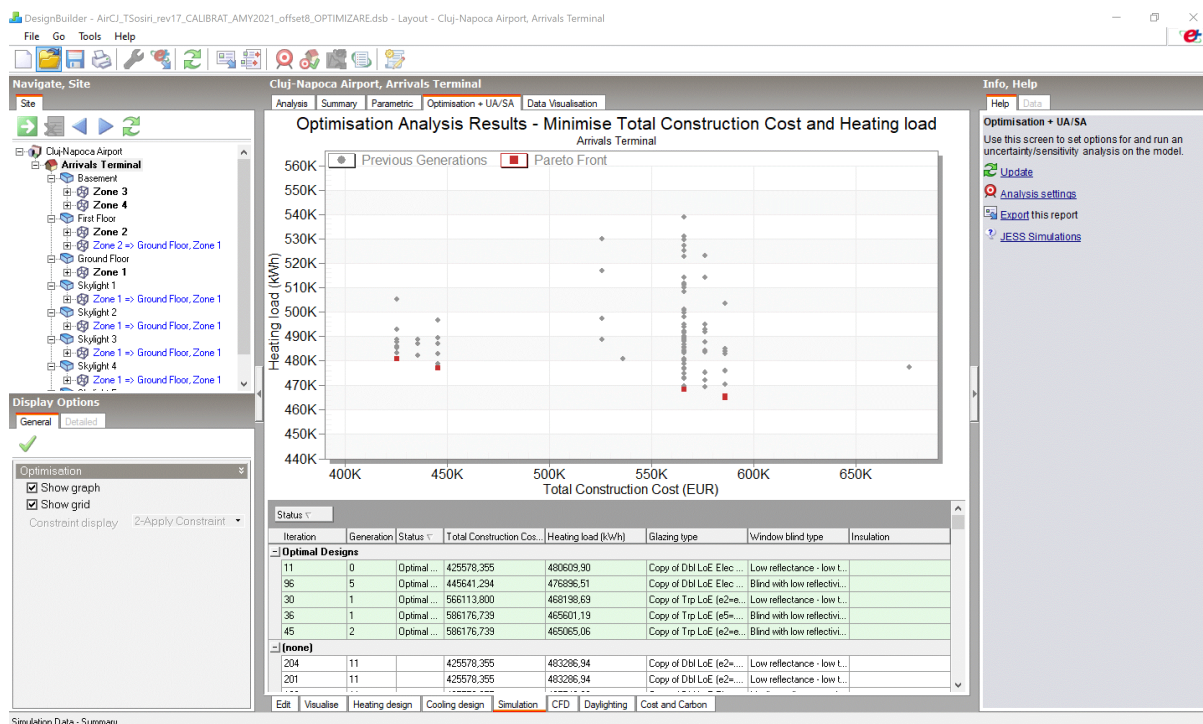


Figure 32 - Interface of Design Builder with optimal designs found in the search space

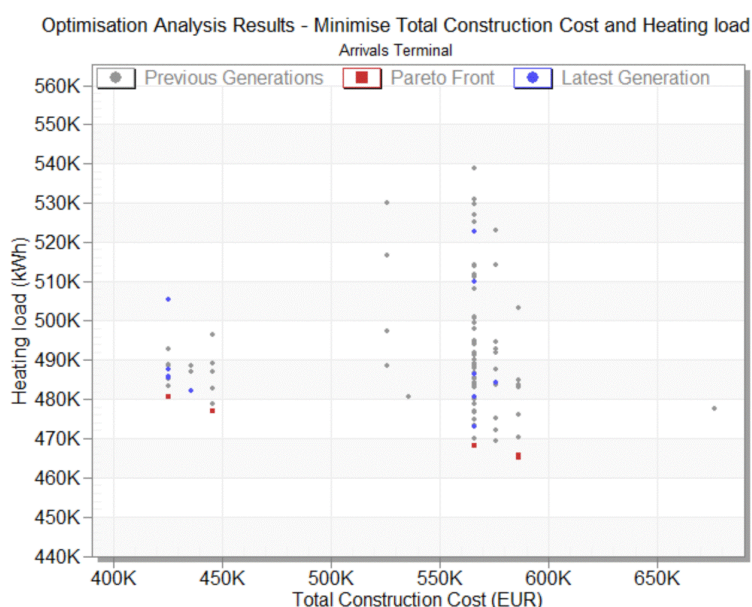


Figure 33 - Optimisation results based on criteria heating load and investment

As regarding the interpretation of these results, it can be noticed that the impact of the solutions is rather reduced within the followed objective (heating load), with less than 16000 kWh/year



reduction in the heating load, between the five optimum designs. If the initial heating load of the calibrated model is considered as a reference, compared to the optimum obtained at Iteration 45, Generation 2 (minimum heating load of 465065,06 kWh), then the savings obtained are 27161,27 kWh/year.

Noteworthy, regarding the objective *Heating load (kWh)* it is stated that its equivalent effectively calculated in Energy Plus solver is the variable *Zone Air System Sensible Heating Rate*. According to the *EnergyPlus Engineering Reference*, the *IdealLoadsAirSystem* computes the full zone heating load required to maintain setpoint conditions, explicitly stating that this total load *includes ventilation and infiltration loads* [4]. This whole-zone load is the basis for the building-level heating demand calculated for this model. In contrast, the *EnergyPlus Input Output Reference* defines the variable *Zone Air System Sensible Heating Rate* strictly as *the sensible heating energy supplied by the system to that zone for the timestep reported* [5]. Because the variable *Zone Air System Sensible Heating Energy* represents only the sensible energy delivered directly to the zone, it excludes ventilation loads, infiltration loads, latent loads, and control-related effects that are part of the total zone load. Consequently, *Zone Air System Sensible Heating Rate* is inherently smaller than the whole-building heating demand.

In addition, the terminal being already well insulated and in very good technical condition, the variation of insulation thicknesses is not technically justified for this building.

Thus, a more suitable approach for this case study was required, so that the first approach is followed by a second approach, more suitable for Cluj-Napoca's Airport Terminal.

Second approach optimization

Considering that the dynamic model was extended to all thermal energy and electricity consumers (*not only heating demand and cooling demand*), and that the calibration was undertaken for all consumers at the building level, it becomes much more relevant to consider a more comprehensive objective for the optimization. Thus, the "Heating load" minimization objective is changed with "Net Site Energy" minimization objective.

We consider that this objective is more sensitive to equipment solutions (e.g., replacing the heating boilers with heat pumps) and aloud the introduction and assessment of the impact of renewable energy sources (e.g., local electricity production with photovoltaic panels). Their implementation impact in the yearly energy savings of the terminal energy consumption can be actually quantified.

This objective is in close line with the target of energy consumption reduction and CO₂ emissions reduction, and its results can be followed easier at the building level, compared to an objective that addresses limited number of energy consumers and only the demand (heating/cooling load),



without energy losses related with the emission, distribution, transportation and generation sub-systems, as the case might be.

For this optimization approach 6 design variables were defined, each of the 6 design variables having from 2 to 16 options, leading to a number of possible simulation combinations of 13824.

The design variables integrate the previous (first optimization approach) glazing types and shading solutions, and equipment solutions are added, such as multiple types of heat pumps (including air-to-water, ground-to-water and air-to-air on VRV technology). Local electricity production is added through 3 production centers (with different inverters), with the associated options of with or without storage. The simulated photovoltaic panels are South oriented, with a tilted angle from horizontal of 30° and a yield of 20%.

Nevertheless, the total electricity power simulated for photovoltaics panels for the Arrivals Terminal is 350 kWe, due to limited availability on the roof of the terminal (considering the building level). However, a larger electricity production share, available at the facility level (the unused land near the airport perimeter, belonging to the airport), might reduce even more the electricity consumption of this building.

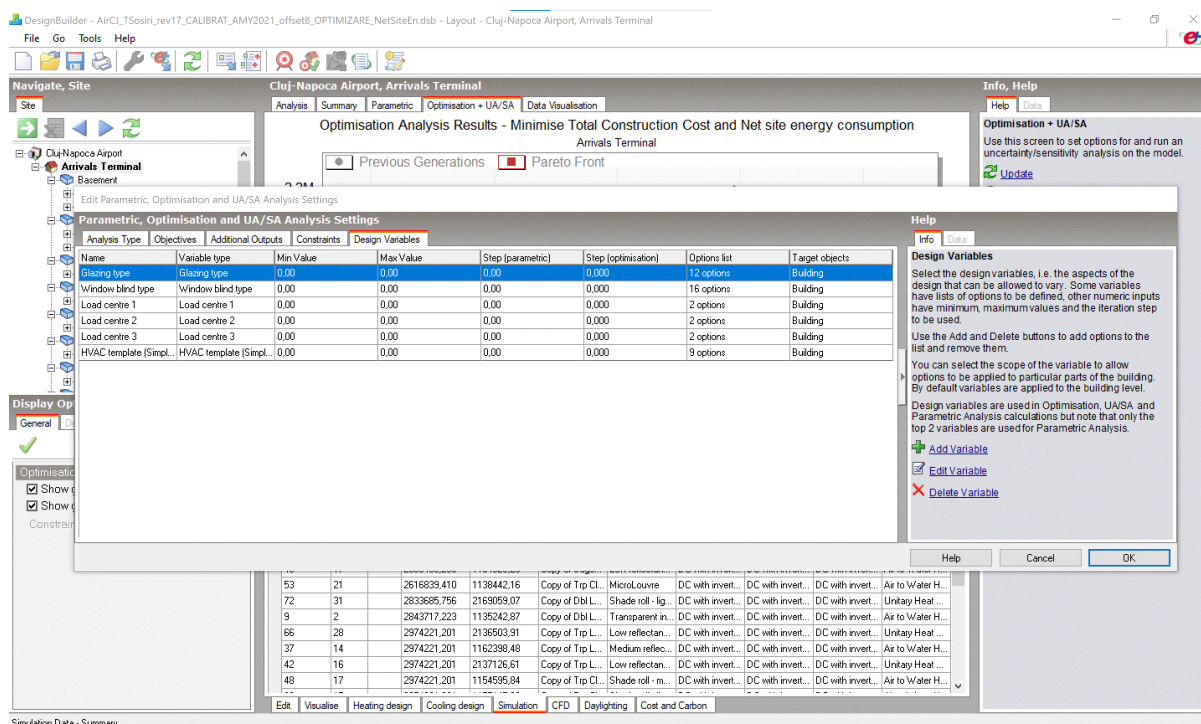


Figure 34 - Interface of Design Builder for setting the design variables

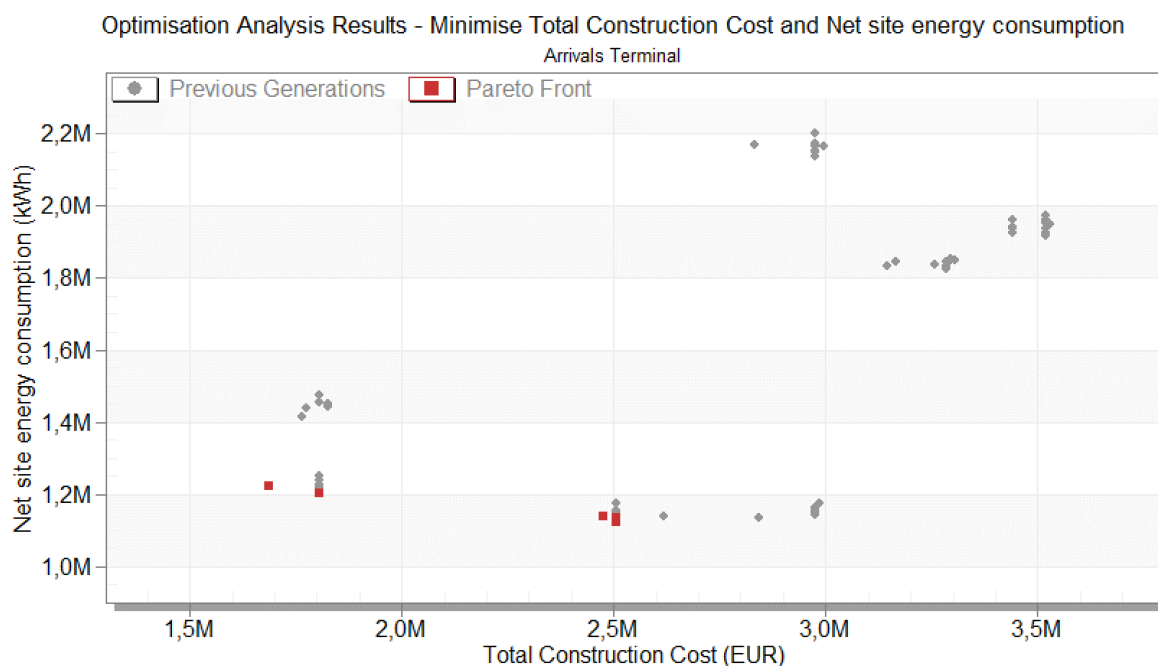


Figure 35 - Optimisation results based on criteria net site energy and investment

Regarding the results, six optimum designs were identified, of which brief description and results is located in the table below. To significantly reduce energy consumption, and furthermore the CO₂ emissions of the Arrivals Terminal consumers, the following strategy was considered:

- **energy conservation measures**, through measures applied to the building envelope, suitable to the current technical condition of this building (glazing replacements and shading solutions);
- **increasing energy efficiency and decarbonization measures** by changing technology, by replacing fossil fuel thermal sources with electric thermal sources, which reduce the final total energy at the building level and make the transition from thermal energy from fossil fuels (methane gas) to thermal energy that uses renewable energy sources (heat pumps);
- **local renewable energy production measures**, through locally produced electricity with photovoltaic panels, should cover as much as possible the electricity consumers already existing in the building, respectively the new electricity consumers, such as the heat pumps.

The results lead to a maximum reduction of the total final energy consumption at the building level up to 53,8% compared to the actual situation, with a required investment of 2,5 mill. Euro.



Table 11 - Optimal Designs for minimum Net Site Energy and investment optimization objectives

Info	Info	Objective	Objective	Variable	Variable	Variable	Variable	Variable	Variable
Iteration	Generation	Total Construction Cost (EUR)	Net site energy consumption (kWh/year)	Glazing type	Window blind type	Load centre 1 - 50 kWe	Load centre 2 – 100 kWe	Load centre 3 – 200 kWe	HVAC
41	16	1684428,85	1223803,88	Dbl LoE Elec Abs Bleached 6mm/13mm Arg	Blind with medium reflectivity slats	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	<None>
47	17	1804901,36	1204064,10	Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg	Low reflectance - medium transmittance shade	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	<None>
62	25	2476303,97	1138649,31	Dbl LoE Elec Abs Bleached 6mm/13mm Arg	MicroLouvre	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	Air to Water Heat Pump (ASHP), Convectors
29	9	2506493,26	1125165,17	Trp LoE (e5=.1) Clr 3mm/13mm Arg	Low reflectance - medium transmittance shade	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	Air to Water Heat Pump (ASHP), Convectors
15	4	2506493,26	1134546,36	Trp LoE (e2=e5=.1) Clr 3mm/13mm Air	Shade roll - light translucent	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	Air to Water Heat Pump (ASHP), Convectors
60	24	2506493,26	1124499,45	Trp LoE (e2=e5=.1) Clr 3mm/13mm Air	Low reflectance - high transmittance shade	DC with inverter - v1	DC with inverter - v2	DC with inverter - v3	Air to Water Heat Pump (ASHP), Convectors



Reference (actual)	No investment	2432862,71	Dbl U = 1,98 W/m²K	NO	NO	NO	NO	see Table in Section 3.1
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Scenario 1: Passive envelope optimization (Design Builder)

The first optimization scenario focuses on reducing the terminal's energy demand through passive architectural measures. The primary interventions involve upgrading the building envelope by replacing standard double-glazed windows with high-performance triple glazing and installing shading devices. These measures improve the thermal resistance of the terminal and control solar heat gain, reducing the energy required for climate control. According to the simulation performed, these envelope enhancements achieve a significant reduction of 27.161,27 kWh/year in the heating load. The following comparison highlights the shifts in environmental performance between the initial building design and the first optimized scenario.

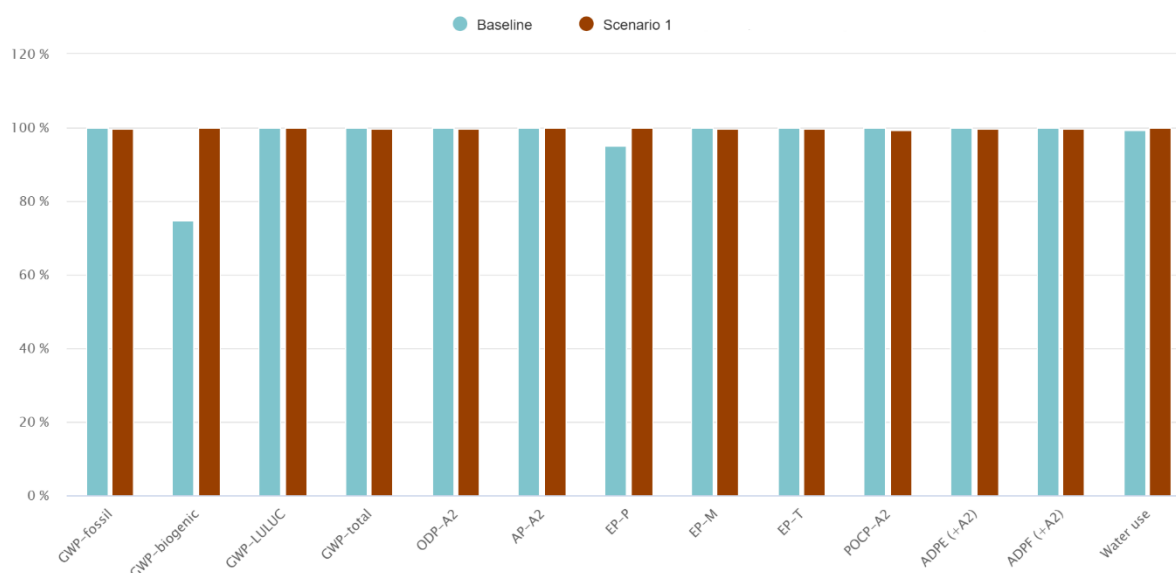


Figure 36 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1

The provided chart illustrates a direct comparison of environmental impacts between the Baseline and Scenario 1 across the thirteen different life-cycle impact categories. The results indicate that Scenario 1, which incorporates passive architectural improvements like triple glazing and shading devices, yields minimal to no significant change across most environmental indicators compared to the baseline. For most categories, including GWP-fossil, GWP-LULUC, GWP-total, ODP-A2, AP-A2, EP-M, EP-T, POCP-A2, and ADPF (+A2), both the Baseline and Scenario 1 show nearly identical values. A notable difference appears in the GWP-biogenic category, where the Baseline impact is approximately 25%, accounting for 18,084 kg CO₂e, lower than Scenario 1 (24,213.9 kg CO₂e), suggesting that the materials or processes in the baseline have a more favourable biogenic carbon profile than the specific upgrades in the first scenario. In the Eutrophication Freshwater (EP-P) category, the Baseline is slightly lower, at 95.24% (74,462.3 kg P eq), compared to the 100%



impact of Scenario 1. Other categories, such as Water Use and ADPE (+A2), remain virtually unchanged between the two version.

While Scenario 1 achieves a specific reduction of 27.161,27 kWh/year in the heating load, the following chart demonstrates that passive envelope changes alone do not significantly shift the overall environmental profile because the dominant impact remains the B6 Energy phase.

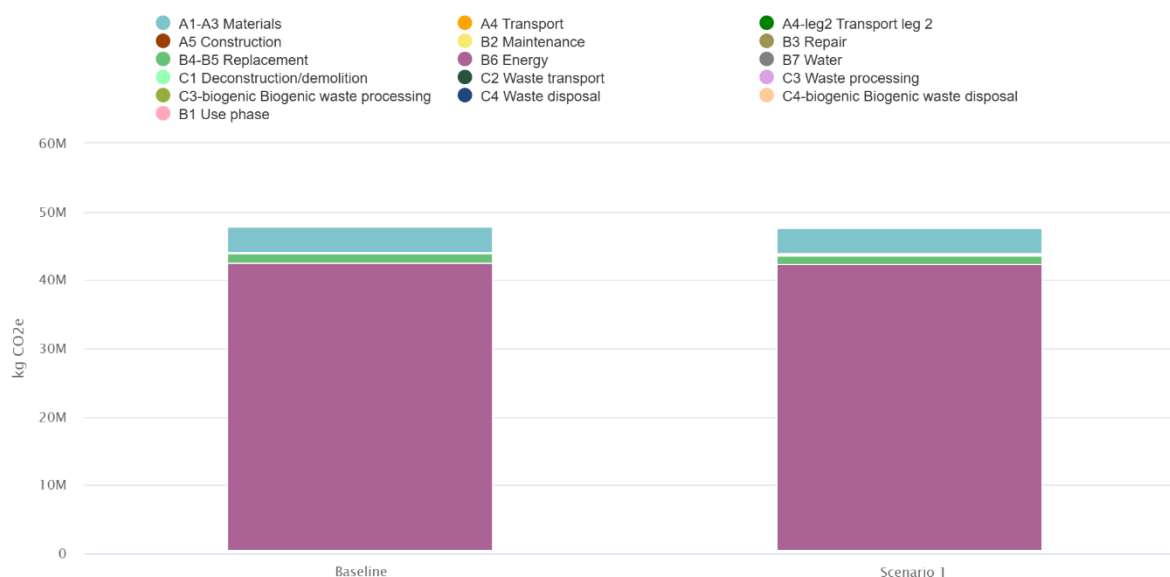


Figure 37 - Global Warming Potential total, kg CO₂e - Life-cycle stages for Baseline vs Scenario 1

At the life-cycle stage level, Scenario 1 results in a 3.71% increase in the A1–A3 product stage, up to 3,860.75 t CO₂e compared to 3,717.49 t CO₂e of the Baseline, reflecting the additional embodied impact of upgraded envelope materials. A 11.05% decrease in the B4–B5 construction and replacement stages is observed compared to the Baseline. Additionally, B6 stage of Scenario 1 decreases from 42,103.05 t CO₂e to 41,749.94 t CO₂e thanks to reduced heating demand.

Scenario 2: Building-level systems & renewables (Design Builder)

The second scenario builds upon the passive measures of Scenario 1 by introducing active mechanical systems and onsite renewable generation. In addition to the triple glazing and shading devices, this scenario includes the installation of one air-to-water heat pump and photovoltaic panels located on the building's rooftop. Results from the simulation run in Design Builder for this scenario show a substantial reduction of the total final energy consumption at the building level by up to 53.8%. This represents a major step toward building autonomy and a drastic reduction in operational carbon.



The following analysis evaluates the environmental performance shifts across all indicators when moving from the passive architectural improvements of the first scenario to the active systems and building-level renewables introduced in the second.

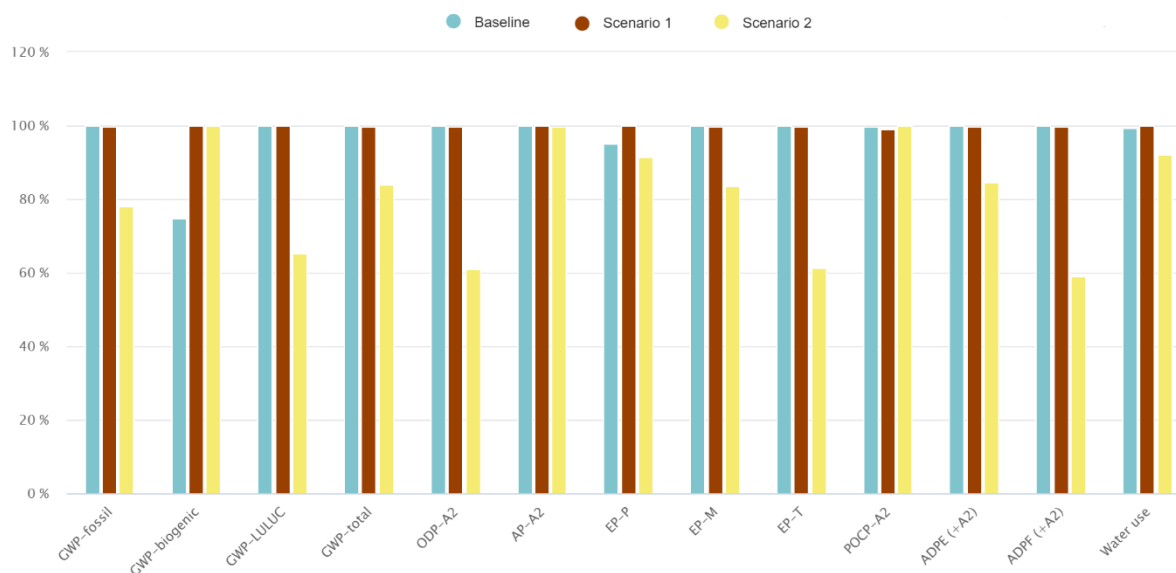


Figure 38 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1 vs Scenario 2

The provided chart illustrates the life-cycle environmental impacts of the Baseline, Scenario 1, and Scenario 2, revealing a significant divergence in performance once active systems are introduced. While Scenario 1 remains largely consistent with the baseline across most metrics, Scenario 2, which incorporates an air-to-water heat pump and photovoltaic panels, shows a dramatic reduction in nearly every category. Most notably, GWP-total and GWP-fossil drops to 83.85% and 78.03% of the baseline. GWP-LULUC falls even more to nearly 65.33%, reflecting the decreased reliance on land-intensive fuel sources (see the next figure). The biogenic carbon category (GWP-biogenic) remains an outlier, with Scenario 2 maintaining the same higher impact level as Scenario 1, roughly 25% above the baseline. Significant improvements are also visible in EP-M and EP-T potentials, all of which drop to 83.72% and 60.94% respectively. Abiotic depletion of fossil resources (ADPF +A2) shows one of the most substantial improvements, falling to 58.86% of the baseline, which directly correlates with the 53.8% reduction in final energy consumption achieved through building-level electrification and solar generation. Interestingly, Scenario 2 also shows the best performance for EP-P (91.89%) and water use (92.02%), successfully lowering these impacts below the levels seen in both the baseline and the first optimization scenario.

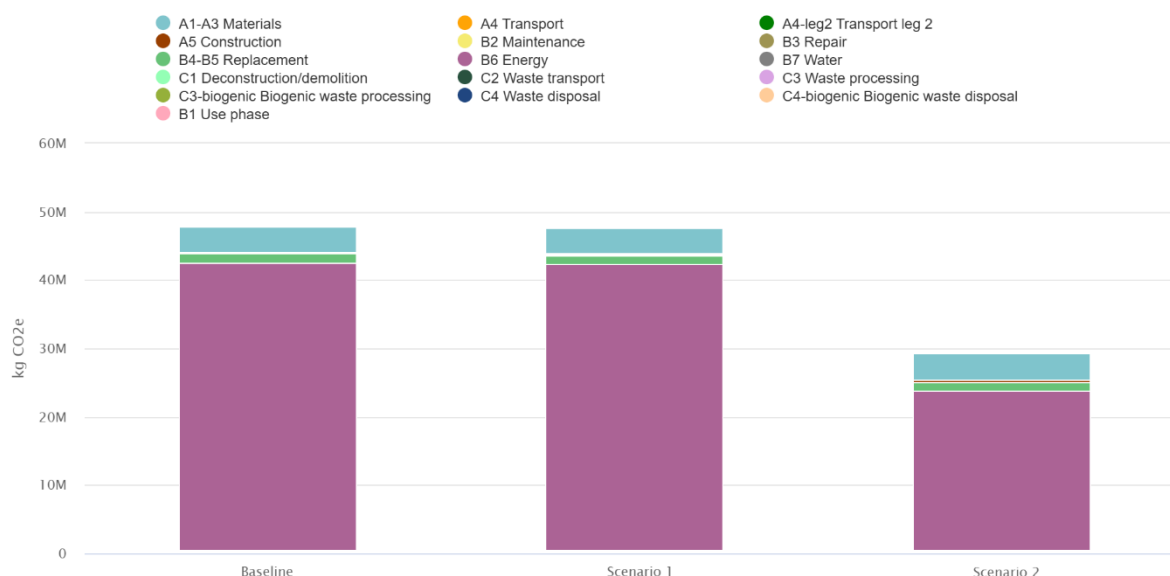


Figure 39 - Global Warming Potential total, kg CO₂e - Life-cycle stages for Baseline vs Scenario 1 vs Scenario 2

From a life-cycle perspective, Scenario 2 shows an increase of 4.01% in the A1–A3 (up to 3,873.77 t CO₂e) product stage compared to the Baseline, and 0.33% relative to Scenario 1, reflecting the embodied impacts of adding mechanical and renewable systems. The B4–B5 construction and replacement phases show a 7.63% decrease (up to 977.1 t CO₂e) versus the Baseline but a 2.11% increase compared to Scenario 1, indicating slightly greater maintenance and replacement effort for the added systems. In contrast, the B6 operational energy stage displays large reductions, 79.78% (23,418.1 t CO₂e) compared to the Baseline and 78.28% relative to Scenario 1, demonstrating the substantial energy and impact savings from heat pump and PV integration.

Scenario 3: Airport-wide green infrastructure (Modernization Fund)

The third scenario integrates the Arrival Terminal into a broader sustainable energy network funded by the Modernization Fund under Key Programme 9: Energy Efficiency in Transport – reducing CO₂ emissions through energy efficiency and new technologies in transport. While this infrastructure project serves the entire airport complex, this scenario evaluates its specific impact on the Arrival Terminal. The project includes a 4,998.87 kWp photovoltaic park (producing ~5,666.38 MWh annually), a 12 MW energy storage unit, and a 300-kW air-to-water heat pump. By utilizing this localized renewable energy, the Arrival Terminal can transition its remaining energy needs to local, carbon-neutral power.



The following analysis outlines the dramatic reduction in environmental burdens achieved by integrating the Arrival Terminal into the airport-wide renewable energy microgrid.

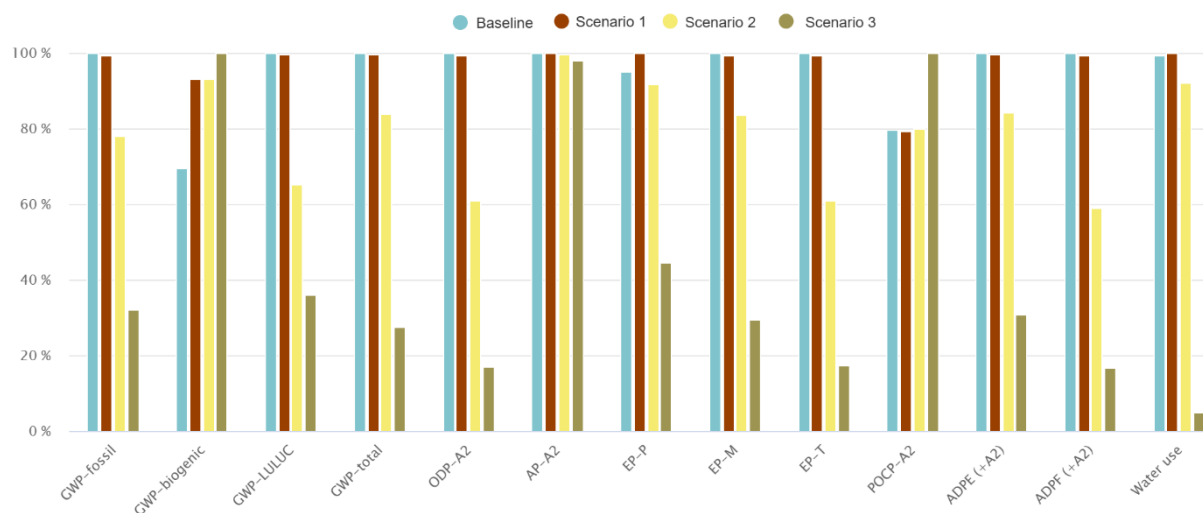


Figure 40 - Comparative analysis of environmental impact categories for Baseline vs Scenario 1 vs Scenario 2 vs Scenario 3

The provided chart illustrates in detail how the life-cycle environmental impacts evolve across the three optimization scenarios, emphasizing the decisive role of the airport-wide green infrastructure and large-scale renewable energy project in reshaping the terminal's sustainability profile. While Scenarios 1 and 2 induce only marginal or moderate changes in most categories, Scenario 3 clearly emerges as the dominant lever, driving most indicators far below their baseline levels.

From a climate perspective, Scenario 3 delivers a marked decarbonization of the terminal's life-cycle performance, with GWP-total and GWP-fossil decreasing to 27.40% and 32.17% of the baseline, respectively. This means that more than two thirds of the original climate impact associated with fossil and total GHG emissions is effectively mitigated, primarily through the substitution of carbon-intensive grid electricity with low-carbon, renewables-based supply at airport scale. Land-use change-related impacts, captured through GWP-LULUC, also decline substantially to 36.19% of the baseline, while the ozone depletion potential (ODP-A2) contracts to 17.21%, indicating that the new energy mix and associated technologies greatly reduce reliance on refrigerants and materials with high ozone depletion potential.

The results further show consistent improvements across several resource depletion and eutrophication indicators, underlining the systemic benefits of Scenario 3 beyond climate change alone. Eutrophication impacts linked to phosphorus (EP-P) and terrestrial environments (EP-T)



drop to 44.52% and 17.29% of the baseline, respectively, suggesting that upstream emissions from electricity generation, fuel extraction and ancillary processes are significantly curtailed when shifting to large-scale renewable energy. Similarly, metal-related eutrophication (EP-M) is reduced to 29.52%, and the abiotic depletion of elements and fossil resources (ADPE (+A2) and ADPF (+A2)) falls to 30.91% and 16.72%, respectively, reflecting a much lower demand for non-renewable raw materials and fossil fuels in the optimized scenario. These reductions indicate that the benefits of the airport-wide intervention extend along the supply chain, reducing both direct and indirect life-cycle burdens.

Water use exhibits the strongest relative improvement among all categories, which is particularly relevant given the persistence of high water-related impacts in earlier, building-only optimization scenarios. Under Scenario 3, water use drops from virtually the full baseline level (≈ 99 –100%) to only 4.76%, effectively neutralizing this previously critical hotspot in the building's environmental profile. This dramatic reduction suggests that the transition towards renewables not only curbs energy-related impacts, but also drastically cuts the water intensity of the energy supply mix, typically associated with conventional thermal power plants and upstream extraction processes.

However, the chart also reveals a change in the impact structure, with two categories increasing in Scenario 3, namely GWP-biogenic and POCP-A2. GWP-biogenic rises from 69.62% in the baseline to 100% in Scenario 3, indicating a stronger involvement of biogenic carbon flows, which can be associated with the use of biomass-based components, bio-sourced materials, or land-related effects embedded in the renewable energy infrastructure. In parallel, POCP-A2 (photochemical ozone formation) increases from 79.66% to 100%, pointing to higher emissions of ozone precursors (e.g., certain volatile organic compounds or NO_x) somewhere along the supply chain of the new technologies. These trade-offs highlight that, although the overall impact level drops substantially, decarbonization through large-scale renewables is not impact-free and shifts some pressure towards biogenic carbon dynamics and ozone precursor formation.

Despite these localized increases, the overall pattern in Scenario 3 is dominated by strong absolute reductions across the most policy-relevant categories, particularly climate change, fossil and abiotic resource depletion, eutrophication and water use. AP-A2 (acidification) and several other indicators remain close to the baseline (e.g., AP-A2 at 97.89%, some categories at $\sim 100\%$ in Scenario 1), confirming that purely incremental, building-level optimizations alone are insufficient to significantly alter the life-cycle footprint of the terminal. In contrast, the airport-wide renewable energy transition in Scenario 3 effectively reconfigures the environmental profile of the building, compressing many of the dominant impacts to one third or less of their original magnitude. Overall, the results demonstrate that scaling up to a comprehensive, airport-wide renewable energy



strategy is the most effective pathway for approaching an environmentally neutral terminal, even if it slightly reshapes the balance between biogenic carbon flows and photochemical ozone formation.

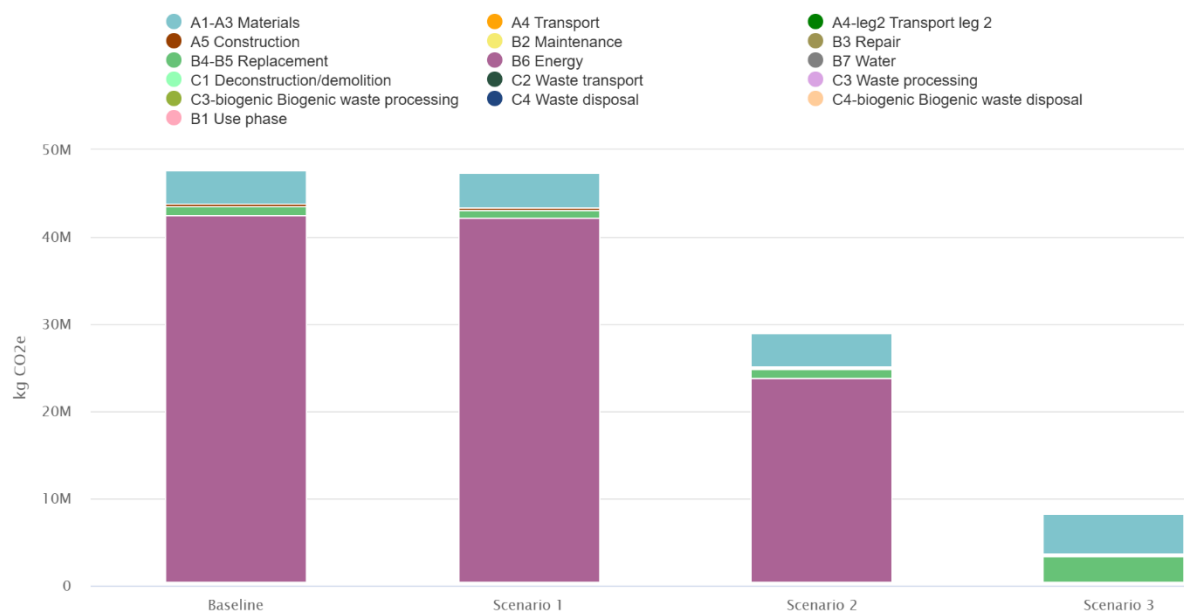


Figure 41 - Global Warming Potential total, kg CO₂e - Life-cycle stages for Baseline vs Scenario 1 vs Scenario 2 vs Scenario 3

In terms of life-cycle stage distribution, Scenario 3 shows a noticeable increase in the embodied impact phases due to the integration of large-scale renewable infrastructure. Specifically, compared to the Baseline, the A1–A3 product stage rises by 23.83% (up to 4,603.26 t CO₂e), while the increase is 19.23% relative to Scenario 1 and 18.83% compared to Scenario 2. B4–B5 register substantially higher embodied loads, with a sharp increase of 169.15% (2,879.04 t CO₂ e) versus the Baseline, 202.59% compared to Scenario 1, and 194.65% compared to Scenario 2. This dramatic rise in B4–B5 reflects the installation and periodic replacement of photovoltaic modules, inverters, battery storage systems, and other renewable energy equipment embedded within the airport-wide energy microgrid. However, these additional embodied impacts are fully offset by a complete elimination of the B6 operational energy phase, as the terminal's energy demand is entirely met by renewable sources within the airport's energy infrastructure, thereby nullifying the approximately 42.1 million impact units previously attributed to grid-supplied electricity in the baseline configuration. The transport phases (A4, C2) and end-of-life stages (C1, C3, C4) remain relatively stable across all scenarios, indicating that the environmental shifts are primarily driven by changes in the production of components (A1–A3), their replacement cycles (B4–B5), and the



operational energy supply (B6). Overall, the redistribution of life-cycle burdens in Scenario 3 highlights a fundamental transition from operation-dominated impacts to embodied, infrastructure-related impacts—a characteristic pattern of renewable energy systems where upfront material investments replace continuous operational emissions.

The following table summarizes the changes in the main life-cycle stages for all scenarios. The results highlight how embodied stages increase progressively with the introduction of advanced technologies and airport-wide renewable infrastructure, while the operational stage is gradually and then fully mitigated through renewable energy integration.

Table 12 - Changes in life-cycle stages

Stage	Baseline [t CO2e]	Scenario 1 [t CO2e]	Scenario 2 [t CO2e]	Scenario 3 [t CO2e]
A1–A3	3,717.49	3,860.75	3,873.77	4,603.26
B4–B5	1,069.69	951.48	977.1	2,879.04
B6	42,103.05	41,749.94	23,418.1	0

The analysis demonstrates that while passive and envelope-oriented measures in Scenario 1 provide essential heating load reductions, they only slightly decrease the total life-cycle impact, because the building remains largely dependent on a carbon-intensive energy grid and delivers only marginal reductions in the dominant B6 operational stage (–0.84% compared to the baseline). In parallel, A1–A3 increases moderately by 3.86% and B4–B5 decreases by 11.05%, indicating that the additional materials required for the envelope upgrades are partially counterbalanced by a reduction in replacement needs, but without fundamentally altering the overall balance between embodied and operational impacts.

The introduction of Scenario 2 marks a more evident turning point, with a further rise in embodied impacts but a substantial cut in operational energy use. The A1–A3 product stage increases to +4.21% relative to the baseline, and B4–B5 sits at –8.57% (representing a +2.79% increase compared to Scenario 1), reflecting the added components and systems needed for higher performance, along with a modest rebound in replacement-related loads. More importantly, the B6 operational stage is reduced by 44.37% compared to the baseline and by 43.85% relative to Scenario 1, signaling a significant shift away from grid-supplied energy and leading to a pronounced drop in use-phase impacts even before the full renewable microgrid is implemented.



However, the most definitive results are achieved in Scenario 3. By leveraging the airport-wide green infrastructure project funded through the Modernization Fund, the Arrival Terminal eliminates the B6 operational energy contribution altogether (–100% compared to the baseline), more than offsetting the higher embodied loads in A1–A3 and B4–B5 associated with the large-scale renewable infrastructure. In this scenario, A1–A3 rises by 23.83% relative to the baseline (and by around 19–19.5% compared to Scenarios 1 and 2), while B4–B5 surges by 169.15% compared to the baseline (and by over 190–200% relative to the other scenarios), capturing the material-intensive nature of the photovoltaic, storage and balance-of-system components that must be produced and periodically replaced over the service life.

This redistribution of impacts results in a system where operational energy emissions are fully neutralized at the building level, and the life-cycle profile becomes dominated by upfront and replacement-related embodied stages rather than continuous operational consumption. In combination with the category-level results for GWP, Water Use and Ozone Depletion, Scenario 3 drives the total GWP down to roughly one quarter of its original value and almost eliminates water-use and ozone-depletion burdens, thereby fulfilling the high-level sustainability goals while clearly illustrating the trade-off between increased material intensity and near-zero operational emissions.



4. Conclusion and outlook

Regarding the dynamic multizone simulation

It has been identified that model calibration is critical for buildings with such complex uses as terminals in airports.

The calibration of the calculated model is closely related to the consumption history at the terminal level, both for thermal energy and for the electrical energy actually used in the normal operation of the building.

The lack of monitoring by consumer category of all electricity consumers leads to a cumbersome calibration exposed to large uncertainties for the input variables in the calculation model.

However, the model once calibrated allows better accuracy of the energy consumption predictions resulting from the implementation of various solutions to increase the energy efficiency of the building, the resulting energy savings and the operational carbon footprint during the considered analysis interval (annual calculation).

Regarding the Life Cycle Assessment approach

The LCA of the Arrival Terminal of Avram Iancu International Airport confirms that the operational phase is the primary driver of environmental impact in the Baseline configuration, with the B6 energy stage dominating the life-cycle profile and accounting for most of GWP-total and Water Use, consistent with literature on building life-cycle emissions. While construction materials (A1–A3) cause the initial carbon spike at year 0, the long-term burden is defined by steady operational emissions, with B4–B5 adding a smaller but non-negligible share over the 50-year period.

The optimization scenarios address this energy dependency through a staged approach. Scenario 1 reduces the heating load via passive architectural measures such as high-performance triple glazing, leading to a modest 0.84% decrease in the B6 stage compared to the baseline. Scenario 2 delivers a more substantial reduction in operational energy by 44.37% versus the baseline, marking a clear shift away from grid-supplied electricity. Scenario 3 then leverages airport-wide green infrastructure to eliminate the B6 contribution, as the terminal's energy demand is fully covered by the airport's renewable microgrid.

Overall, the results show that large-scale renewable energy microgrids are the most effective strategy for moving the terminal toward a near-carbon-neutral and resource-efficient state over its 50-year lifespan, despite a clear redistribution of impacts toward embodied stages and a moderate increase in GWP-biogenic and photochemical ozone formation.



Regarding the optimization approach

The optimization considered two main approaches, the first approach being similar to that from the followed methodology (deliverable D4.6), which actually is not suitable for Cluj-Napoca's case study, in terms of technical meaning; and the second approach is tailored for the actual technical condition of the Cluj-Napoca Arrivals Terminal.

Considering that the dynamic model for the Cluj-Napoca's Airport Arrivals Terminal was extended to **all thermal energy and electricity consumers (not only heating demand and cooling demand)**, and that **the calibration was undertaken for all consumers at the building level**, it became much more relevant to consider a more comprehensive objective for the optimization, the "Heating load" minimization objective being changed with "Net Site Energy" minimization objective. This objective can emphasize and quantify the impact of implementing specific measures at the equipment level (heat pumps, PVs) on final energy consumption and carbon emissions reduction, considering that this building is already well insulated and in very good technical condition. Therefore, energy conservation measures are limited and secondary, in terms of technical and economic justification.

To significantly reduced net site energy consumption (up to 53,8% compared with the reference), and furthermore the CO₂ emissions reduction of the Arrivals Terminal consumers, an integrated approach was considered, by using as design variables for the optimization setting: energy conservation measures, increasing energy efficiency and decarbonization measures and local renewable energy production measures, with a total number of possible combinations of 13824.



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