



D4.5: Report including a methodology proposal for design and conception of refurbished airport Terminals

Grant Agreement number: 101036871

Project acronym: OLGA

Project title: hOListic & Green Airports

Funding scheme: Innovation Action (IA)

Start date of the project: 1st October 2021

Duration: 60 months

Project coordinator: Virginie Pasquier, Project Manager Environment / Energy, ADP

Tel: +33 7 88 35 16 07

E-mail: virginie.pasquier@adp.fr

Project website address: www.olga-project.eu

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

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DOCUMENT INFORMATION

Document Name	Report including a methodology proposal for design and conception of refurbished airport Terminals
Version	V1
Version date	19/11/2025
Author	Bruno PEUPORTIER, Patrick SCHALBART, Long PEI, and Caipeng LIANG (ARMINES), Lionel LAUTRIDOU, Laurine FEINBERG and Audrey GAYAT (ADP)
Security	Public

APPROVALS

	Name	Company	Date	Visa
Coordinator	Virginie PASQUIER	ADP	16/11/2025	OK
WP Leader	Laurine FEINBERG	ADP	15/10/2025	OK
Subtask 4.1.5 Leader	Bruno PEUPORTIER	ARMINES	12/05/2025	OK
Quality Manager	Melike RIOLLET	LUP	19/11/2025	OK

DOCUMENT HISTORY

Version	Date	Modification	Authors
V01	07/09/2023	Initial version	Bruno PEUPORTIER and Long PEI (ARMINES), Lionel LAUTRIDOU and Audrey GAYAT (ADP),
V02	01/02/2024	Ex-ante case study	Bruno PEUPORTIER and Long PEI (ARMINES), Lionel LAUTRIDOU and Audrey GAYAT (ADP)
V03	22/04/2025	Ex-post case study	Bruno PEUPORTIER and Long PEI (ARMINES), Lionel LAUTRIDOU and Audrey GAYAT (ADP)
V1	19/11/2025	Quality review	Melike RIOLLET (LUP)



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List of Abbreviations

AB	Advisory Board	HSE	Health, safety and Environment
A-CDM	Airport CDM (certification)	IA	Innovation Action
ACI	Airport Council International	IDEP	Interactive Data Exchange Platform
AI	Artificial Intelligence	IP	Intellectual Property
API	Application Programming Interface	IPR	Intellectual Property Rights
APU	Auxiliary Power Unit	LCA	Life Cycle Assessment
AQ	Air quality	LH2	Liquid Hydrogen
ASTM	American Society for Testing and Materials	LIDAR	Light Detection and Ranging (camera)
BEMS	Building Energy Management System	LTO	Landing and Take-off
BES	Building Energy Simulation	MaaS	Mobility as a Service
BEV	Battery Electric Vehicle	MDO	Multidisciplinary Design Optimisation
BIM	Building Information Modeling	ML	Machine Learning
bioNGV	bio- Natural Gas Vehicle	MXP*	Malpensa airport
CA	Consortium Agreement	MRV	Measurement, Reporting and Verification
CAGR	Compound annual growth rate	NGV	Natural Gas for Vehicle
CAV	Connected and Autonomous Vehicles	OEM	Original Equipment Manufacturer
CDG*	Paris-Charles de Gaulle airport	OMS	Operation Management System
CDM	Collaborative Decision Making	PAX	Passenger
CFS	Certificate on the Financial Statement	PC	Project Coordinator
CLJ*	Cluj Airport	PMC	Project Management Committee
CNG	Compressed Natural Gas	POBT	Predicted Off Block Time
DL	Deep Learning	R&D	Research and Development
EAQM	Emissions and Air Quality Monitoring	RES	Renewable Energy Source
EC	European Commission	RGB	red, green, and blue (camera)
EoL	End of Life	SAF	Sustainable Aviation Fuel
EPC	Engineering Procurement and Contract	SC	Steering Committee
EU	European Union	SME	Small and Medium Enterprise



(P)(H)EV	Plug-In hybrid Electric Vehicle	TRL	Technology Readiness Level
FLW	Food Loss and Waste	UAV	Unmanned Aerial Vehicle
FMS	Fleet Management systems	UFP	Ultra-fine Particles
FP	Framework Programme	VOC	Volatile Organic Compounds
GHG	greenhouse gas	WG	Working Group (of the AB)
GIS	geographic information system	WP	Work Package
GPU	Ground Power Unit	WPL	Work Package Leader
H2020	Horizon 2020	XOPS	Operation / Fleet Management System (RMP4 product)
HEFA	Hydroprocessed Esters and Fatty Acids	ZAG*	Zagreb airport



1 Executive summary

1.1 Introduction

ADP's Terminal Buildings are old and complex industrial buildings. Objectives of this sub-task are to develop an innovative methodology based on a software platform developed at ARMINES integrating building energy simulation (Pleiades STD Comfie) and life cycle assessment (Pleiades ACV Equer). This subtask is based on 3 steps:

- Step 1: Complementing the software platform with an optimization module to comply with terminal buildings specificities and complexity (ARMINES). Improvements will be based on existing data provided by ADP,
- Step 2: Implementation of an ex-post experiment (ARMINES). Results expected are to verify the relevance and reliability of the customized software and study a possible use for energy performance guarantee,
- Step 3: Experimentation on a future refurbishment project by ARMINES to evaluate interactively the energy and environmental impacts of design and construction choices.

1.2 Brief description of the work performed and results achieved

The existing software platform was improved regarding the import of a BIM, the extension of number of elements allowing large and complex buildings like airport terminals to be studied, and the application of optimization. This allowed an ex-post study to be performed in the case of two buildings in Paris CDG airport (terminal 2B, and link between terminals 2B and 2D).

The proposed methodology, including modelling, energy simulation, life cycle assessment and optimisation is presented in this report, as well as its application in the ex-post experiment. Simulation results were compared with energy consumption measurements, showing that the model is consistent with the measured performance given the large uncertainties regarding occupancy scenarios (heating and cooling set points, internal gains related to occupants and electricity consumption, air renewal flow-rate...). The optimisation module allowed solutions to be identified, minimising the energy consumption for a given investment. Environmental impacts of the renovated buildings were evaluated, considering several variants.

This first version of the deliverable was transmitted to Cluj and Zagreb teams in order to study a possible replication. The next phase was to apply the methodology to a future refurbishment project. Experience from the ex-post case study was used so that a more efficient process was applied including modelling, thermal simulation, optimisation and life cycle assessment. Results were shown to decision makers in order to study the relevance of the renovation proposal.



1.3 Deviation from the original objectives

1.3.1 Description of the deviation

Generating a BIM model and importing it in the energy simulation software was more complex than expected and this activity was longer than planned. It was also difficult to find a research engineer. Fortunately, this did not cause too much delay so that it had no impact on the rest of the project.

1.3.2 Corrective actions (links with other deliverables/WPs)

A more efficient way to model the studied building was found, i.e. using floor plans instead of a complete BIM. One advantage is the duration of the modelling step, but this also allowed the computation time of the simulation to be reduced because connected rooms of the same use were aggregated in thermal zones. A lot of advice of this kind was passed on to partners in charge of studying replication.

2 Proposed design methodology

2.1 Data collection

2.1.1 Building information model

The first step is to create a digital model (BIM) of the existing terminal, and making this model compatible with an energy simulation tool. Ideally, the BIM developer should be familiar with energy simulation standards like gbXML (green building XML) so that the modelling options are appropriate. Because this is not always the case, treatments have possibly to be carried out on this model (for example creation of rooms, fusion of different modelling layers, information enrichment regarding wall composition etc.). Different formats will be tested: IFC4 and gbXML, as well as several levels of information detail (name of wall compositions, list of materials, physical properties of materials) depending on the possibilities offered by the models available from ADP.

Some advice was generated following the first activities of the project.

- a) define rooms and spaces, and if needed specific space boundaries in your building (including boarding bridges if you wish that they are included in the thermal analysis, e.g. comfort, and life cycle assessment). The room / space must be simple as possible (excluding video game corner...).
- b) join material layers in walls instead of defining one wall for each layer (or allow this possibility for adaptation of the model when exporting it to gbXML). It is not required to define all physical properties of materials in e.g. REVIT: a name is sufficient, and energy engineers can input the properties in the energy simulation tool (same as for use scenarios).



c) define opaque walls and windows in façades instead of curtain walls (except if there is really a curtain wall) otherwise an adaptation work will be needed to transform such curtain walls into opaque walls and windows.

d) export your BIM in the gbXML format and check that all spaces and walls are integrated using a gbXML viewer, e.g. <https://www.ladybug.tools/spider/gbxml-viewer/r12/gv-app/gv-app.html>

e) Avoid to use e.g. generic Revit families for replicable part of the building (e.g. boarding bridges), if you wish to include them in the thermal analysis.

f) To facilitate exchanges between BIM designer and the thermal/environmental experts, choose names for materials and components as much informative as possible (e.g. glasswool instead of insulation). The family type parameter "Type Comment" may be used in order to include supplementary information.

2.1.2 Occupancy scenarios

Data has to be collected or estimated regarding the use of the different premises, in the form of hourly-daily scenarios specifying over time:

- The number of people present,
- The set-point temperature (heating and air conditioning),
- Internal heat gains linked to electricity consumption (including shops),
- The air flows extracted and possibly blown in by mechanical ventilation,
- The opening of doors and other possible elements,
- The management of any solar protection (e.g. blinds).

2.1.3 Climate data

A typical year file must include hourly values at least for external ambient air temperature, global horizontal solar radiation, and if possible diffuse horizontal and direct normal solar radiation, relative humidity, wind speed and direction.

2.2 Energy simulation

A dynamic building energy simulation (BES) must be performed to evaluate the performance of the existing building and study improvement measures. Several tools are available, see for instance (Peuportier and Blanc-Sommereux, 1990), (Clarke, 2001), (Crawley, 2001), (Seem, 1987). Model reduction techniques reduce the computation time while keeping a satisfactory precision level (Munaretto et al., 2017). This allows thousands of simulations, needed for optimization, to be performed in a reasonable time.



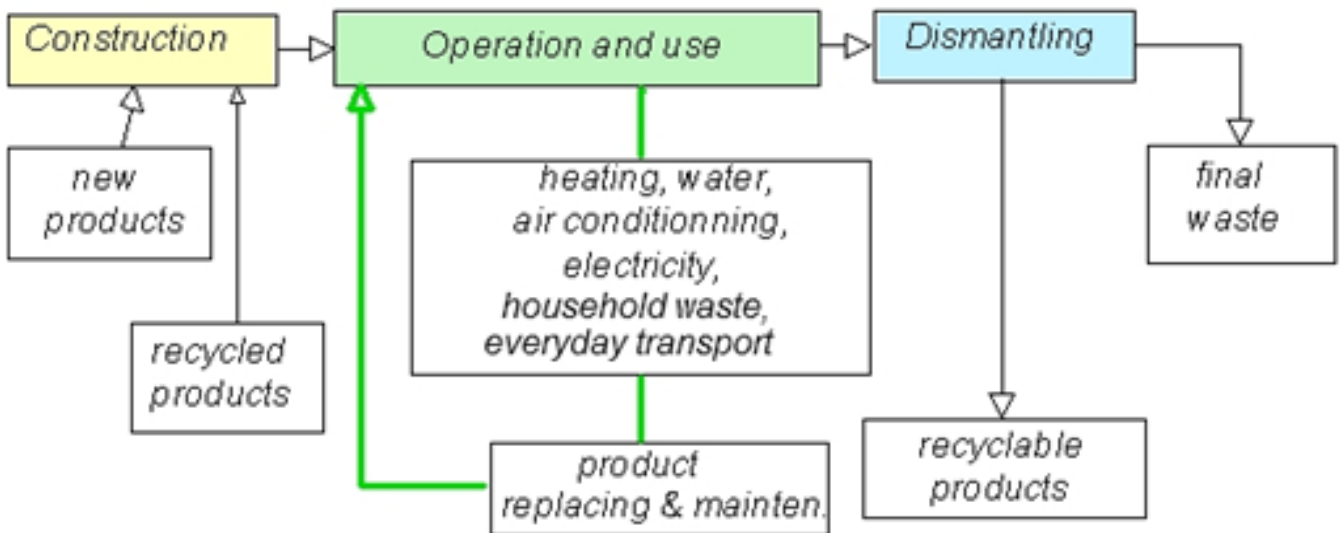
The results in terms of energy consumption should preferably be compared with measures or invoices if they exist. Uncertain parameters influencing the most simulation results (e.g. air change rates) can be adapted to reduce the gap between the model and measurements. If time is available for a more precise study, influential parameters can be identified by a sensitivity analysis, see e.g. (Morris, 1991), and the model can be calibrated considering the most influential parameters, see e.g. (Kennedy and O'Hagan, 2001), (Heo et al., 2012), (Beaumont et al., 2009).

Different renovation scenarios can be defined (thermal insulation, replacement of glazed elements, improvement of ventilation, actions on systems and / or their control, etc.). These scenarios can then be evaluated using the preferably calibrated model.

2.3 Life cycle assessment

Building energy simulation can be followed by life cycle assessment in order to evaluate the environmental impacts of the renovation works, and impact reduction obtained by energy saving. Different tools may also be used like Pleiades (Polster et al., 1996), Simapro¹, Open LCA², Brightway³.

The principle is to account for environmental impacts over the life cycle of a building: from the extraction and transport of raw materials, fabrication of building products, transport to the construction or renovation site, implementation works, use of the building, replacements of products until the end of life and possible recycling (see figure hereunder).



Building life cycle simulation (Peuportier, 2015)

¹ <https://simapro.com/>

² <https://www.openlca.org/>

³ <https://brightway.dev/>



LCA addresses global warming, but also other environmental impacts in order to avoid impact transfer (e.g. reducing greenhouse gases emissions but increasing impacts on human health), see an example in the table below.

Impact indicator	unit	Reference
GHG emissions	kgCO ₂ eq.	(IPCC, 2013)
Acidification	kg SO ₂ eq.	(Seppälä et al., 2006 ; Posch et al., 2008)
Eutrophication	kg PO ₄ eq.	(Struijs et al., 2009)
Photochemical ozone production	kg ethylene eq.	(van Zelm et al., 2008)
Cumulative energy demand	kWh	(Hischier et al., 2010)
Water used	m ³	(Hischier et al., 2010)
Land use	m ² .year	(Koellner et Scholz, 2006)
Waste	t	(Hischier et al., 2010)
Radioactive waste	dm ³	(Hischier et al., 2010)
Abiotic resource depletion	kg antimony eq.	(Oers, 2016)
Damage to biodiversity	PDF.m ² .year	(Huijbregts et al., 2016)
Damage to human health	DALY	(Huijbregts et al., 2016)

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

LCA has been applied to numerous new construction projects, but also to renovation (Palacios-Munoz, 2019).

2.4 Optimisation

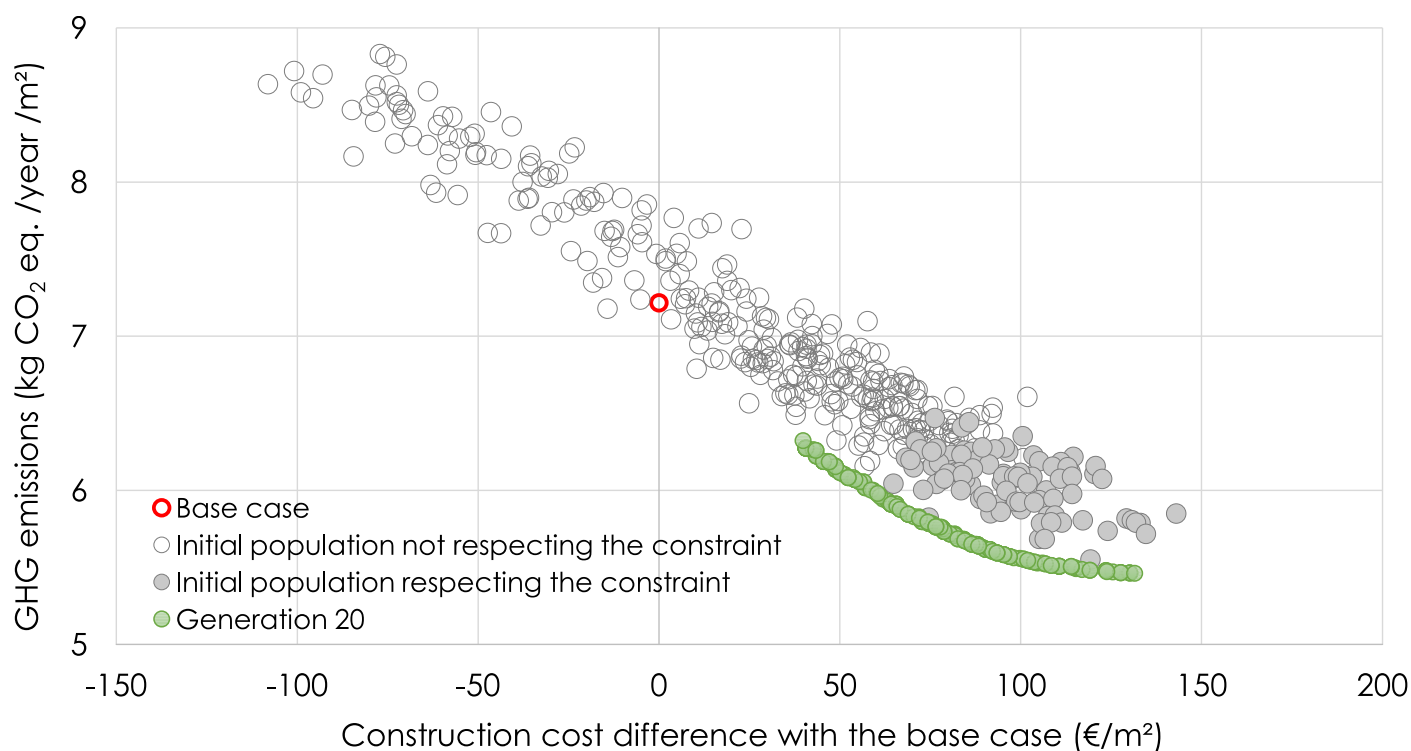
Cost data can also be collected. An optimization step can be experienced, e.g. based on a genetic algorithm, leading to the identification of non-dominated solutions (that is, there is no less expensive solution for a given performance and vice versa). Various performance criteria can be optimized: energy, greenhouse gases emissions, cost of work, etc.

Some BES tools are complemented with optimization modules, e.g. Genopt complementing EnergyPlus and TRNSys (see <https://simulationresearch.lbl.gov/GO/>), AMAPOLA complementing Pleiades STD (Recht et al., 2016).



The optimization criteria(s) have to be selected, as well as the design parameters, e.g. insulation thickness in façades, roofs and floors, glazing properties etc. Constraints may be considered, e.g. plus energy balance (renewable energy production being higher than the consumption in the building), or comfort level.

Multi-criteria optimization allows non-dominated solutions to be identified, e.g. corresponding to a lowest cost of renovation works for a given energy or environmental performance, and a highest energy or environmental performance for a given cost. These solutions can be represented on a “Pareto front”, see the figure hereunder.



Example Pareto front, green points respecting also a plus energy constraint (Recht et al., 2016)



3 Results for the ex-post case study

3.1 Presentation of the case study

CDG Terminal 2B was studied. A comprehensive renovation of the envelope was performed, allowing thermal insulation and low emissivity double glazing to be implemented. Energy consumption measurements after renovation are available, as well as some data regarding the use of the different spaces (occupancy, heating and cooling temperatures).



3.2 Elaboration of a building information model

The software REVIT (editor Autodesk) is used to create model shapes and systems in 3D with data and parametric rules. It is also used to produce documentation work like plans, elevations, section and bills of objects or materials. The 3D,2D or only alphanumeric data can be exported into several different formats. The Pleiades solution is able to import three 3D models formats:

- Revit (RVT)
- IFC
- gbXML⁴

⁴ gbXML is an open-source file format used to facilitate the transfer of building properties stored in a 3D BIM model to energy calculation applications. The format is now supported by all major BIM and energy analysis software publishers and has become the industry standard.



We preliminary balanced the advantage/inconvenience of each format, and the exchange using a gbXML format was chosen after this analysis.

Format	Benefit	Inconvenient
Revit	<p>No specific action necessary to export Native format used</p> <p>Result can be injected in the Revit mock-up</p> <p>Improvement to identify the walls / slab / ceiling bordering a space</p> <p>The best solution for an iterative design process</p>	<p>Specific requirement with methods which are sometime conflicting with Design needs (for example the axis of wall is a limit for Pleiades while Architects use the internal face for room measurement, Curtain wall must be split by level).</p> <p>Unable to import model with several linked models</p> <p>Useless object for STD cannot be removed</p> <p>Important File size</p> <p>Require a Revit operator</p> <p>Troubleshooting with the French official Lambert conformal conic projection</p> <p>Pleiades import process failed</p>
IFC	<p>Selection of pertinent object and data for STD</p>	<p>Object' shape must sometimes be modified</p> <p>Troubleshooting with the French official Lambert conformal conic projection</p> <p>Important File size</p> <p>Pleiades import process failed</p> <p>Each Revit file must be exported separately then be merged into a unique IFC file</p> <p>It takes a long time to export / import the data</p>
gbXML	<p>Import works in Pleiades</p> <p>Air volume and surfaces bordering the volume are the only objects exported.</p> <p>Identification of the activity inside the volume and the nature of the wall</p> <p>File size is lower than the two other formats</p>	<p>Export process takes a long time.</p> <p>Some walls are not associated as a boundary with the space volume.</p> <p>Material's properties are not included</p>

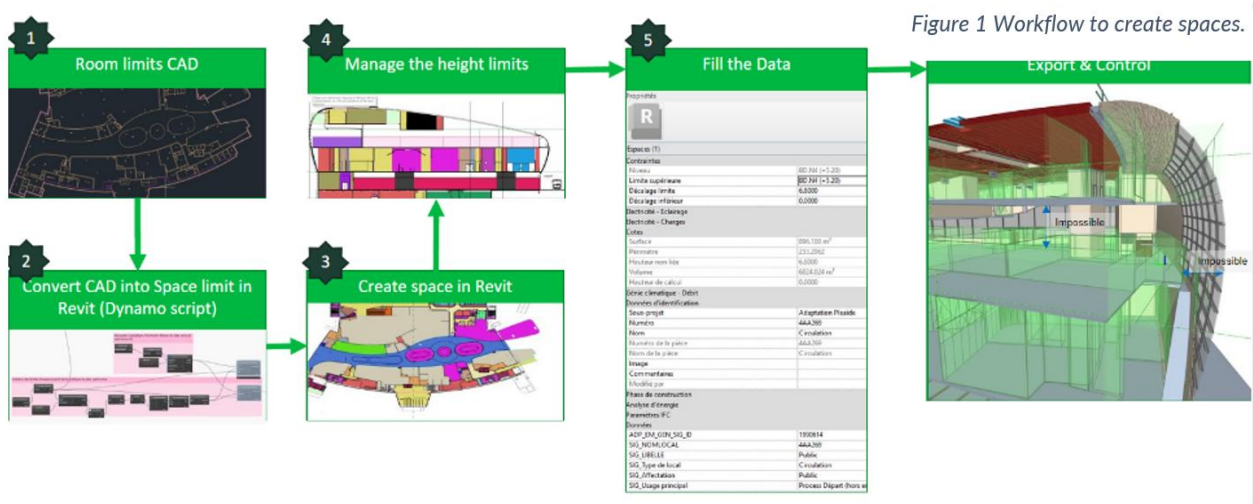
Considering the fails with IFC and Revit, we conclude that the best format to exchange the data is gbXML.

3.2.1 Adapting the REVIT MODEL

Before exporting the model into a gbXML file, the first task is to adapt and complete the model. The model contains Rooms defined by the architects, but we cannot use them for thermal analysis. Indeed, rooms and spaces are independent components used for different purposes. Rooms are architectural components used to maintain information about occupied areas. Spaces are



exclusively used for the MEP disciplines (Mechanical, Electrical and Plumbing) to analyze volume. They contain parameters that maintain information about the areas in which they have been placed. This information is used in order to perform a heating and cooling loads analysis using a simulation software. Spaces can be placed (added) and deleted independently with rooms. Spaces are immediately assigned to the Default zone when they are initially added to a project. Spaces can be viewed in a section view, but spaces cannot be viewed or placed in elevation or 3D views. We can add a space separation line to divide it and we can set its elevation, but we cannot change its geometry. Spaces should be placed throughout the model, including unoccupied areas such as plenums areas. Spaces that are created in an area that contains a room are created as occupied (Occupiable parameter selected).



When placed in an enclosed area, the volume for a space is calculated to the surfaces of room-bounding components, such as walls, floors, ceilings, roofs, and space separation lines. The volume for the space expands horizontally and vertically to the extent of the face of the room-bounding components. The bounding Surfaces of the volume fall into one of two categories:

- Exterior.

Except when the component's type parameter, Function, is specified as Interior or Core/Shaft, surfaces for room-bounding components (such as walls) have spaces adjacent on one side only, or they have no spaces adjacent and are treated as exterior surfaces. Heating and cooling loads analysis treats these surfaces as exterior, even if they are interior.
- Interior.



These surfaces for room-bounding components that have spaces adjacent on both sides are treated as interior surfaces or components whose type of parameter. Function is specified as Interior or Core/Shaft.

We had to adapt the model with these different changes in order to produce a correct volume model:

Passenger Bridge

The initial model of the bridge, connecting the boarding gate with the boarding bridge, cannot be used to define the boundaries of space with the slab, the windowpane, or the roof. This object is a generic model that cannot distinguish each part into the gbXML exported file.

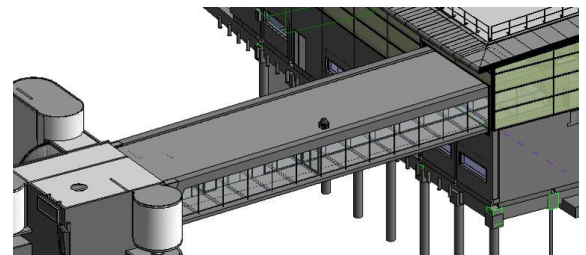


Figure 1: Initial passenger bridge

The solution consists of switching those generic models with a correct model that distinct the floor, glass, and the ceiling. Each object is also correctly designed with materials (e.g. insulation) and their thickness. Each one is named to facilitate the future analysis (producing a BIM).

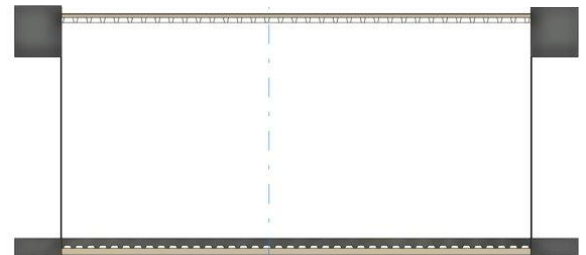


Figure 2 : Sectional plan of the modified passenger bridge

Filling the gaps in the shell

The façade from the original model contains several gaps and consequently it is not possible to create an air volume (aka space) beside these gaps. This oversight is probably due to a problem during the upgrade of Revit version or simply due to a human error.

A solution is to fill these gaps with a correct façade element.

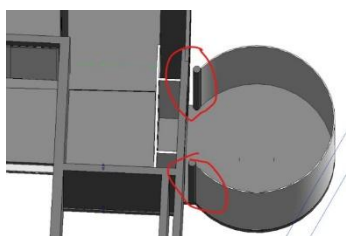


Figure 3: missing façade element

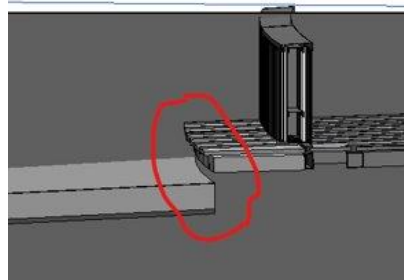


Figure 4 : Gap between roof junction element

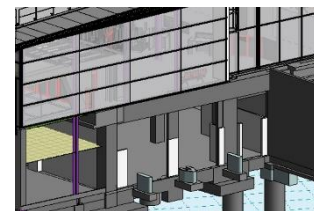


Figure 5: Gaps between the rotunda of the boarding bridge and the façade



Disactivate space separation object

Different furniture in the terminal is activated as a space boundary. This option means that the object creates useless limits (planar or vertical) in the space delimitation. The problem is that the same property is used both to manage room and volume limits. This property is sometime activated in order to split an area to quantity a part of a room like the waiting area and the boarding area. The solution consists to disactivate this property and when necessary to create manually a room separation border.

Structural object

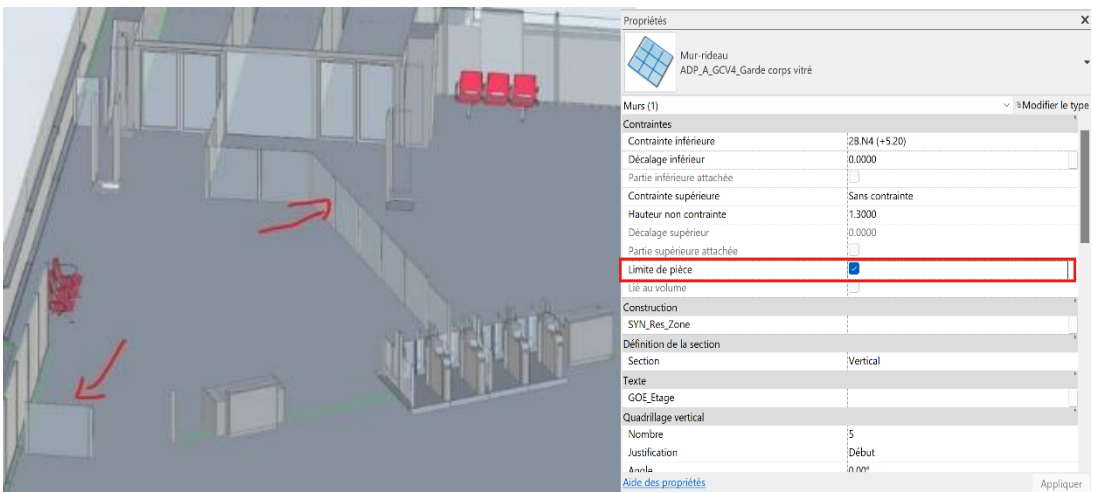


Figure 6: Passenger separation barrier

A few structural objects were created as generic objects. The problem is the same as for the Passenger bridge. The solution consists of switching those generic models with an object in the correct category (floor, columns, walls, and the roof).

The junction portico was decomposed into 7 objects. These objects are set with the correct parameter Function (Exterior or Interior).



Figure 7 : junction portico before change

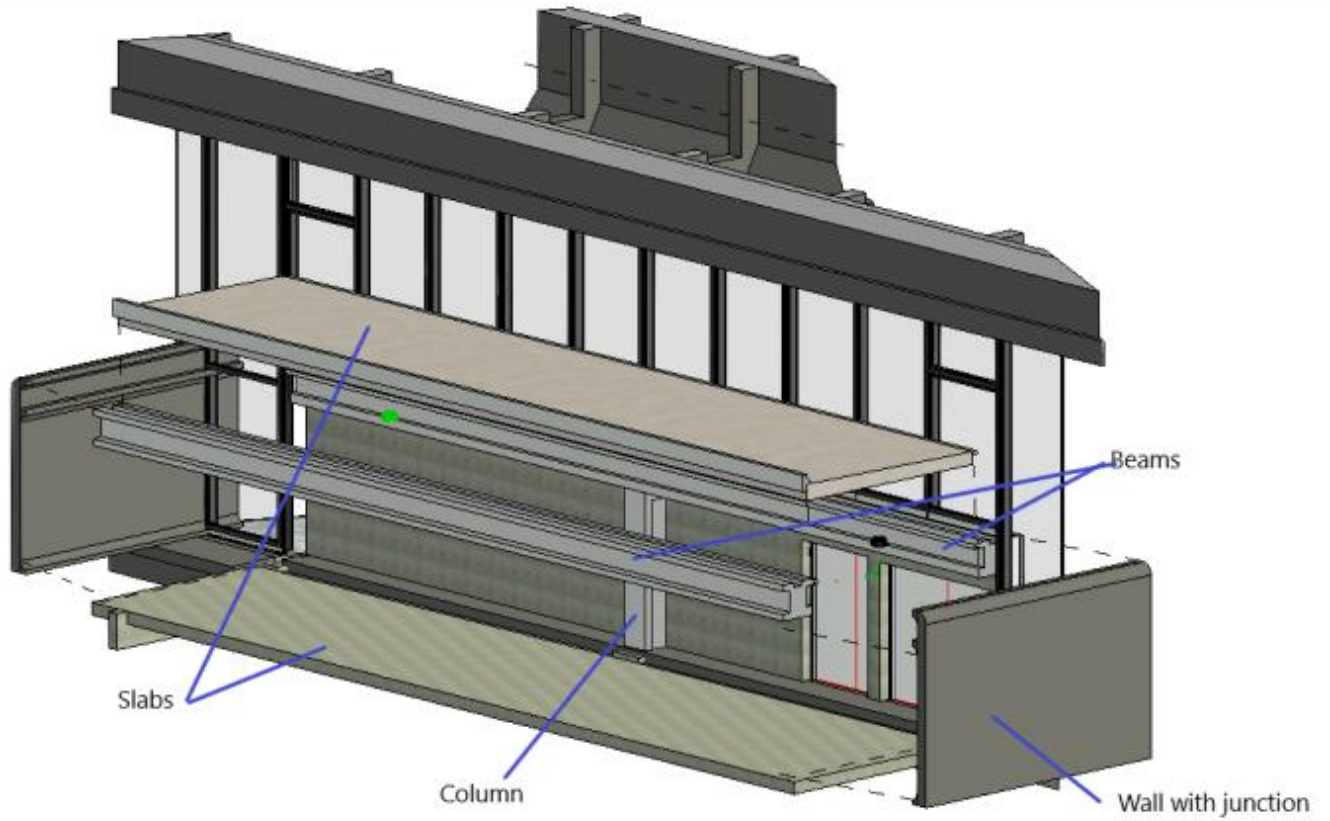


Figure 8 junction portico after change



Building façade limits.

Three problems had to be solved to export a correct model.

1. Air volume near the curtain walls cannot be created.
2. All façade's surfaces are not exported
3. Some limits of air volumes don't match with the Revit mockup

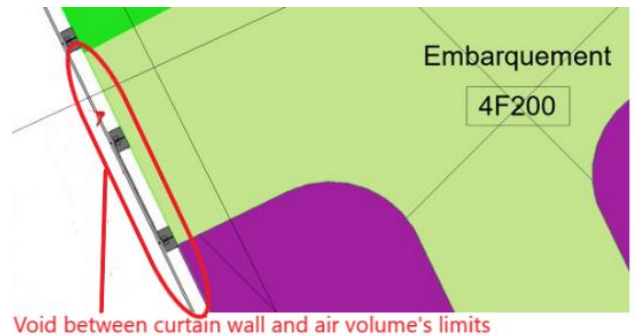


Figure 9 Example of limits problem

The first problem is caused by Revit which does not recognize all the limits bordering the volume. When the user wants to insert a volume, Revit automatically creates the space for areas greater than 0.25 sq ft. In many cases, if the room is created then the space can also be created.

We also observe that the data produced by the construction company are not adapted with the needs of a thermal simulation model. The façade model contains a lot of details that makes difficult to export into a gbXML model (like overlapping walls). Moreover, the company models focus on the objects on their responsibility and the connection with the models produced by other companies doesn't always match perfectly. Consequently, there are some gaps in the exterior boundaries that we must correct because space requires a closed limit

Concerning the second problem, the offset of curtain wall ignites this problem.

Revit defines volume's limits considering the axis of wall panels, but a curtain wall is composed with mullions and wall panels. The wall panels can be offset from the limits but this offset of curtain wall components (the panel or mullions) is not applied to define the volume limits.

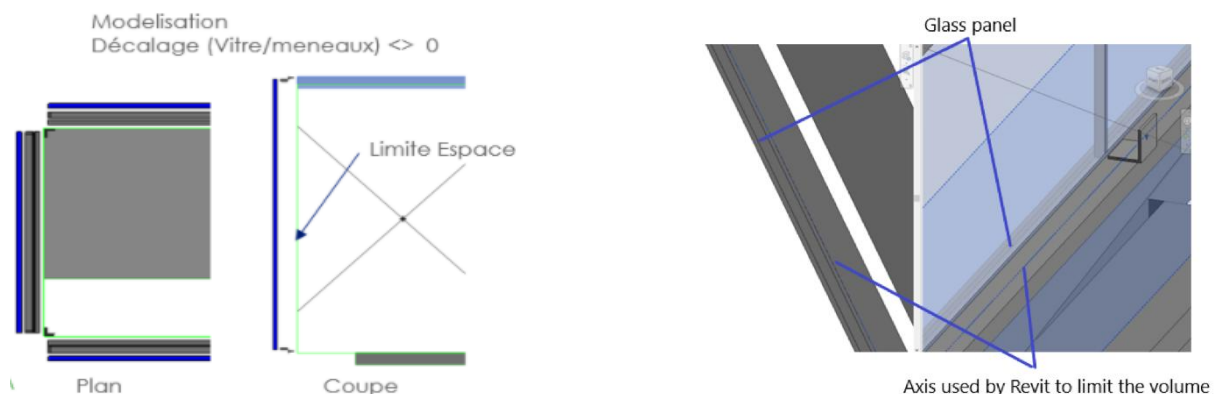


Figure 10 Offset doesn't change the space limit.

The third problem concerns the separation lines that are stored in a linked model. It is a complex troubleshooting that we encountered during our work. Room boundary can usually be split by a



room separation line and space can also be split by a space separation line. The room boundary line should not interact with space. But when several models are linked, Revit doesn't make any distinction between the lines used for a room separation or for a space separation.

These three types of problem should be solved to have a correct thermal 3d model, but it takes a long time to solve them one by one.

The solution is composed with two actions. One is to inactivate the limits from linked models and on curtain walls and to draw the space separation line for all the exterior boundaries. It is simple to inactivate the limits, the Room Bounding parameter must be uncheck for each linked model or object.

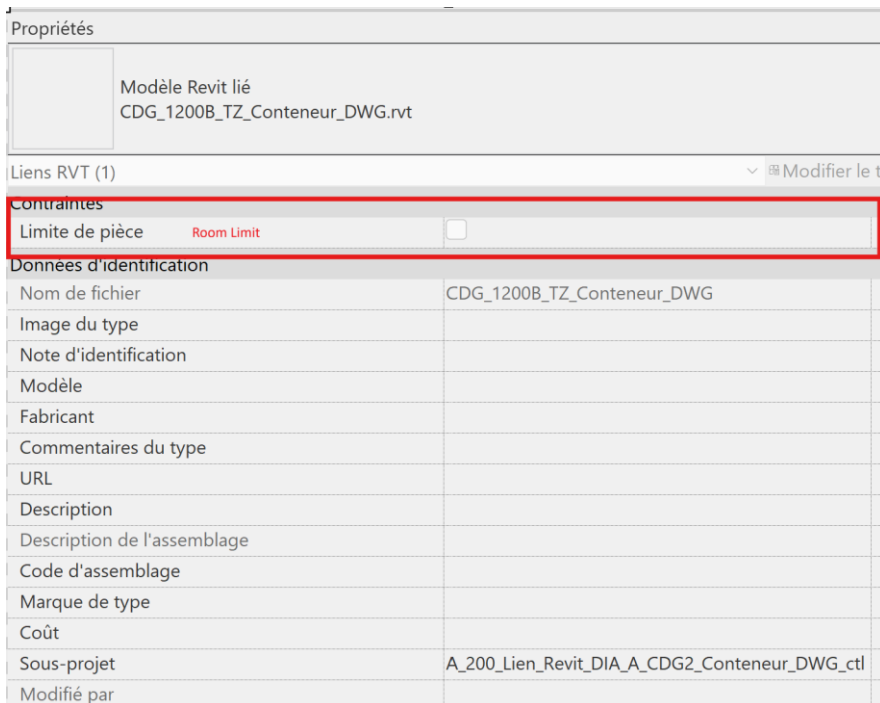


Figure 11-1: inactivating limits

The second is more complex, we must create a specific exterior boundary that intersect the face of the panel or wall. We use a limit from a floor plan to create these space separation lines. The size of the building needs to automate the creation of these separation lines. We use Revit Dynamo for that. Revit Dynamo is a graphical programming interface that lets you customize your building information workflow. The script selects the lines from a CAD drawing and transforms them into space separation lines.

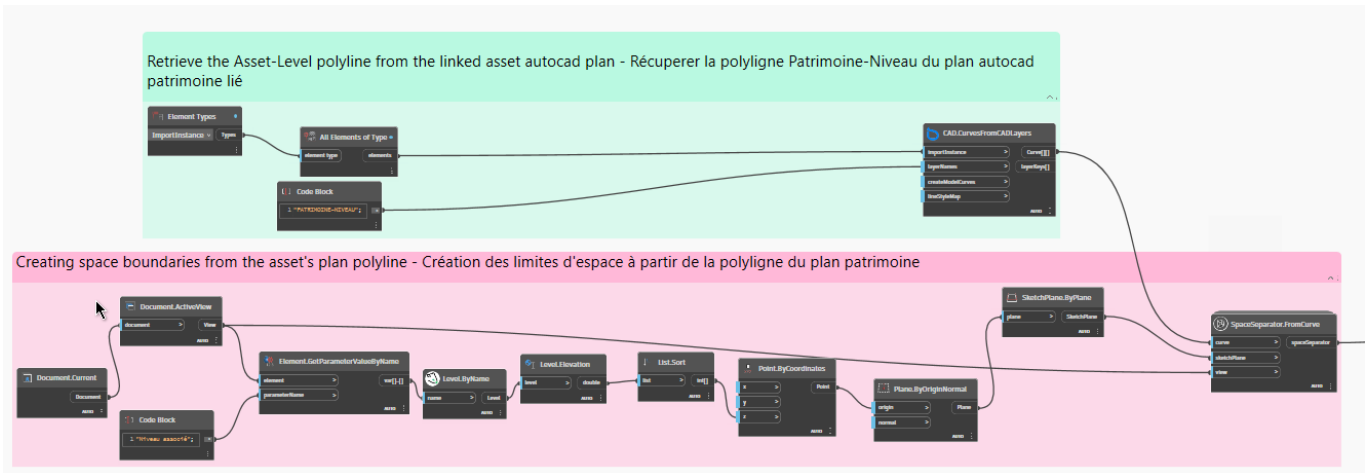
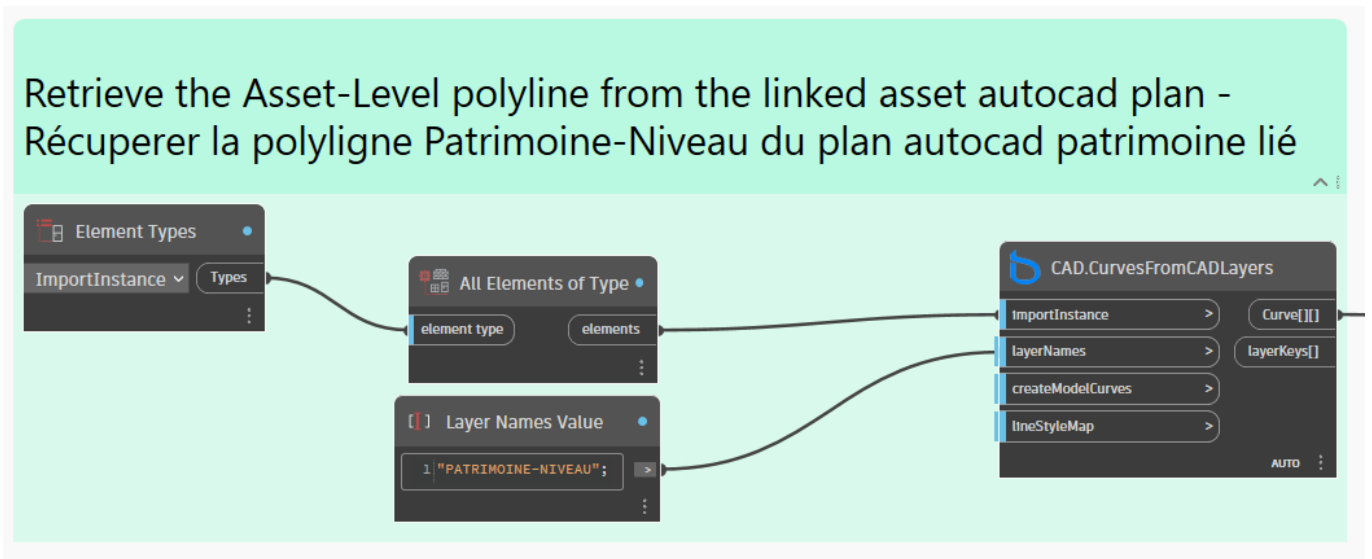
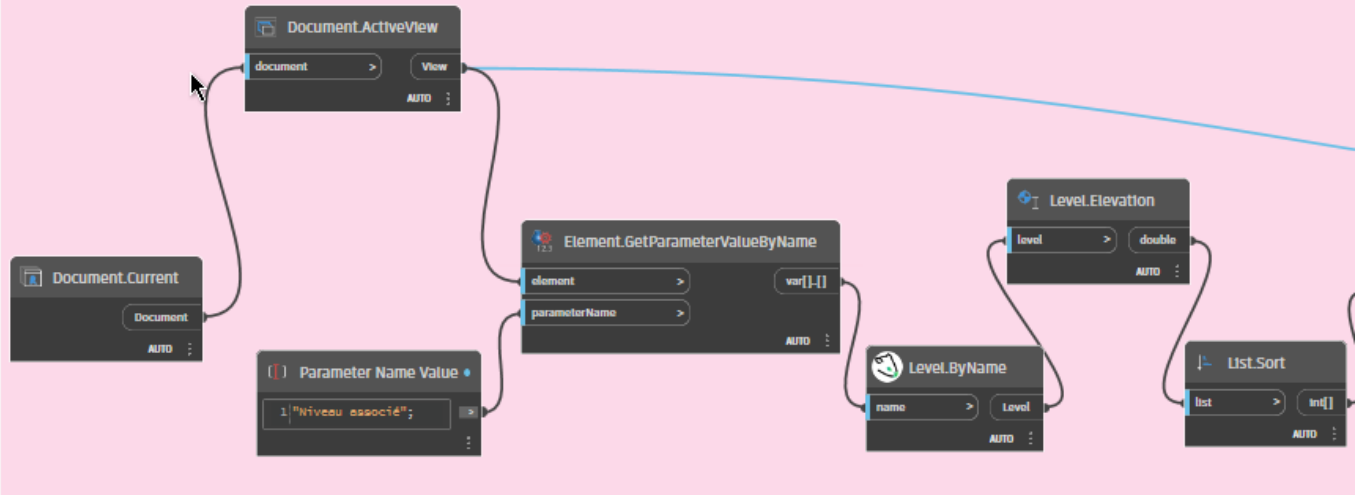


Figure 12-2: Dynamo script to convert drawing line into space separation line object, global view, see details hereunder





Creating space boundaries from the asset's plan polyline - Création des limites d'espace à pa



es limites d'espace à partir de la polygline du plan patrimoine

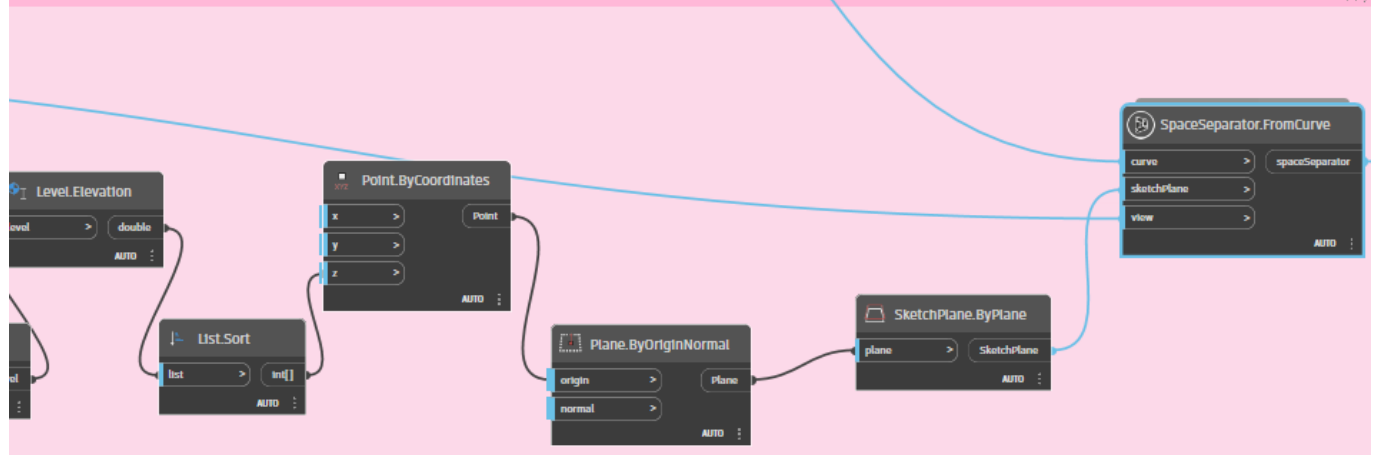


Figure 13-3: Dynamo script to convert drawing line into space separation line object

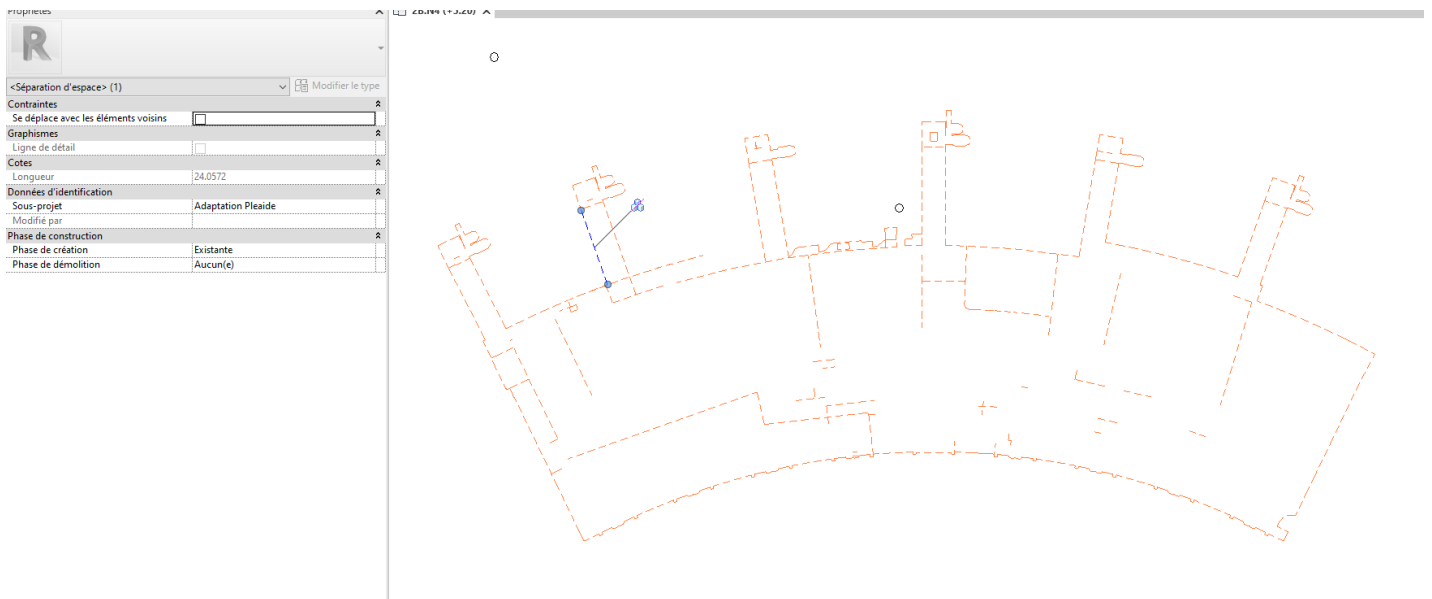


Figure 14 Result of script Space separation lines

After making all these changes in the Revit model, the spaces have been manually inserted into each floor plan. The space name is a legacy from the overlapping room. This task requires human control because the spatial intersection between room and space sometimes returns erroneous results. Once correctly parameterised, the volumes inherit the functionality data defined in the properties of the room object.

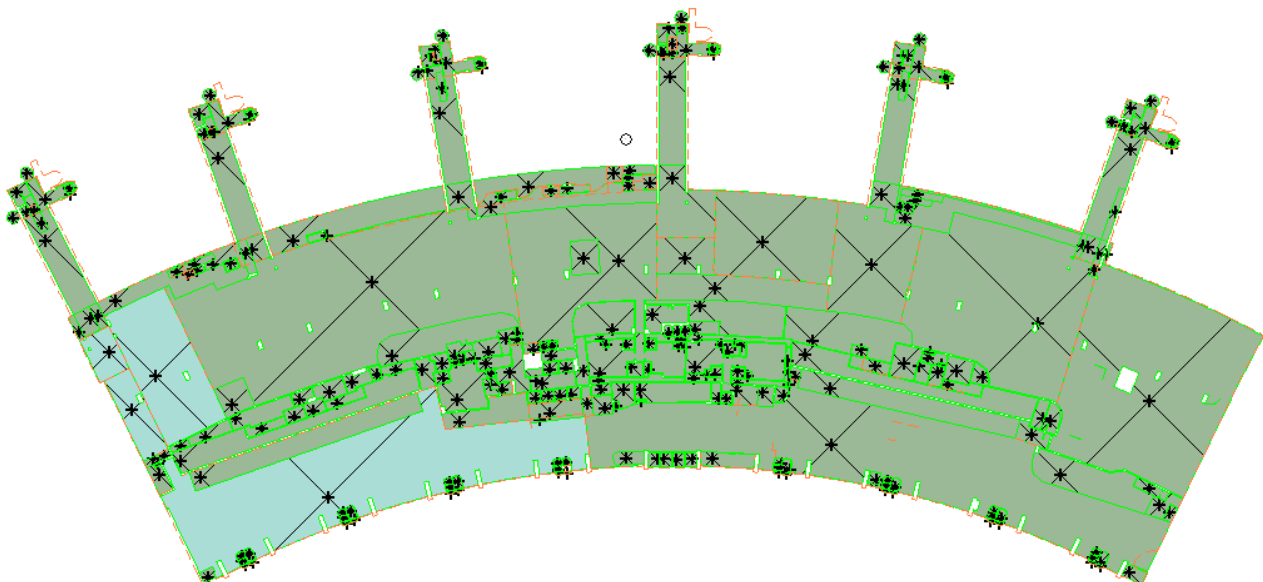


Figure 15 Result of treatment Spaces for all departures level



Space overlapping.

A space overlapping cannot be exported into gbXML, all the conflict should be resolved before export. Revit doesn't show in a 3D view the space element; therefore, several section views are created to detect location of conflict. In a section view, the upper and lower limits can be changed. In a same plan, a space cannot overlap another one. In a complex area, we must deal with these rules and the only way to eliminate overlapping is to split a space in order to manage separately the different heights of the volume.

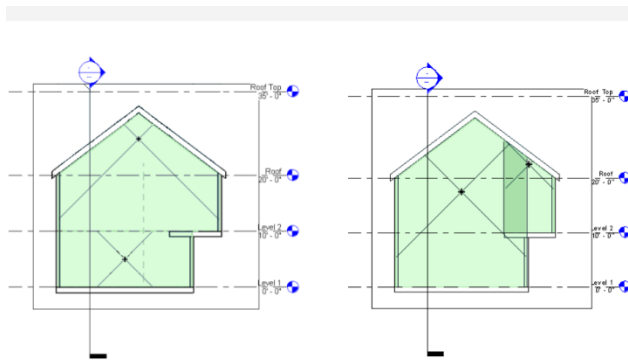


Figure 16 the Right section shows a space overlap, the left section shows a correct space model

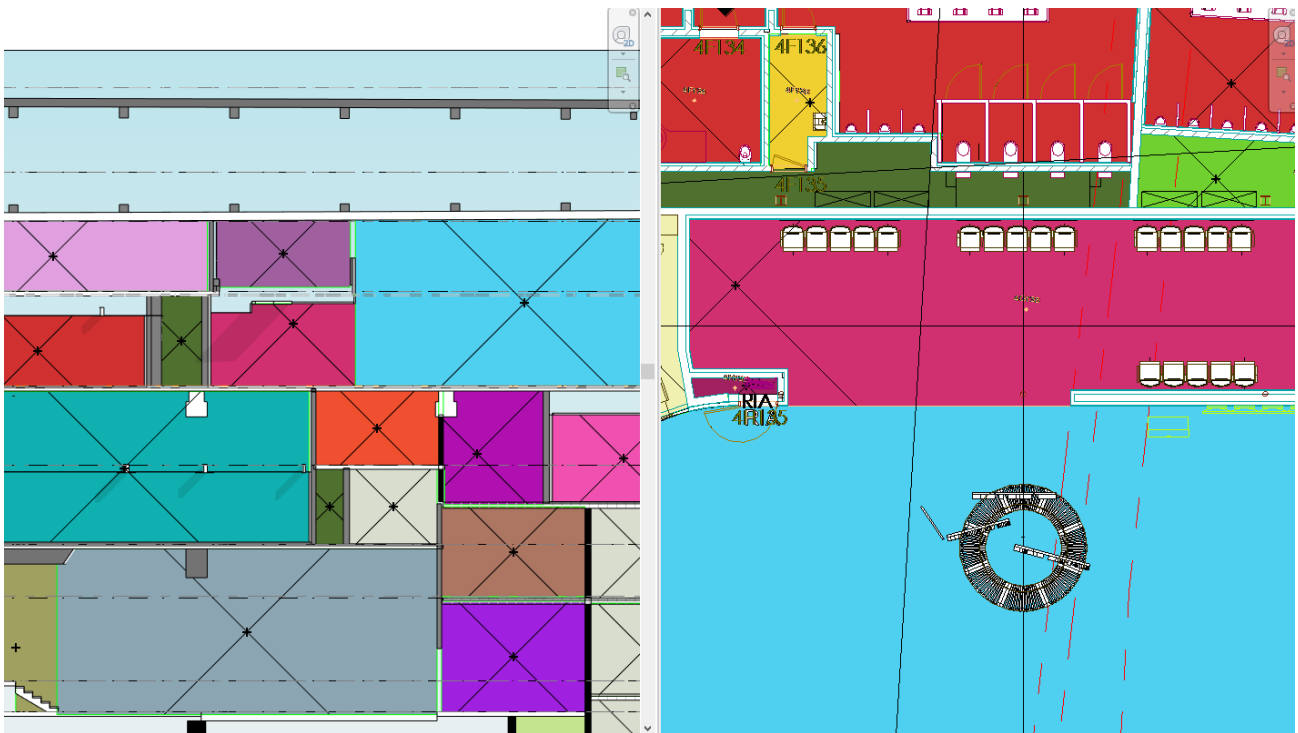


Figure 17 Example of complex space in the Terminal 2B



Methodology of modelling

The thermal model was created in two steps: first a sample corresponding approximately of 1/9 of the area and in a second step the entire terminal.

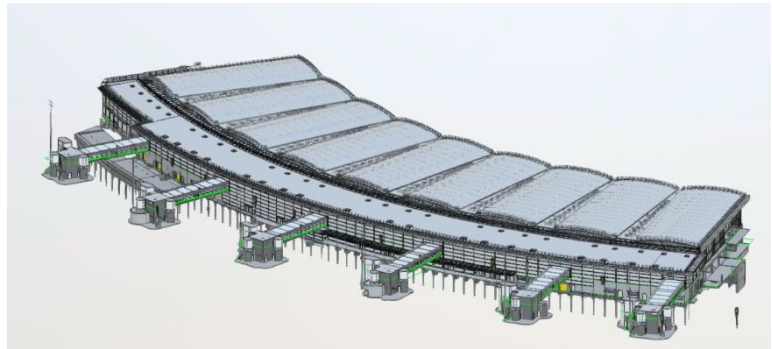
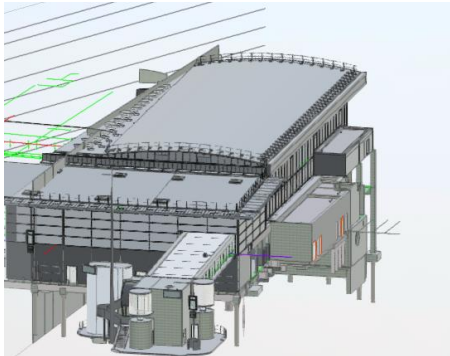
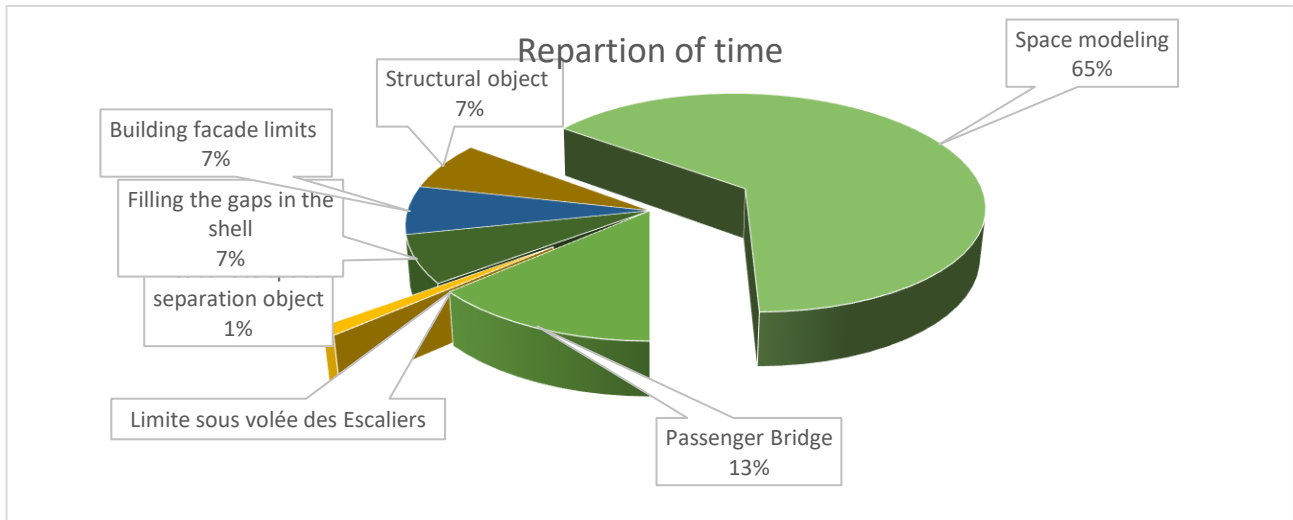


Figure 18: Sample test & Figure 19 Terminal 2B

Some issues were identified during the sample and we searched a solution to solve or mitigate them.

The duration of each step was measured in the sample model then the time needed to replicate in the complete terminal model was forecasted. The forecast indicated that the space modeling process of work was too important, and we had to find a way to reduce it. We use dynamo (figure 11) in order to automate a part of process.

Topic	duration (testing sample)	Size coefficient	Forecast (hr)	Real (hr)
Passenger Bridge	2	6	12	16
Limit under staircase flights	2	50	100	0
Deactivate space separation object	1,5	1	1.5	1.5
Filling the gaps in the shell	8	8,23	66	8
Building façade limits	16	3,87	62	8
Structural object	8	1	8	8
Space modelling	67	8.23	551	76



3.2.2 Unsolved issue

Some shape's complexities of the building envelope do not allow to create accurate volumes with revit modelling tools. For example, we didn't successfully model the vertical curvature of the link BD building. Revit automatically creates volumes by projecting planar boundaries perpendicularly.



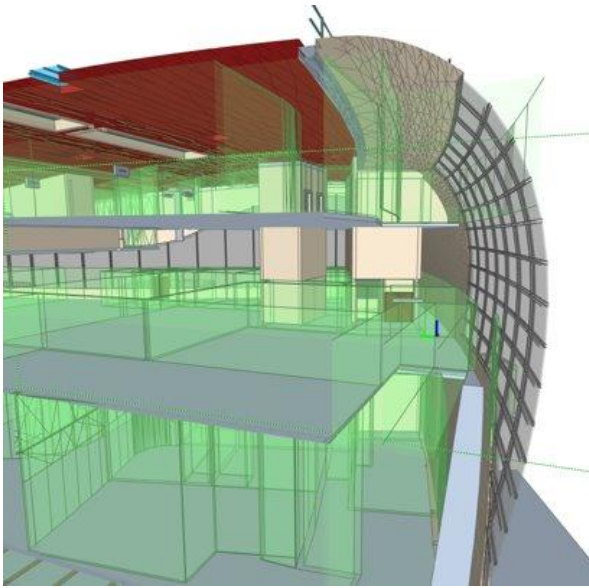


Figure 20: Spaces in Revit

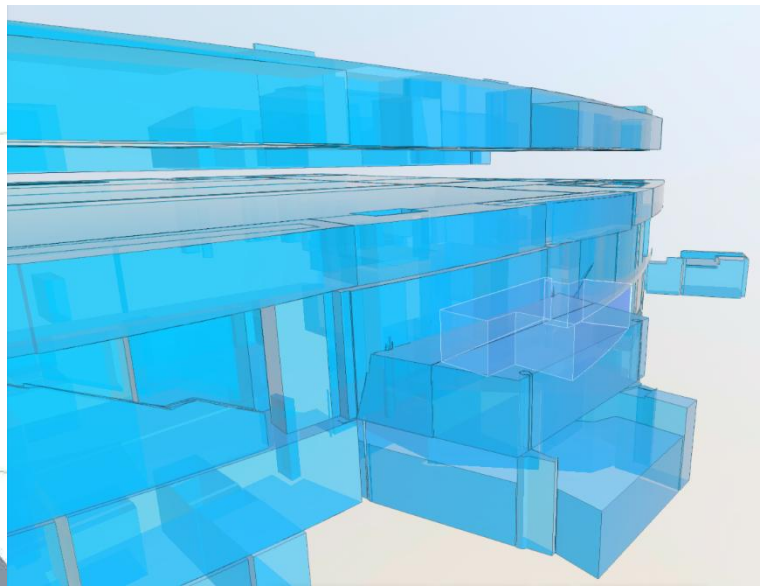


Figure 21: Result after export into GBXML

The workaround to create the thermal model was to export from Revit the wrong volumes into gbXML, and the floor plans and several sections views of the envelope into DWG format. The gbXML model was used to init the study with Pleiades software and was after manually corrected with the CAD data (DWG). Finally, it was more convenient to use only the DWG plans.

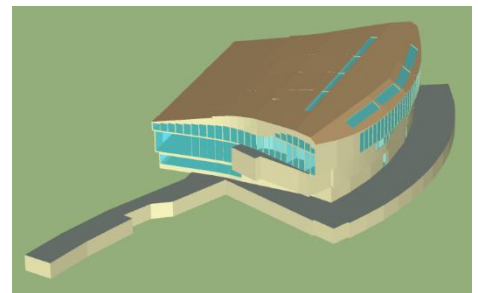
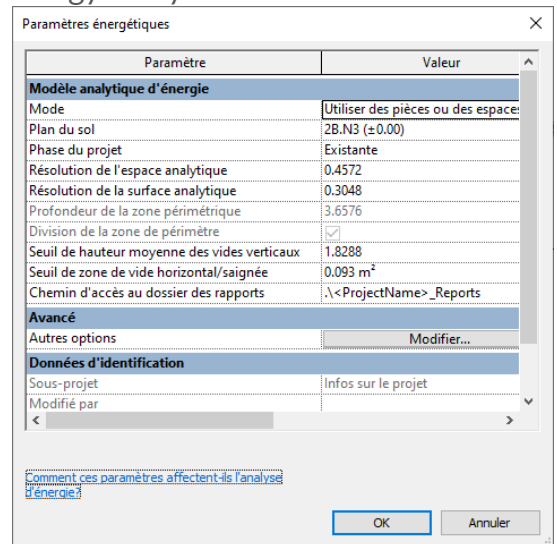


Figure 22 Pleiades model

3.2.3 Generating a gbXML model in REVIT

Once the digital mock-up is updated with the objects modelling the volume of the air for each space/room, you must export the model to a gbXML file format before to perform the energy analysis using Pleiades software. This format focuses on the energy analysis information needed by the thermal analytical model. The energy analytical model is composed of analytical spaces and analytical surfaces, which are created based on parameters defined in the Energy Settings dialog.

- The parameter "analysis mode" specifies the type of object to export. Revit offers three options for exporting to gbXML which correspond to the options for the analysis mode in the Energy Settings dialog:
 - Use building elements: Creates analytical spaces and surfaces from building elements.





-
- Use rooms/spaces elements: Creates analytical spaces and surfaces from room/space volumes.
 - Use conceptual masses and building elements: Creates analytical spaces and surfaces from conceptual masses and building elements.

We choose the " Use rooms/spaces elements " option, which best matches the state of the terminal model.

- The parameter "Ground plane" specifies the level below which the surface of the energy analytic model is assumed to be in contact with the ground for heat transfer. For a building where the first floor is partially buried (e.g. built into a slope), use the level with the greatest exposure as the ground plane.

We choose the APRON level corresponding to N3 level.

- The parameter " Project phase" filters the building elements and/or design volumes assigned to the specified phase or to a previous construction phase that are included in the energy analysis. Elements and volumes assigned to a later construction phase are omitted from the energy analysis. We choose the phase "Existing".

The other parameters are useless with the workflow chosen.

Then we export and control the energy analytical model, which is composed of analytical spaces and analytical surfaces, which are created according to defined parameters and with the objects correctly modelled in the BIM. The quality control is a visual inspection made with a free and open source gbXML viewer (Aragog gbxml viewer). The quality control was iteratively made during the modelling of each level's spaces. The figure below illustrated the progress with the export model.

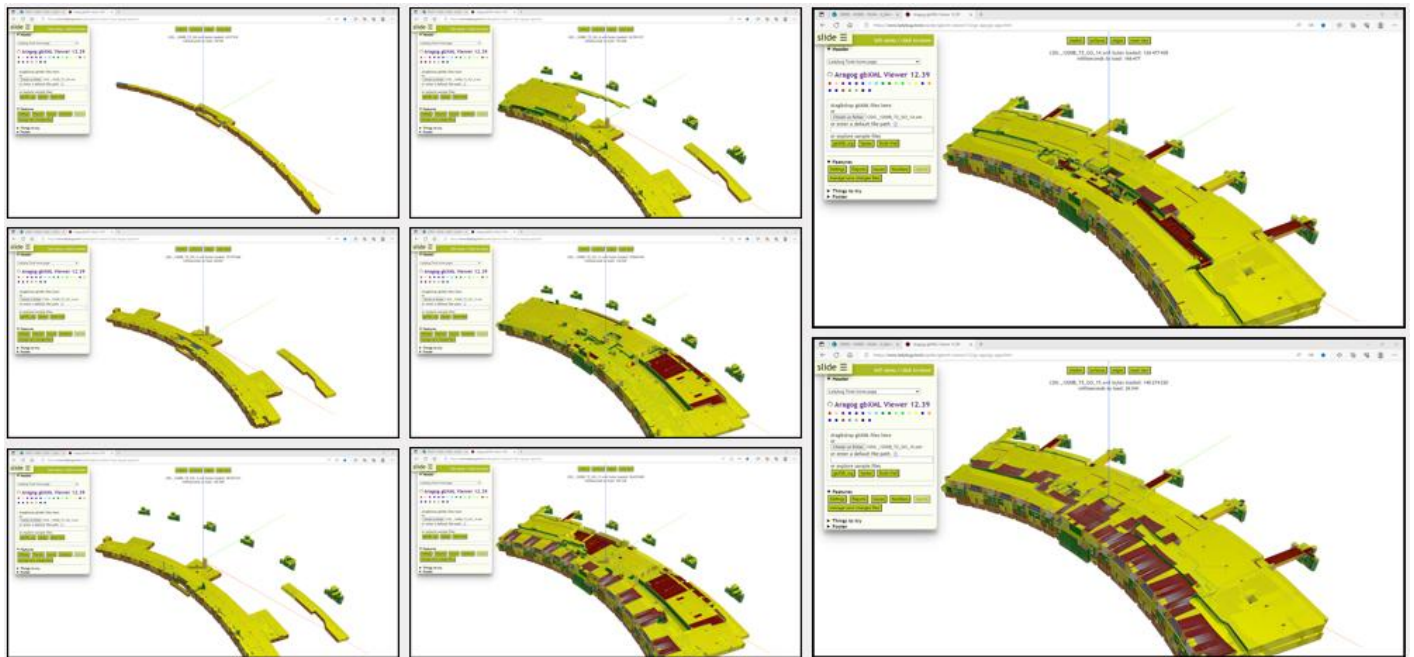


Figure 23: Evolution of digital model export into gbXML

3.2.4 Importing and adapting a gbXML model in Pleiades

❖ Level choice

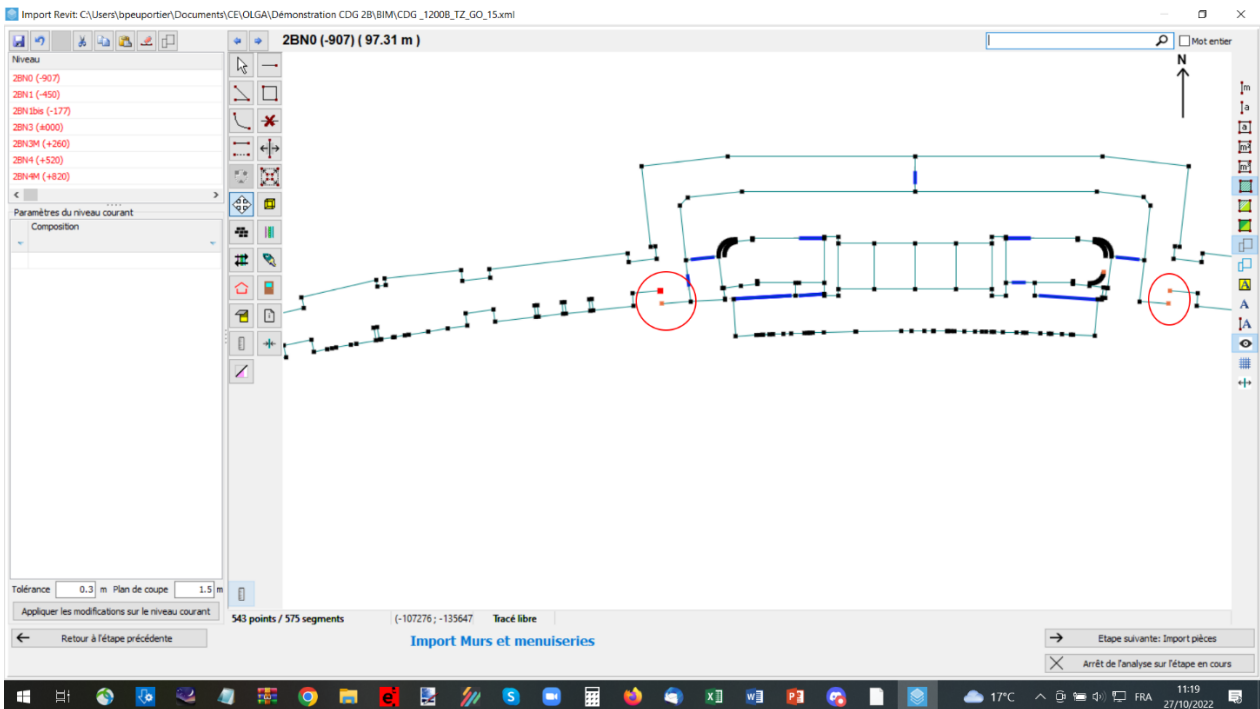
Relevant levels have first to be selected, choosing altitudes corresponding to floors and not to beams.



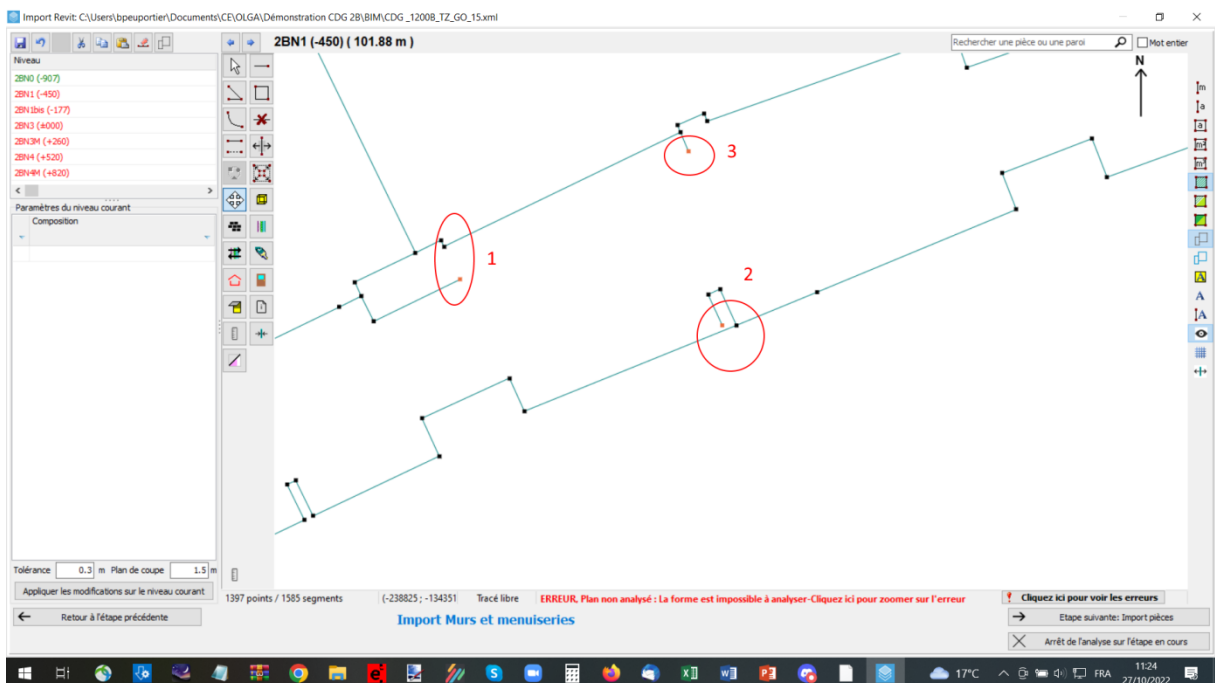
	Level	Altimetry (m)
<input type="checkbox"/>	Niveau depuis dalle 11	95.310
<input checked="" type="checkbox"/>	2BN0 (-907)	97.310
<input type="checkbox"/>	Niveau depuis dalle 1	98.310
<input type="checkbox"/>	Niveau depuis dalle 2	100.880
<input checked="" type="checkbox"/>	2BN1 (-450)	101.880
<input type="checkbox"/>	Niveau depuis dalle 5	103.550
<input type="checkbox"/>	Niveau depuis dalle 4	104.080
<input checked="" type="checkbox"/>	2BN1bis (-177)	104.660
<input type="checkbox"/>	Niveau depuis dalle 7	105.671
<input checked="" type="checkbox"/>	2BN3 (±000)	106.380
<input type="checkbox"/>	Niveau depuis dalle 10	106.880
<input type="checkbox"/>	Niveau depuis dalle 3	107.780
<input checked="" type="checkbox"/>	2BN3M (+260)	108.980
<input type="checkbox"/>	Niveau depuis dalle 6	110.130
<input type="checkbox"/>	Niveau depuis dalle 8	110.880
<input checked="" type="checkbox"/>	2BN4 (+520)	111.580
<input checked="" type="checkbox"/>	2BN4M (+820)	114.580
<input type="checkbox"/>	Niveau depuis dalle 9	116.900

❖ Plan modification

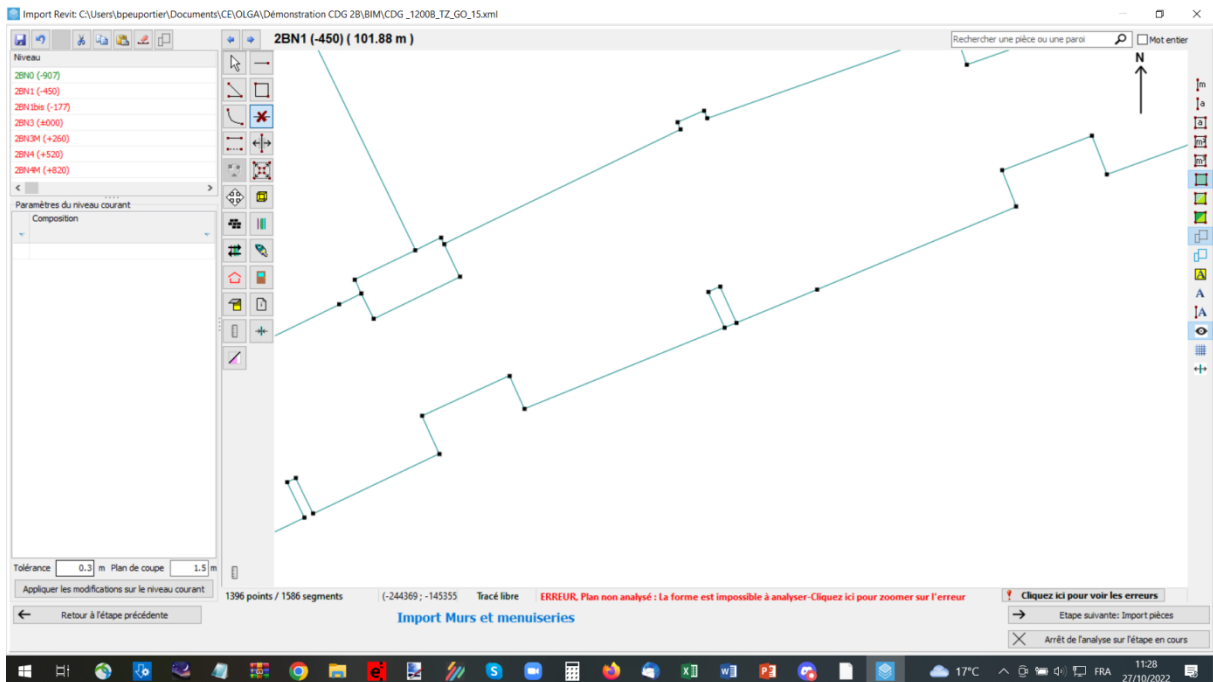
Some walls are missing, which create isolated points and errors, as shown in the figure below. Lines are therefore added in order to close the corresponding spaces.



Situation 1 in the figure below, a line is added; Situation 2, the point in red is moved to close the space; Situation 3, the point in red is suppressed.



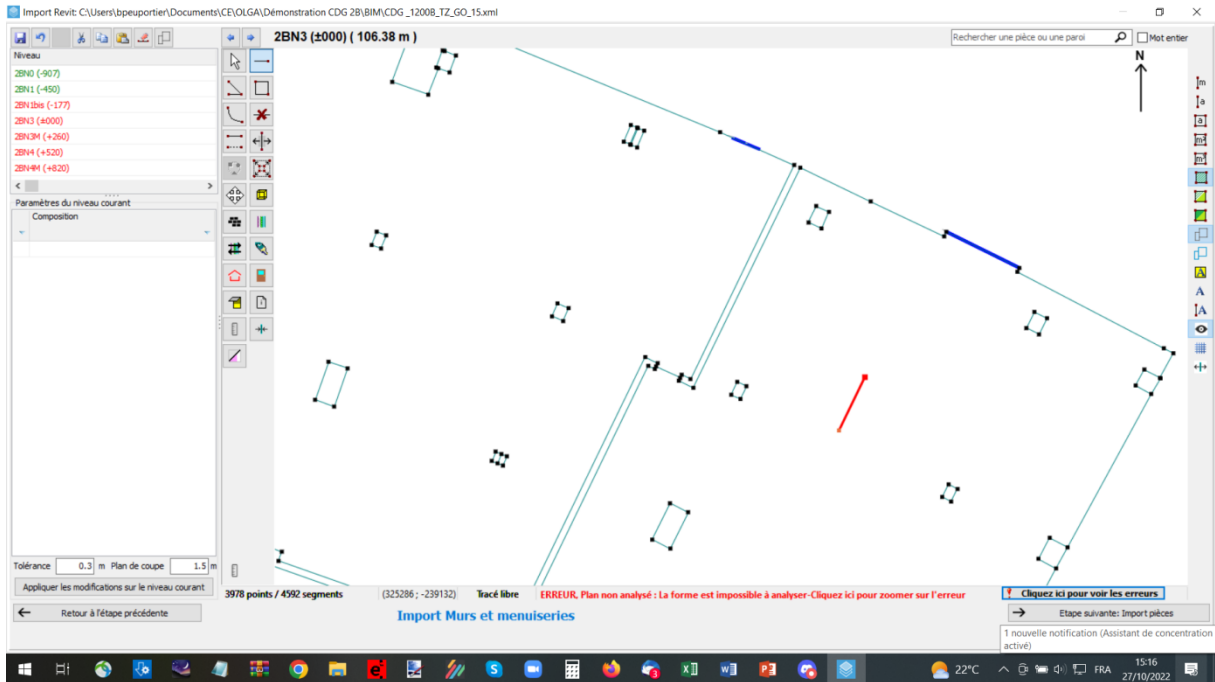
The result is shown below.



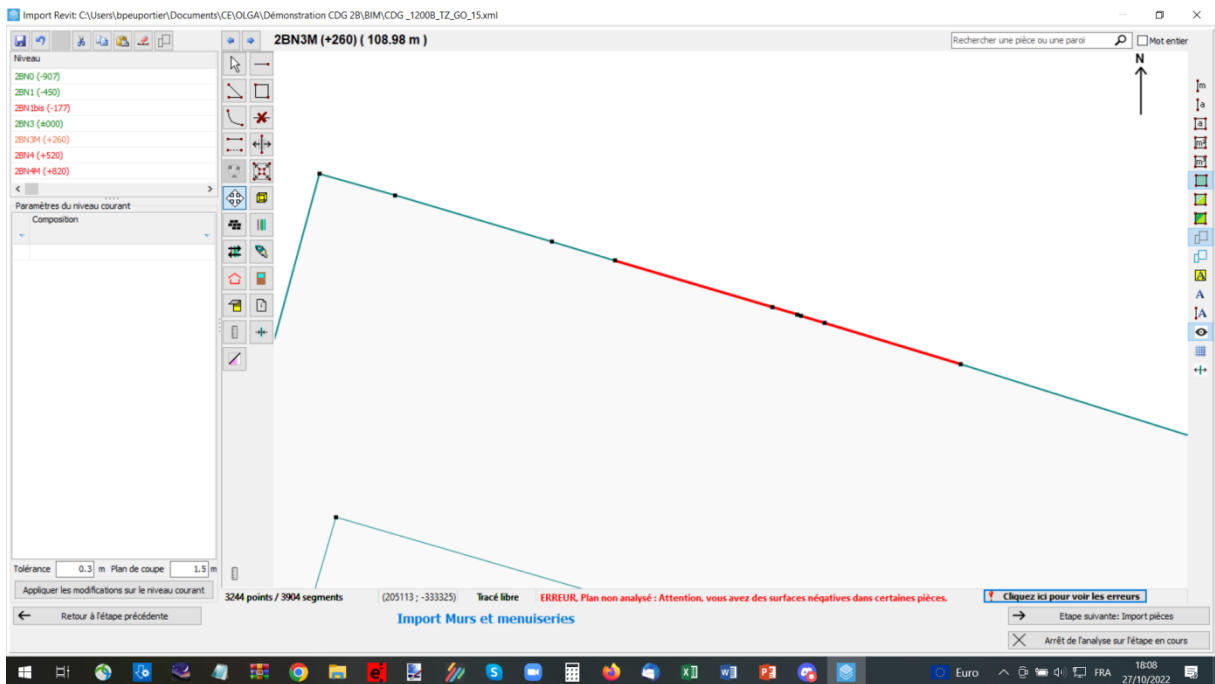
The import of curved walls generates extra walls which form triangles and which must be removed.

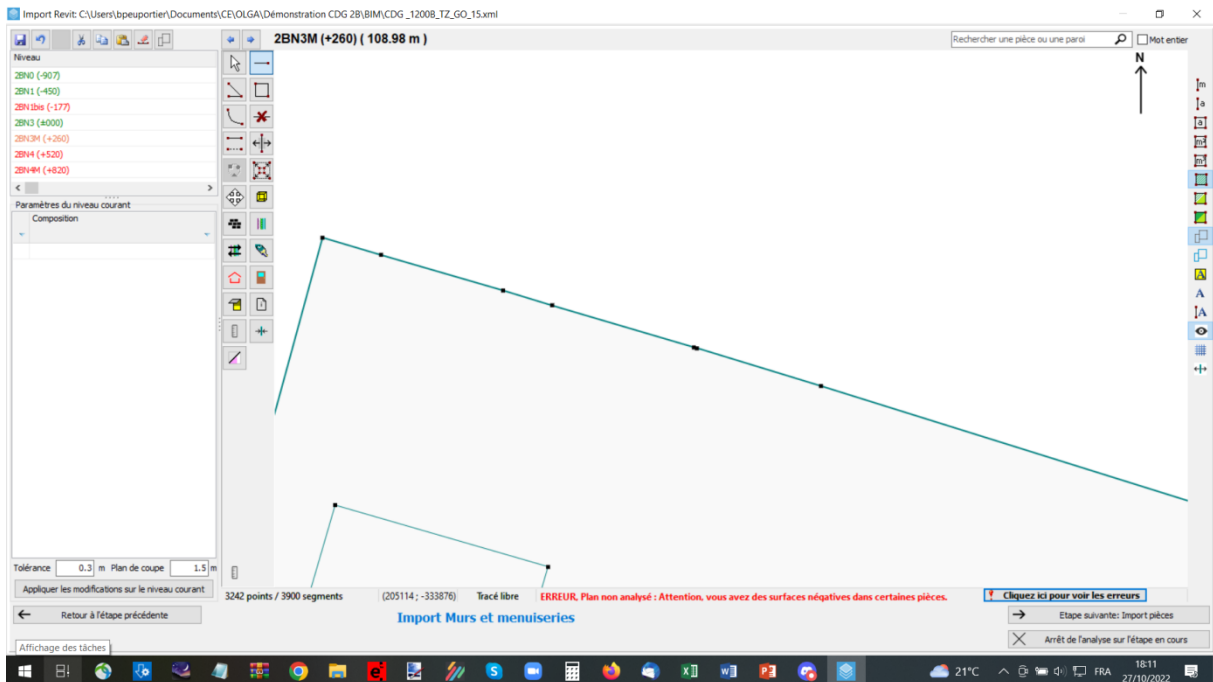


The extra walls are suppressed, as well as some internal walls like hereunder.

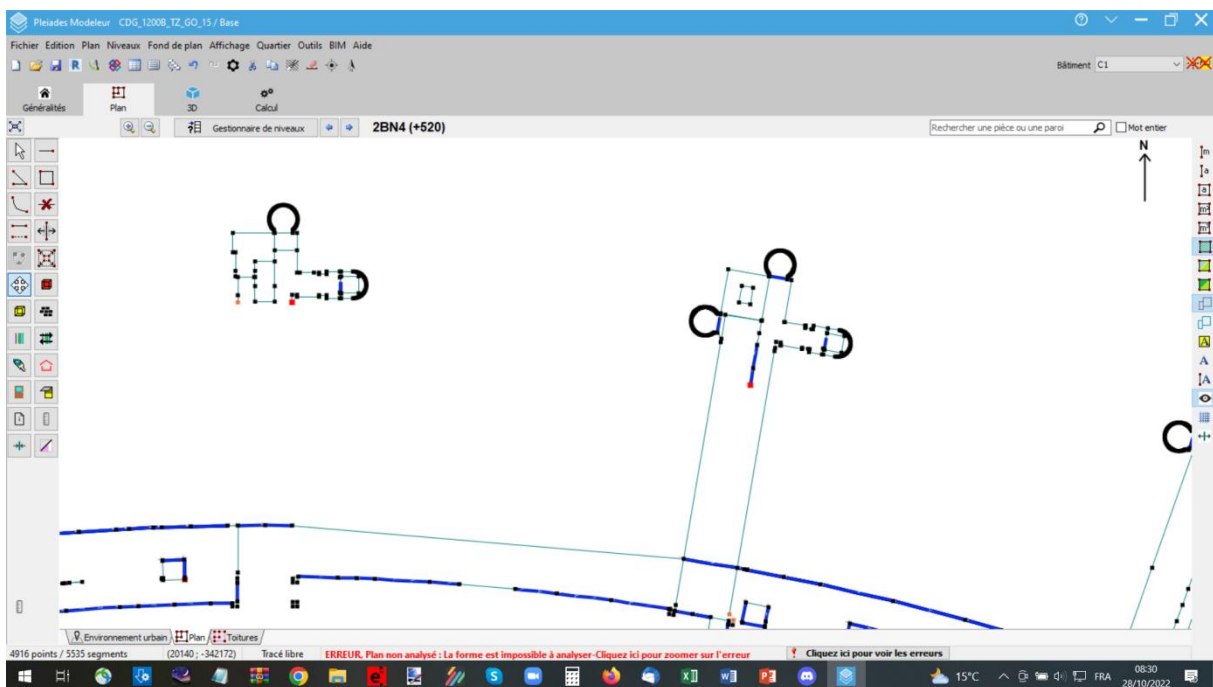


Some extra points in a wall have also to be suppressed.

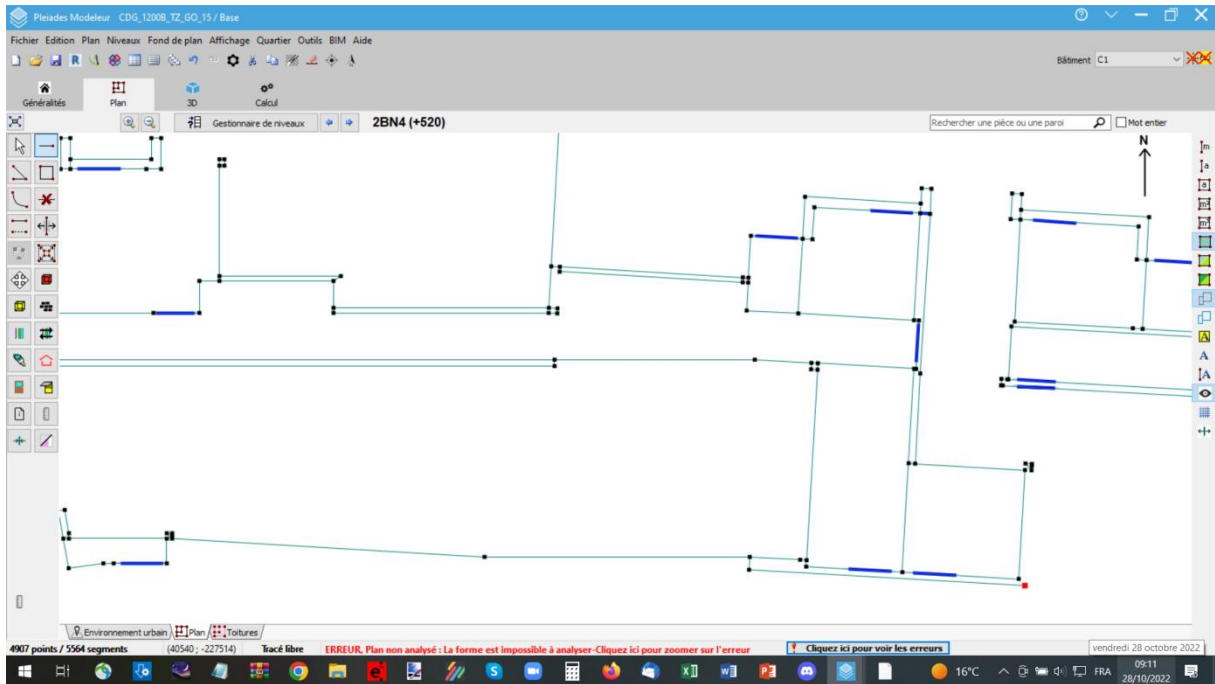




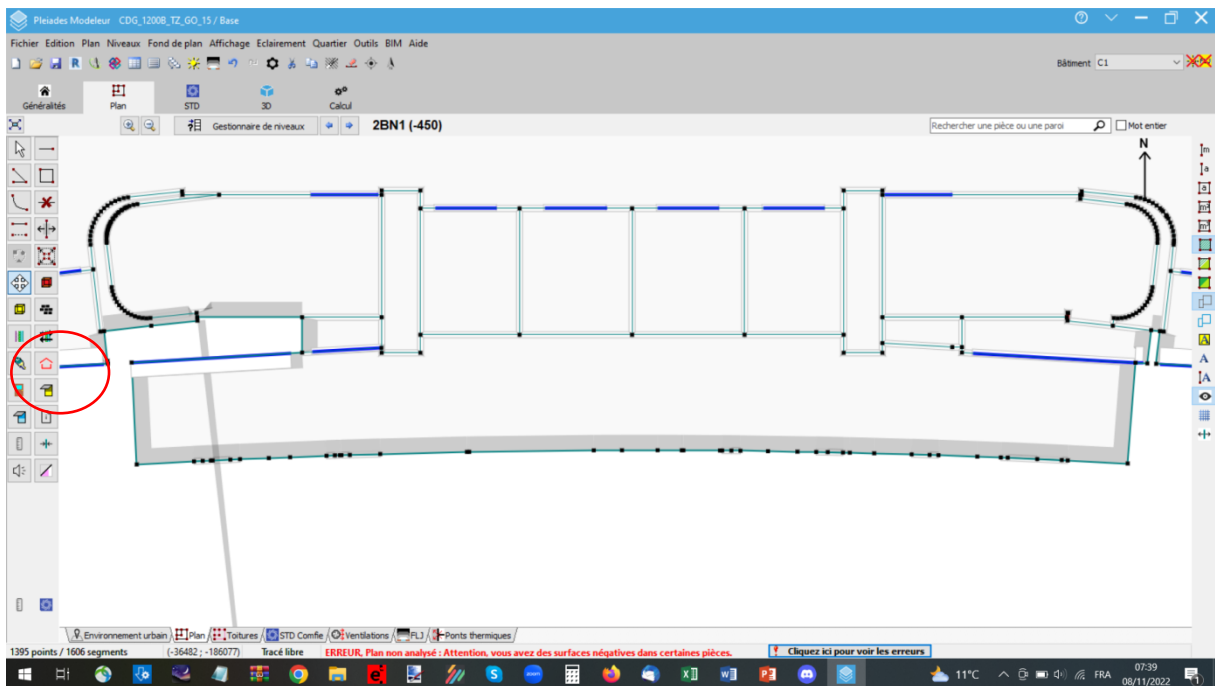
The BIM of the gangways is sometimes incomplete. Supplementary walls are added by copying complete parts.

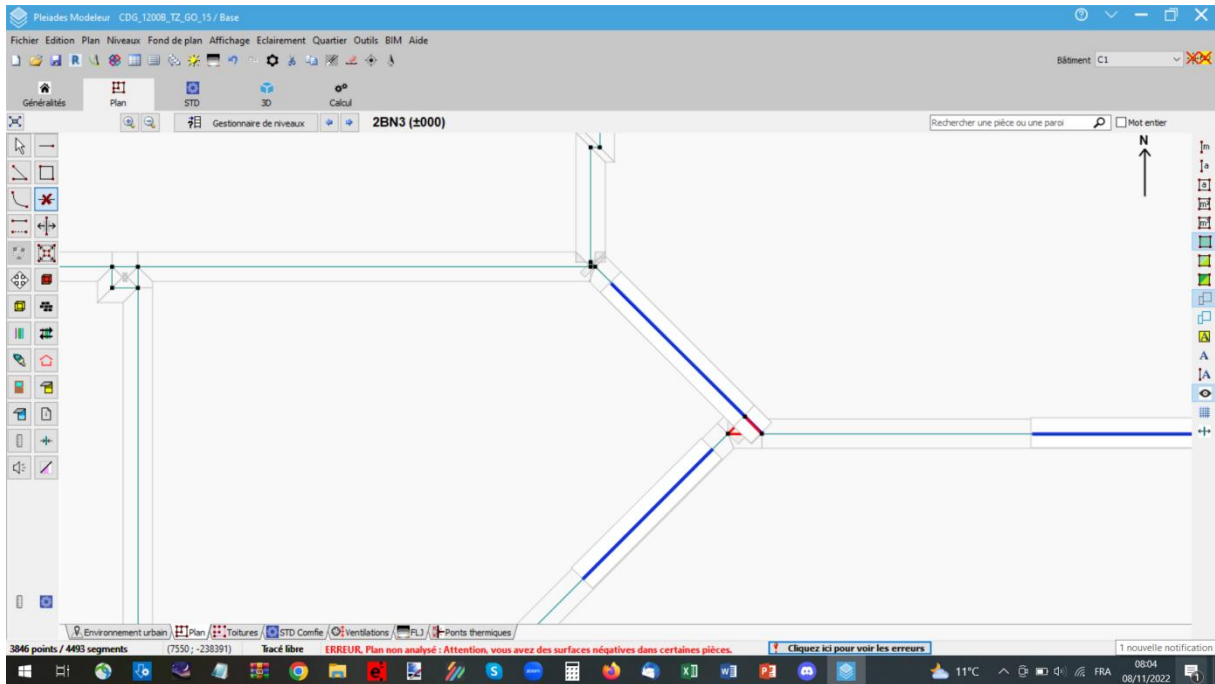


Some double walls have to be suppressed.



Some parts remain strange, e.g.

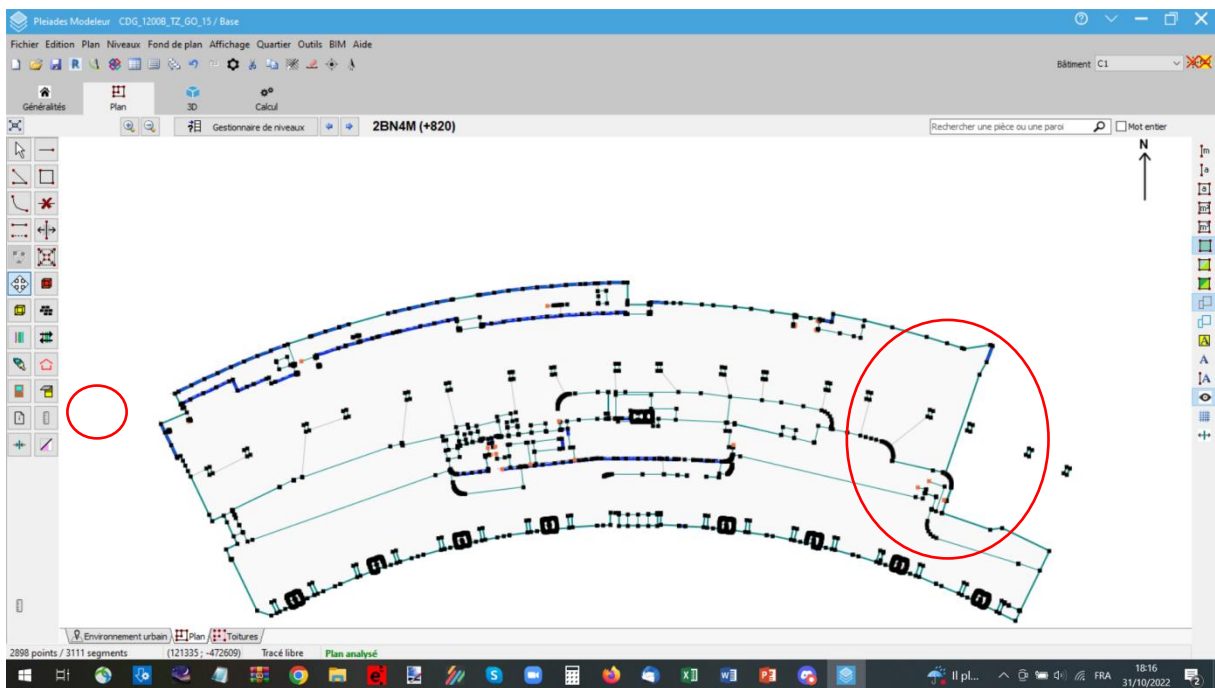
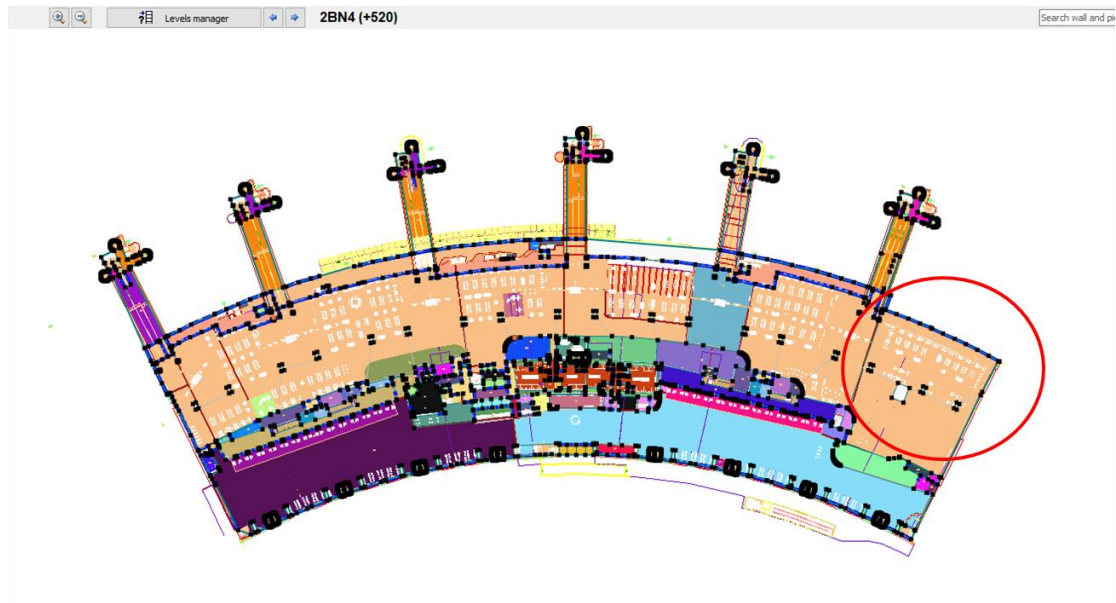




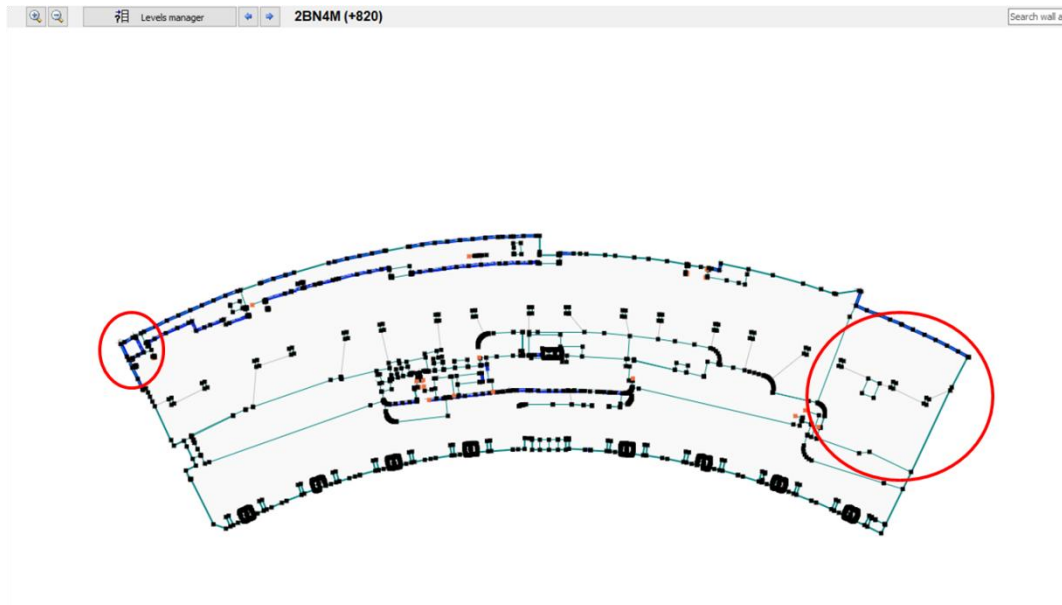
❖ Missing areas



A part of the terminal is lacking on level 4. It should be added from level 3M. After improvements, the plan of 4M is shown in the figure below.

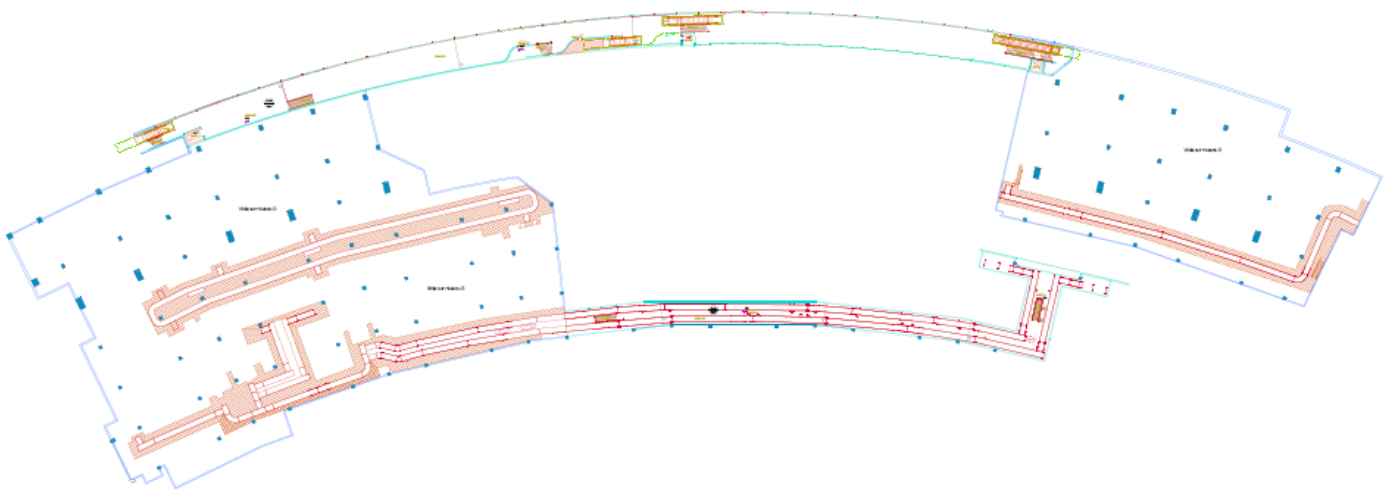


Parts of the terminal are lacking on level 4M. They should be added from level 3M and 4. After improvements, the plan of 4M is shown in the figure below.

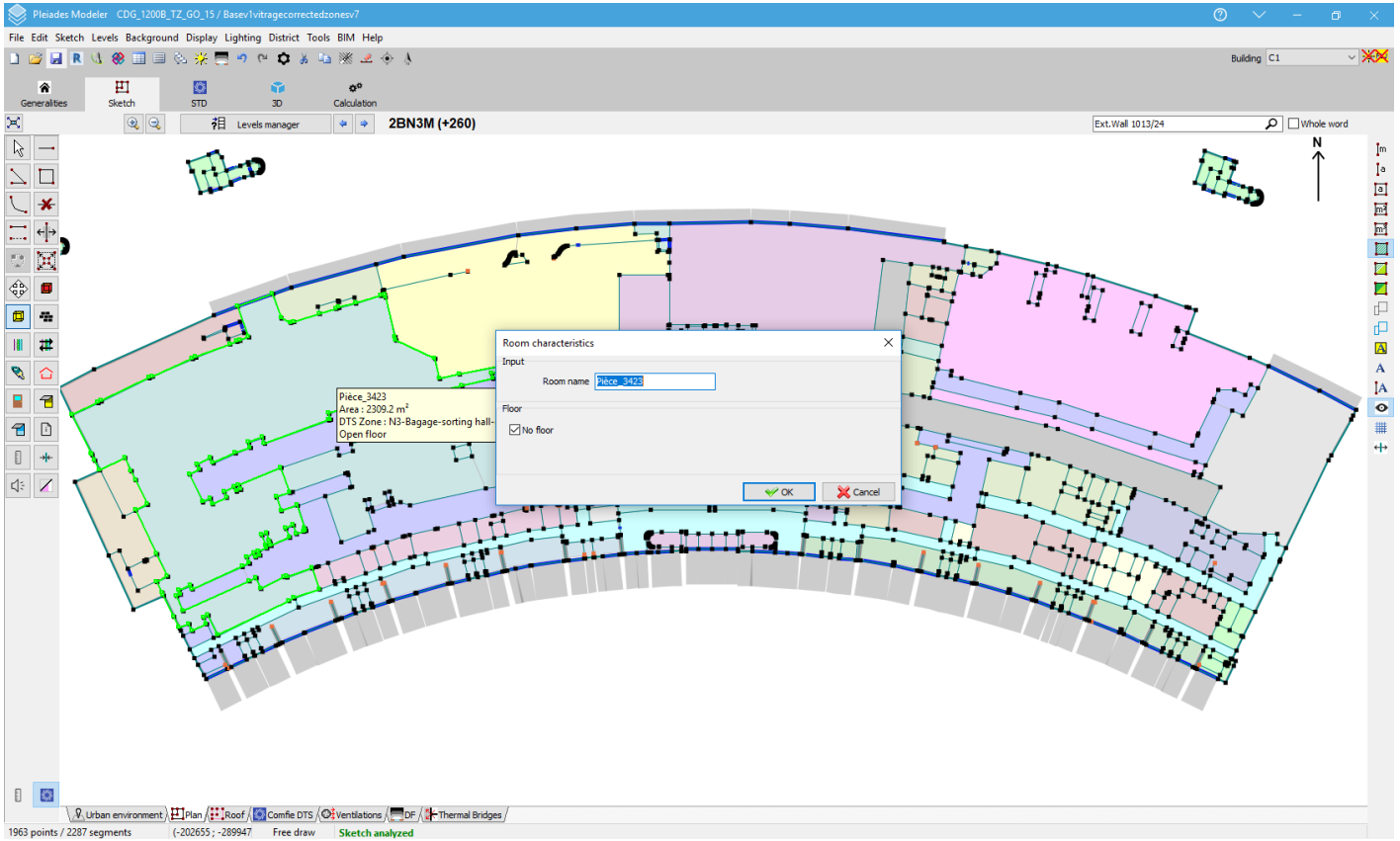


❖ Floors of mezzanine levels

1bis, 3M and 4M levels contain only some mezzanines, and the rest of these areas is empty. However when the model is imported in Pleiades STD, their floors are set as covering the full area. Therefore it is necessary to refer to the plans (e.g. CAD files, see figure below) to identify which part of the floors do not exist and set them as open state in the software.

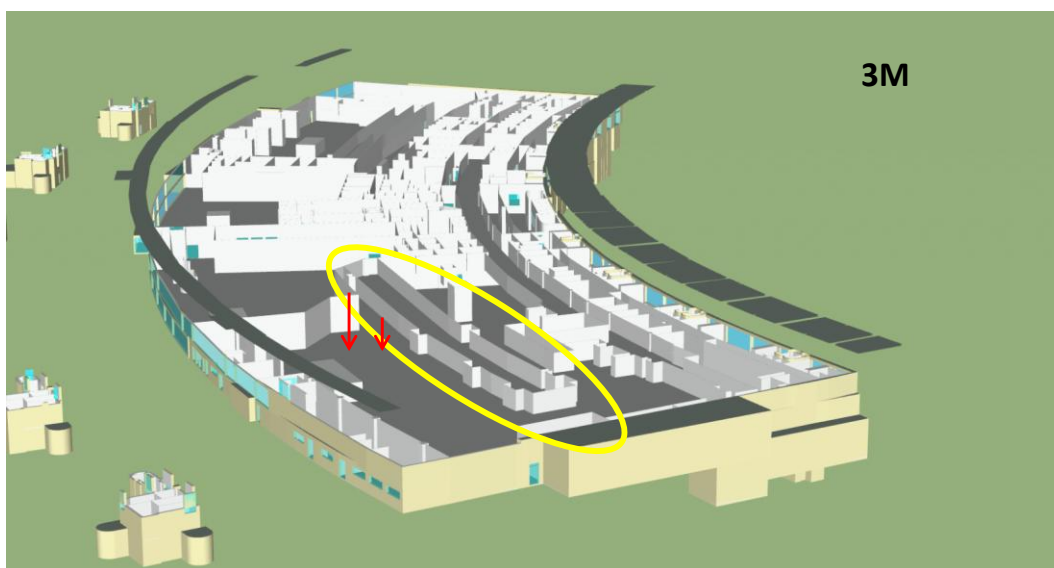


CAD map of mezzanine level N3M



Setting open state of a floor in Pleiades

The result is the following. One part of the mezzanine N3M is shown in the yellow circle. It can be seen that the height of the floor of mezzanine level to the floor N3 (the short red arrow) is half of that where there is no mezzanine (the long red arrow).

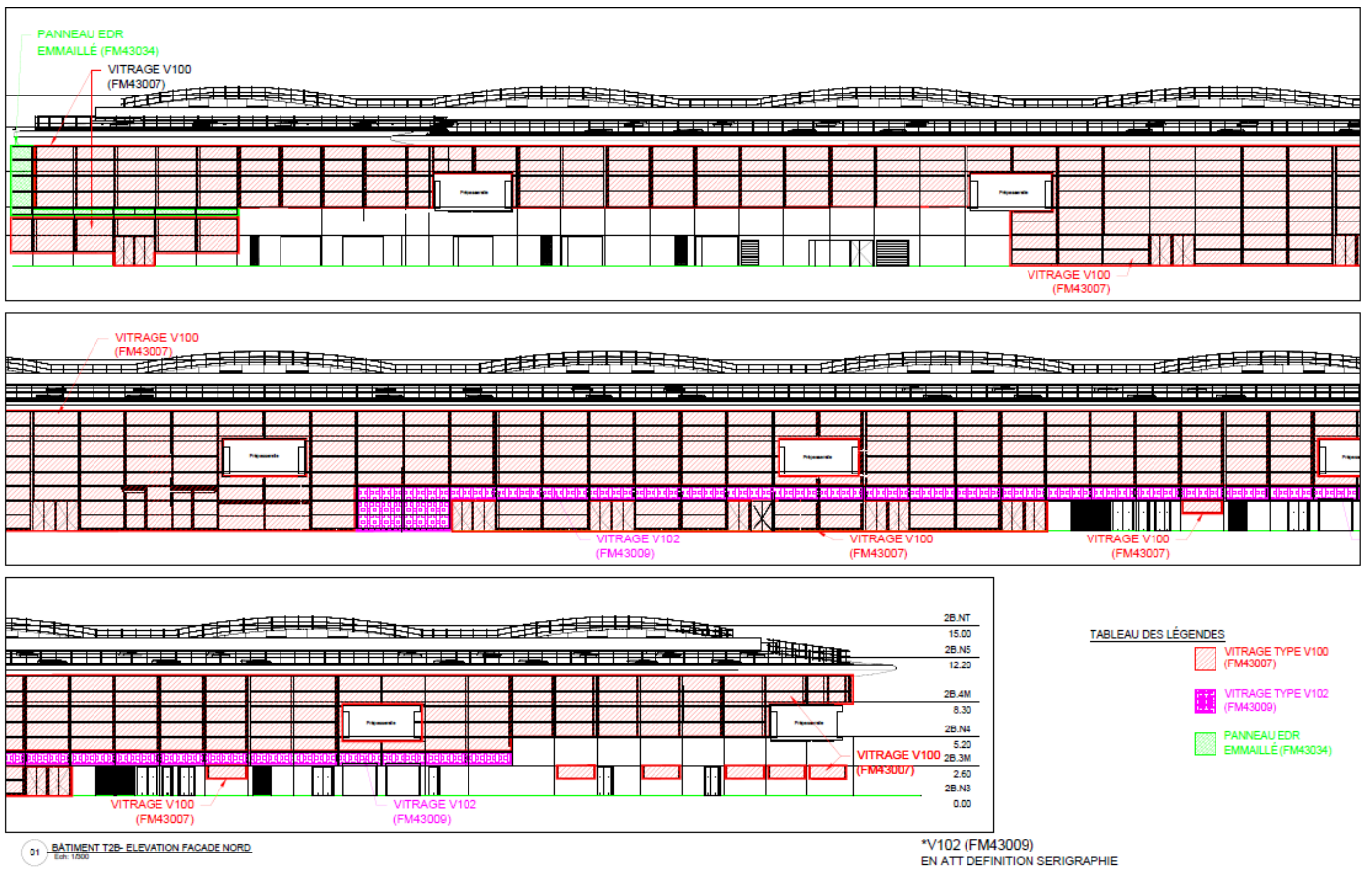




View of mezzanine level N3M

❖ Glazing area problem

The first observation is that we found that the imported windows are often not correct. For example, the size and position of the windows are not reasonable and the windows of the gangways are missing. The windows are improved by comparing to the façade glazing design map. The glazing design map of façade north is shown below.



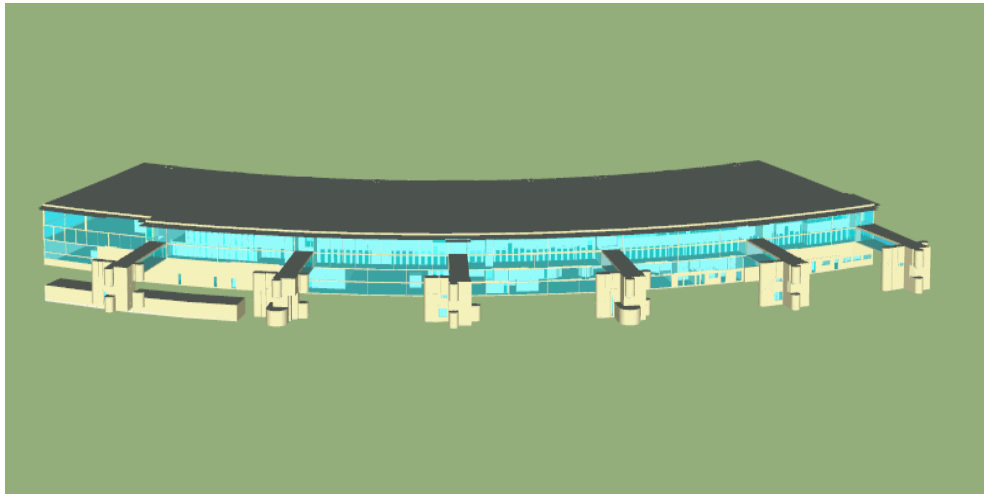
MOA : CDG: Frank GOLDNADEL
 MOD : DIAP: Vicente SAPENA MUÑOZ
 MOE : diam: Julien GICQUEL
 Emis par : Ana ENRIQUEZ

AEROPORT ROISSY CDG
 CARNET DÉTAIL FAÇADES
 Repérage Vitrages, Façade Nord

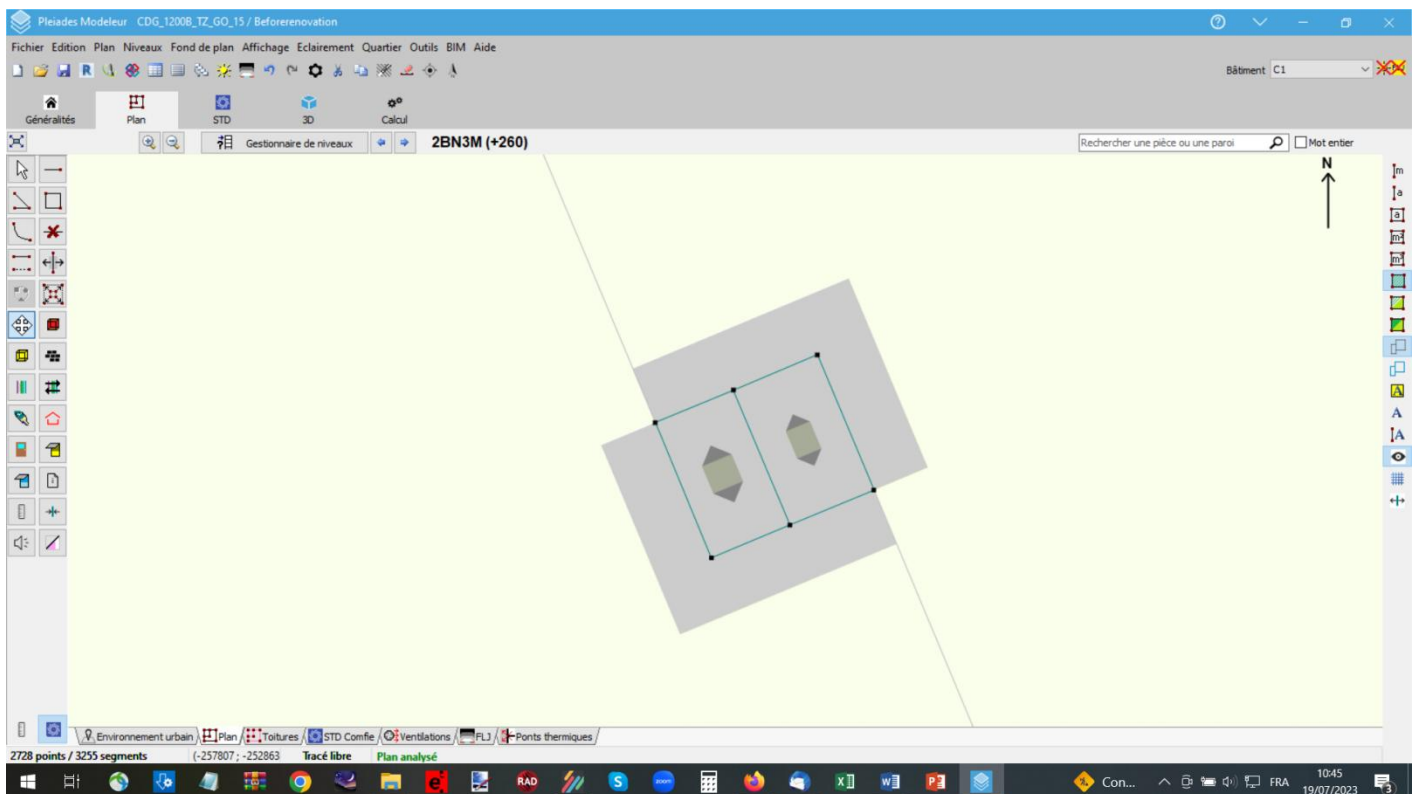
158019	S	FAC	-	41083	01
N° Affaire	Disc	Spéc	Proc	N° Carnet	Folio
1/300	A3	REC	20/01/2020	F	F
Finale	Format	Divise	Date	Etat	Incl. Print

Glazing design of façade north

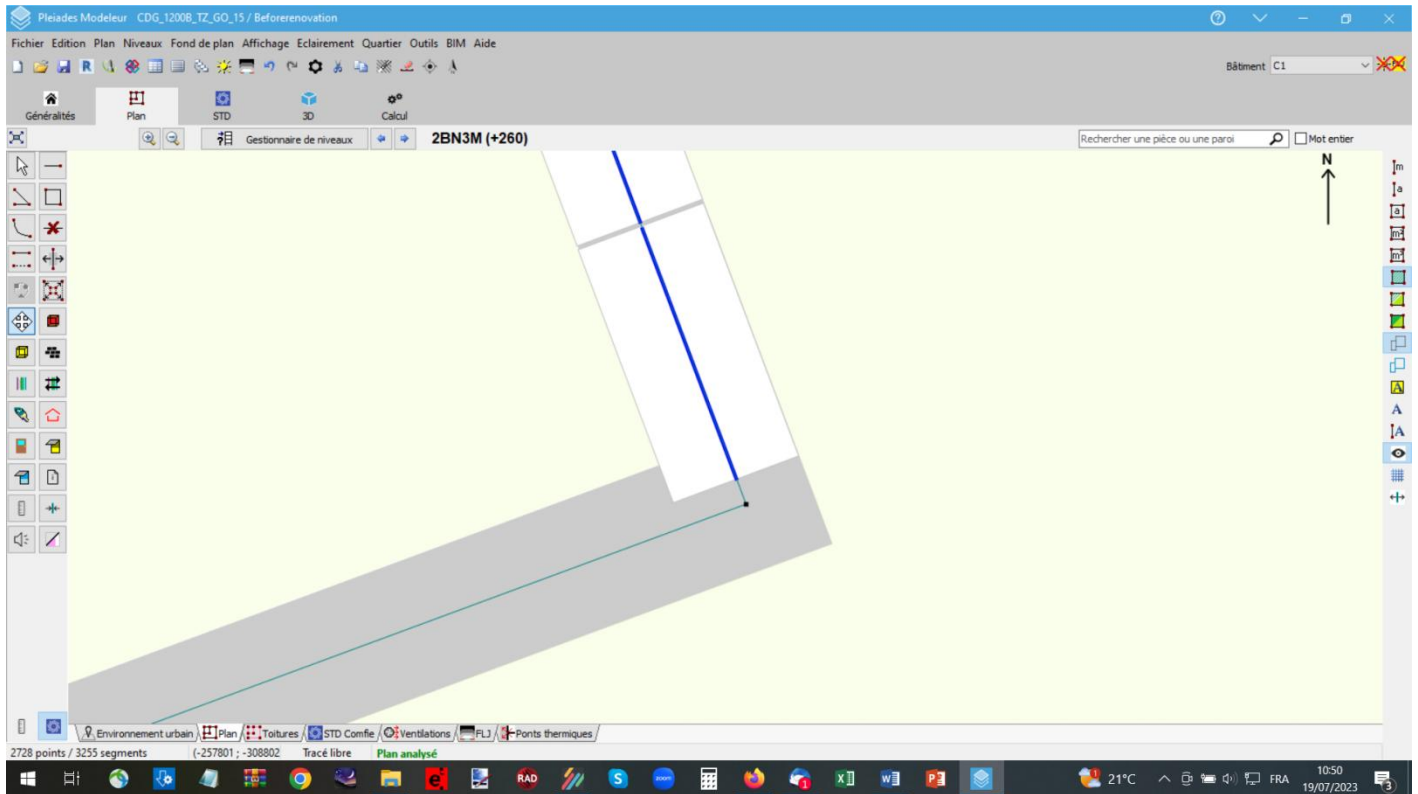
The north façade of the model after improving is shown below:



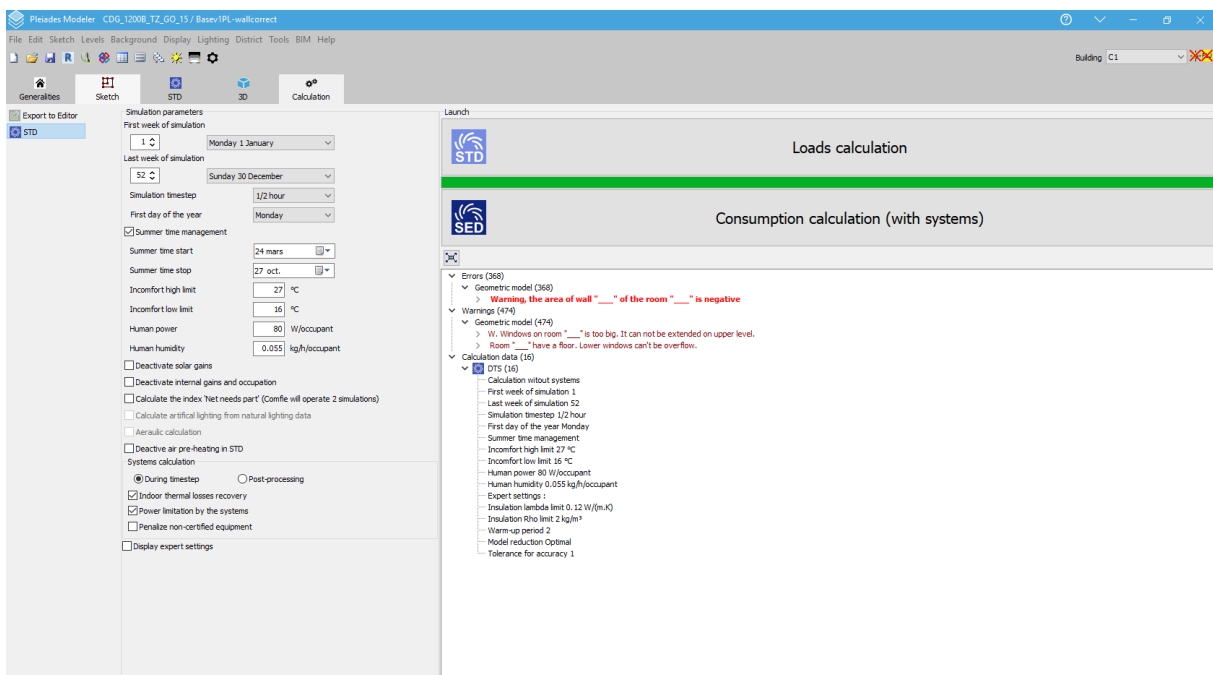
The second observation is that when the compositions of walls are set in the software, many errors occur such as “the area of wall XXX of the room XXX is negative” (see figure below). This occurs when the wall thickness is too large compared to the size of the room (see below).



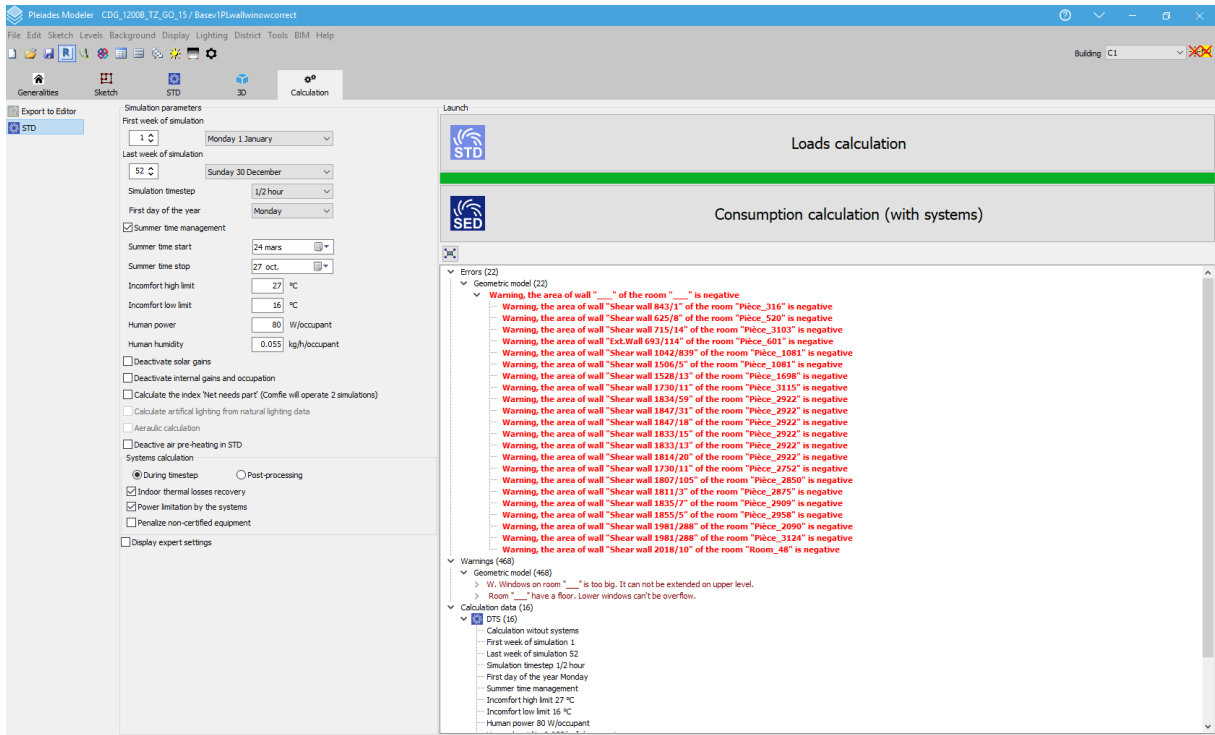
A similar problem occurs if there is a window or a door in the wall, which covers a part of the wall thickness (see below).



The software developer provided a patched version to solve this problem: we can use a button to automatically change windows size. The number of errors decreases from 368 to 22. Then it is possible to solve the remaining problems one by one.

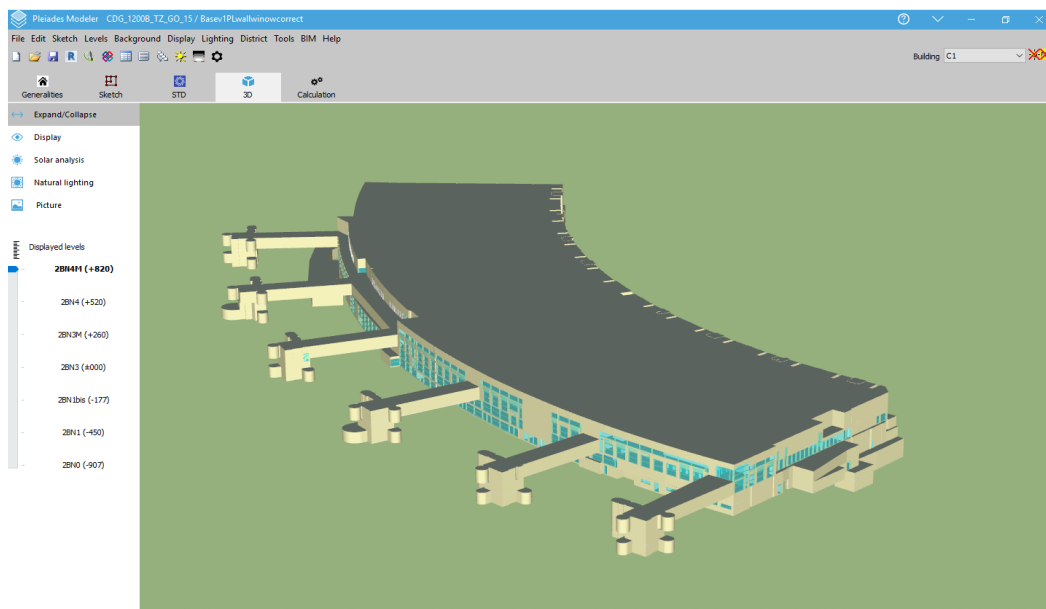


Before using the automatic resizing function

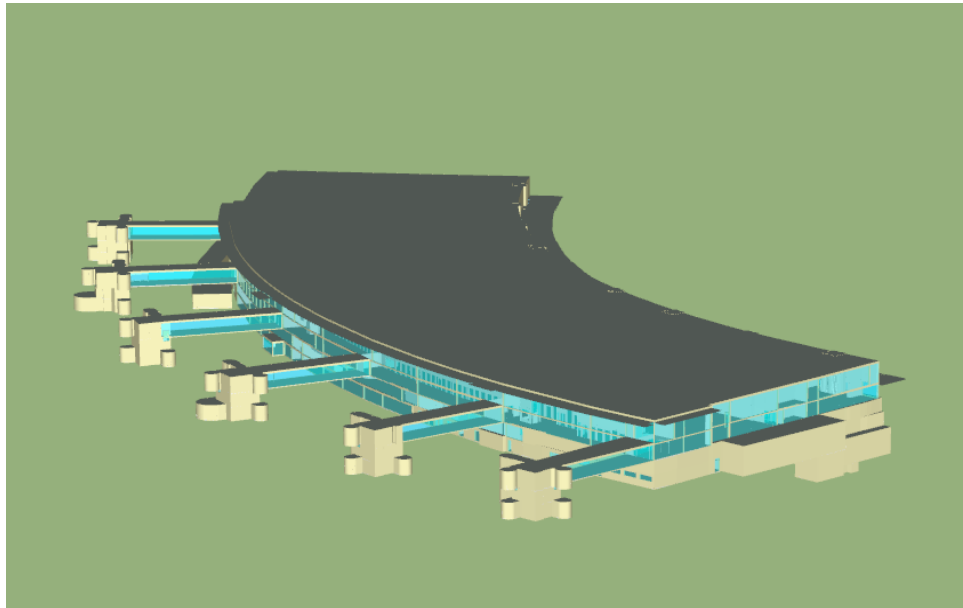


After using the automatic resizing function

The glazings before and after improvements are shown in the following figures.



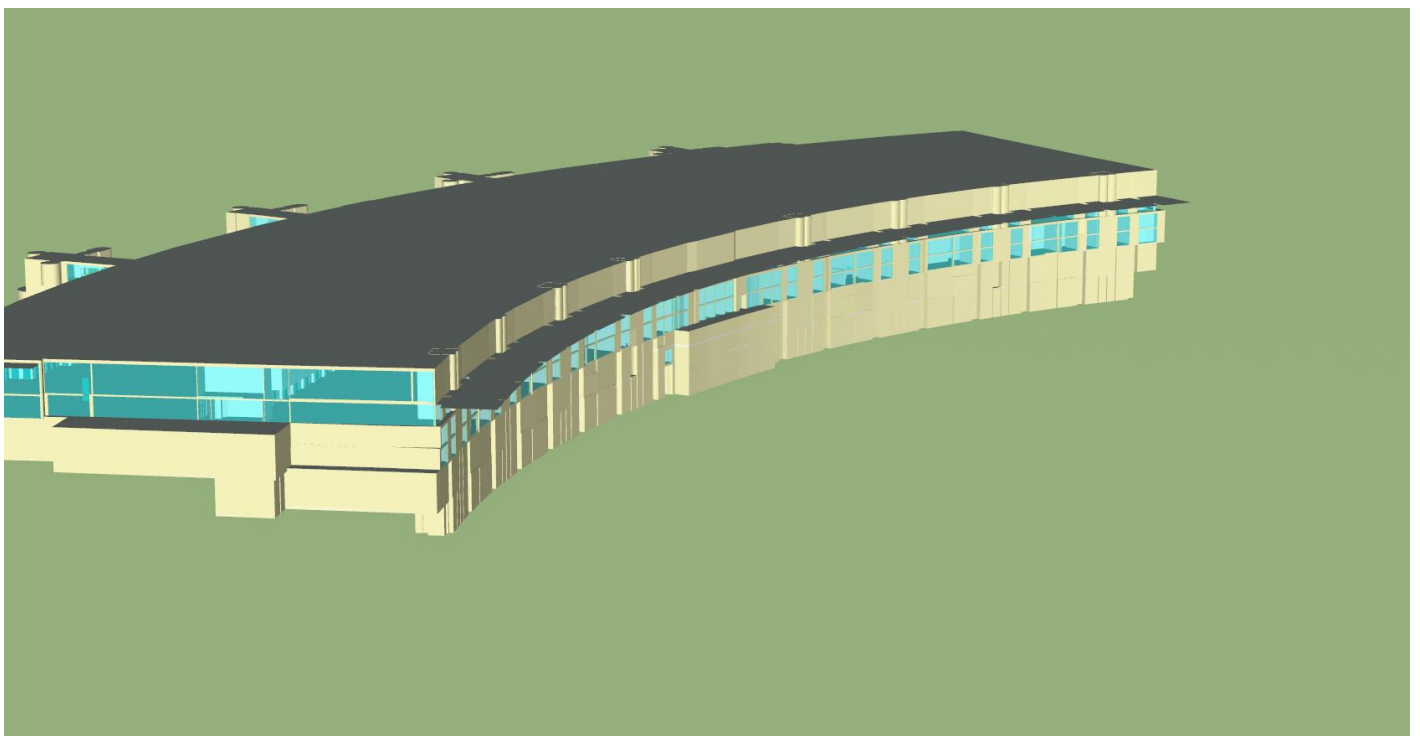
Glazings before improvements



Glazings after improvements

❖ Integrated shadings

There are integrated shadings for the glazings on the north, south and west façades. Their depths are measured to the top of the highest glazings: south: 7.5 m; west (previous 16m to north): 2.6m and north: 2.8m. An example of the integrated shading on the south façade is shown in the figure below.





Integrated shading on the south façade

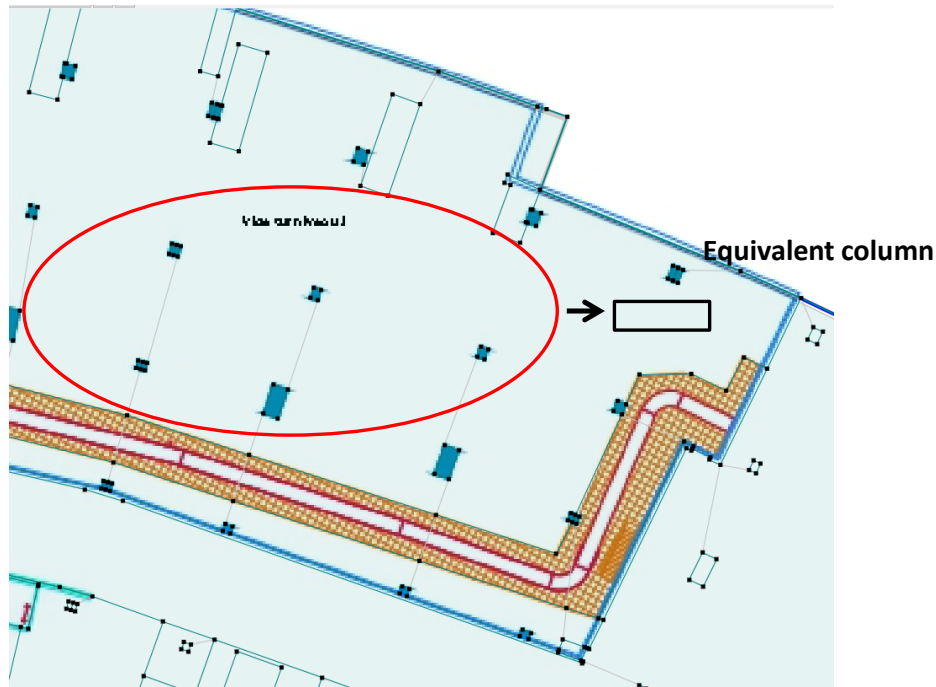
This information is integrated in the Pleiades model for each glazed façade. It should be noted that for the glazings of each level, the integrated shading information should be redefined because the height between the glazing and the shading is different.

❖ Concrete columns modelling

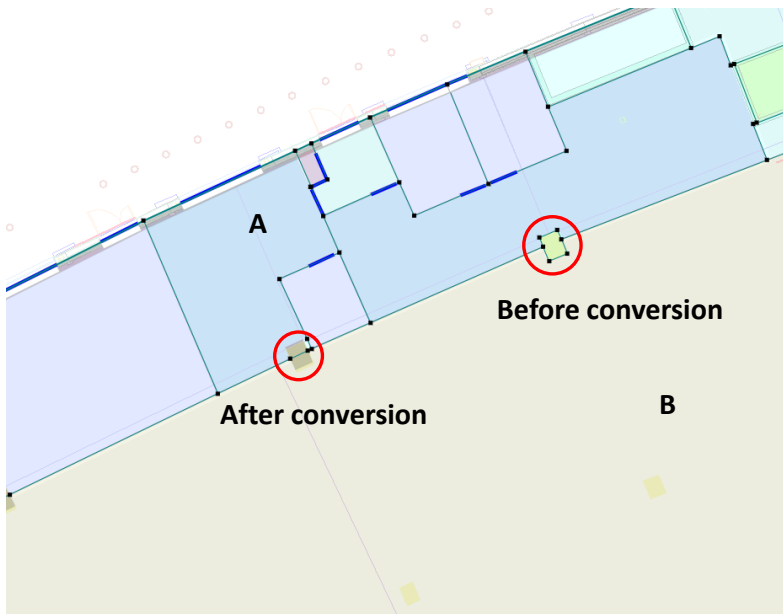
The concrete columns serving as structure elements are normally very large in airports. This brings some thermal mass. However, when the model is imported in CAD, the concrete columns are usually modelled as small rooms and their four vertical walls are given as the internal wall composition. This could not correctly model the concrete's behavior. We propose to improve it in these two situations:

Situation 1: if the columns are totally inside one zone, or one edge is in contact with another zone, we can delete it and sum all surfaces and have an equivalent thermal mass modelled as an internal wall. It should be noted that, in order to also simulate the columns in the mezzanine floor, we should multiply the area by two (if level height is identical for a normal level and a mezzanine level, e.g. N3 and N3M, otherwise multiply by a corresponding scaling factor based on the level height ratio). Once we obtain the area of the equivalent column, e.g. 3m X 1m, we can draw one line of 3m to be the internal wall and set the wall to be a composition of concrete with a thickness of 1m.

An example as shown below: there are four 0.5m×0.5m and one 2m X 1m concrete columns on level N3 in the red circle, which is $0.25*4+2=3m^2$ in total. We can delete them and draw a line of 6m (also considering the mezzanine floor N3M) and set it a composition of concrete with a thickness of 1m to be the equivalent thermal mass (i.e. black box).

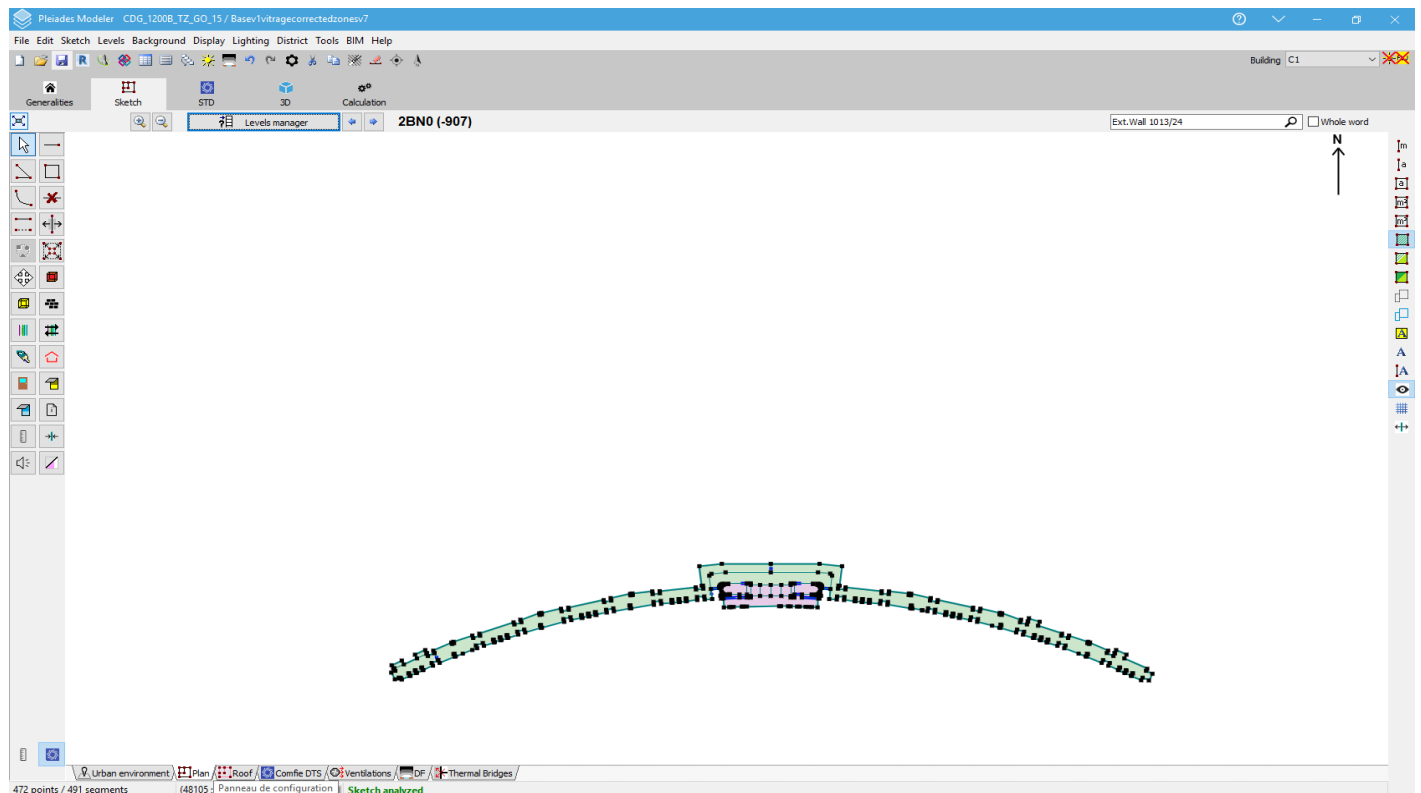


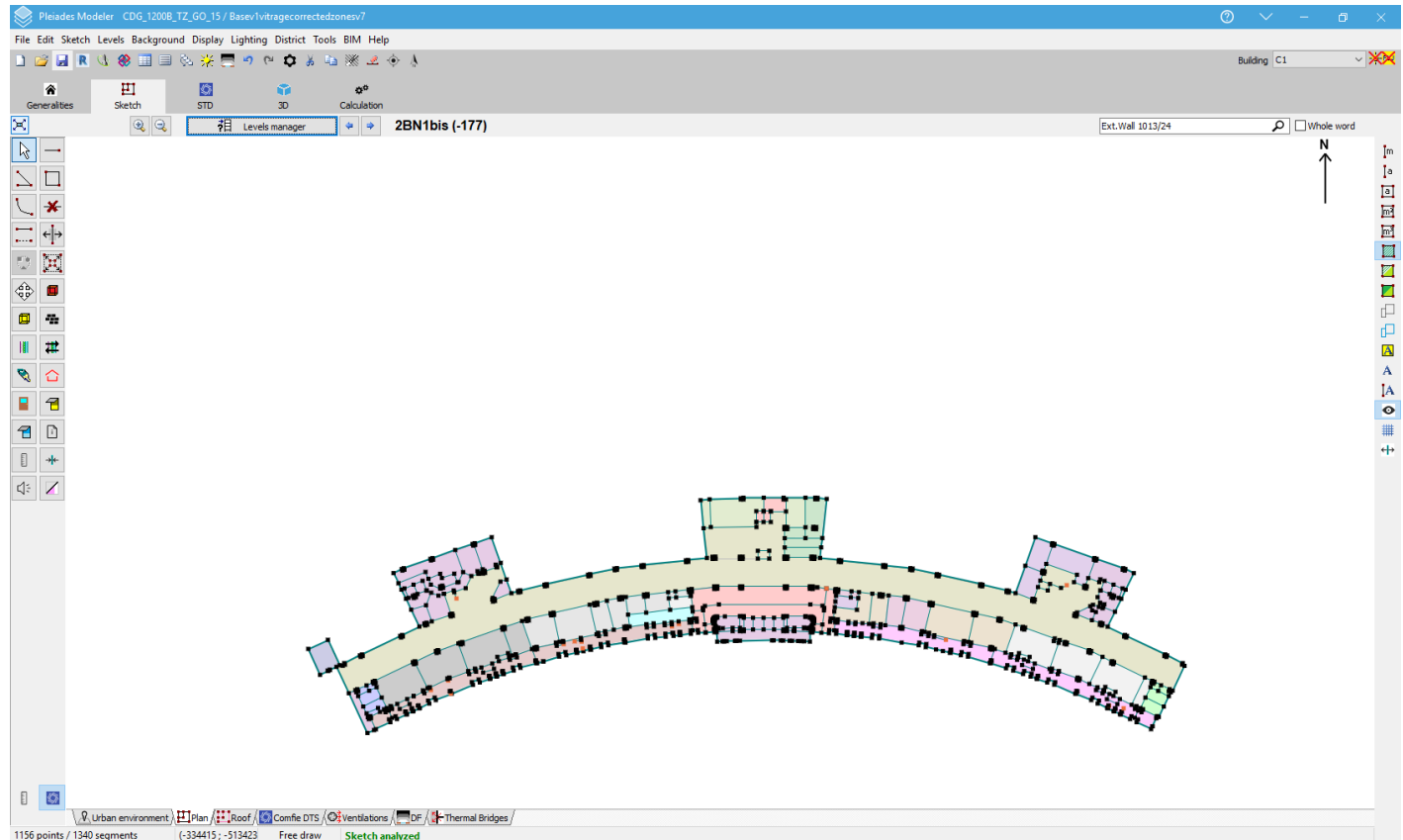
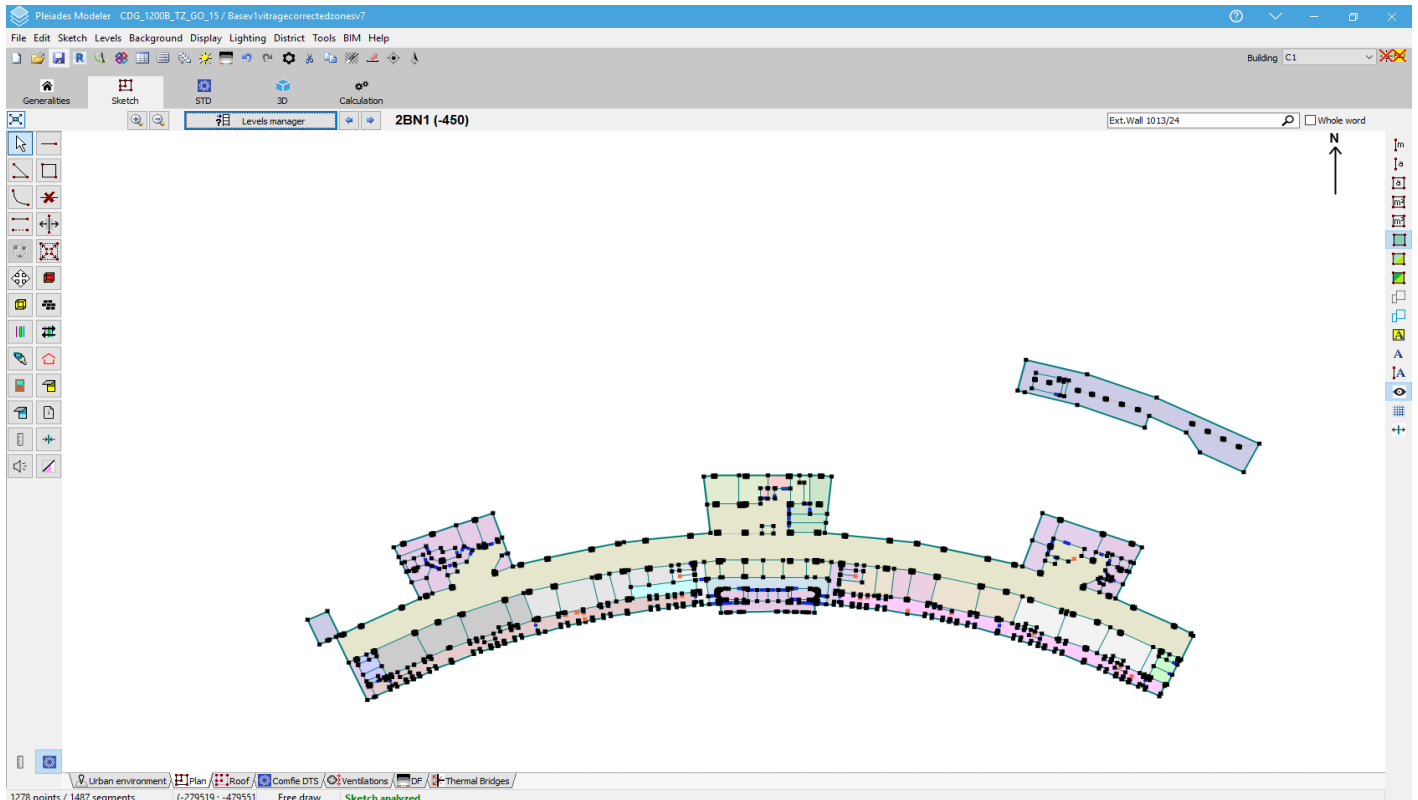
Situation 2: if the column is one part in Zone A and one part in Zone B, we can delete the four walls of the concrete column, and line the two points of the zone. Then we set a composition of concrete with a thickness of previous wall length to this line, as shown in the figure below. It should be noted that this should also be done for the mezzanine floor, because the columns are extended to the mezzanine floor.

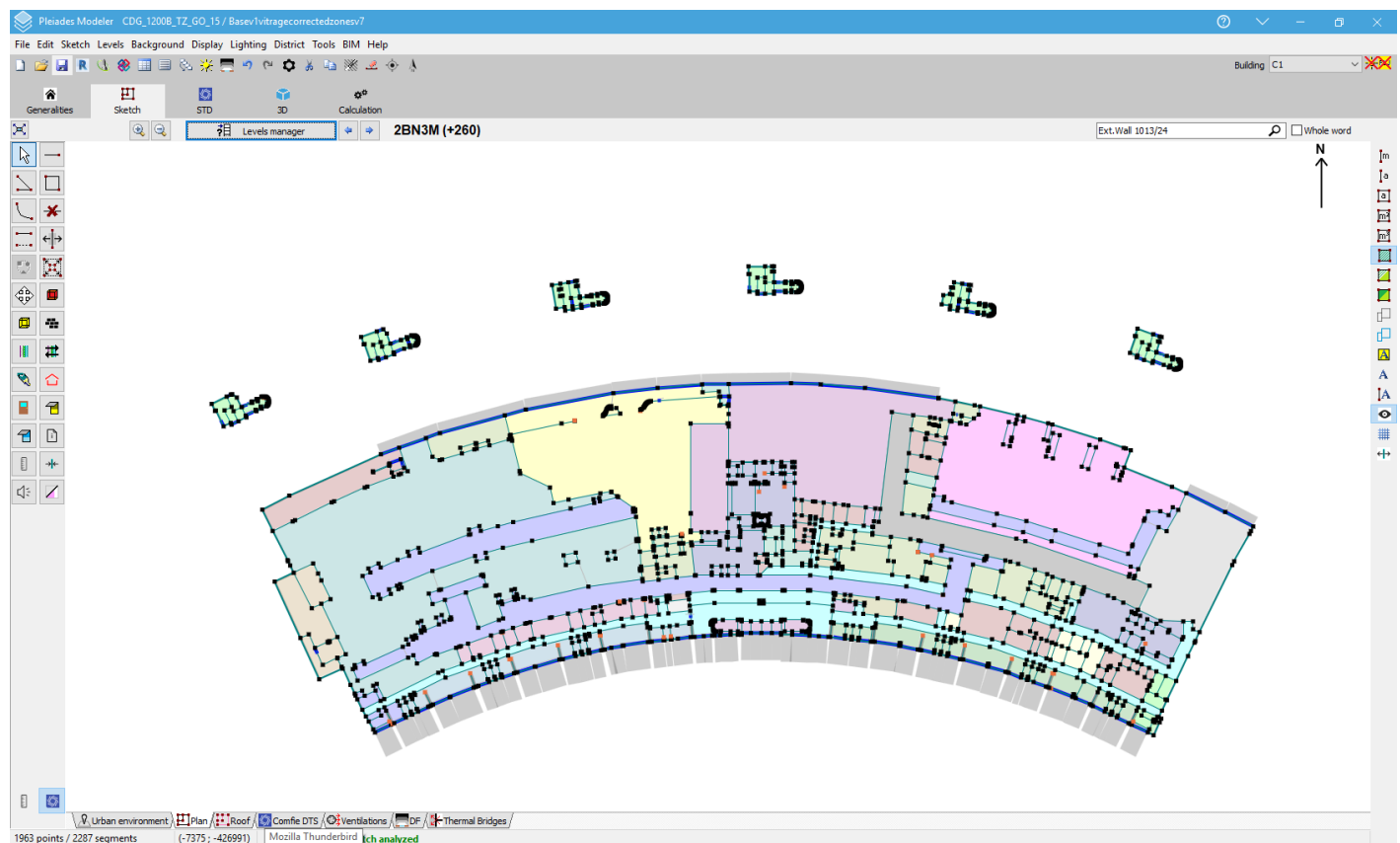
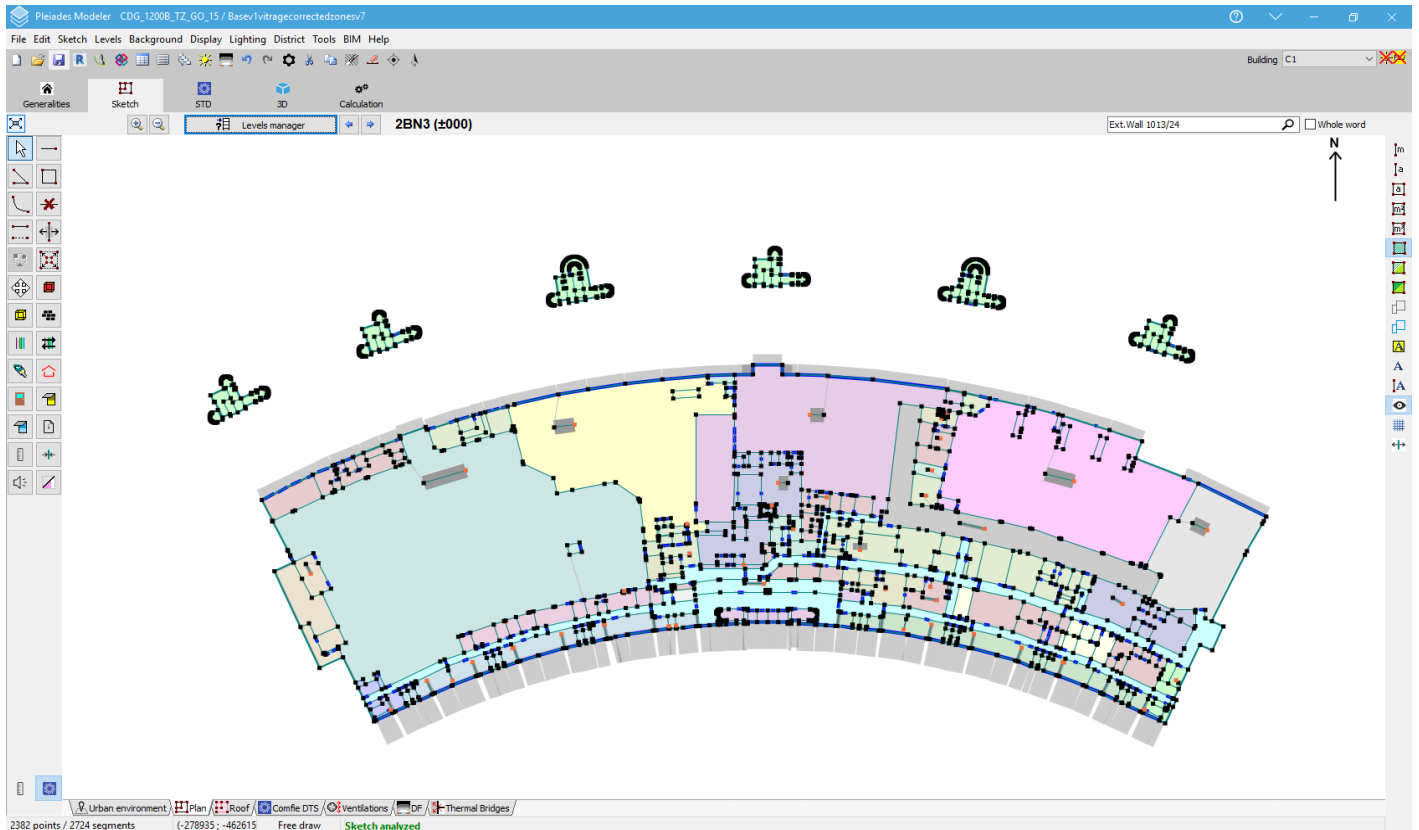


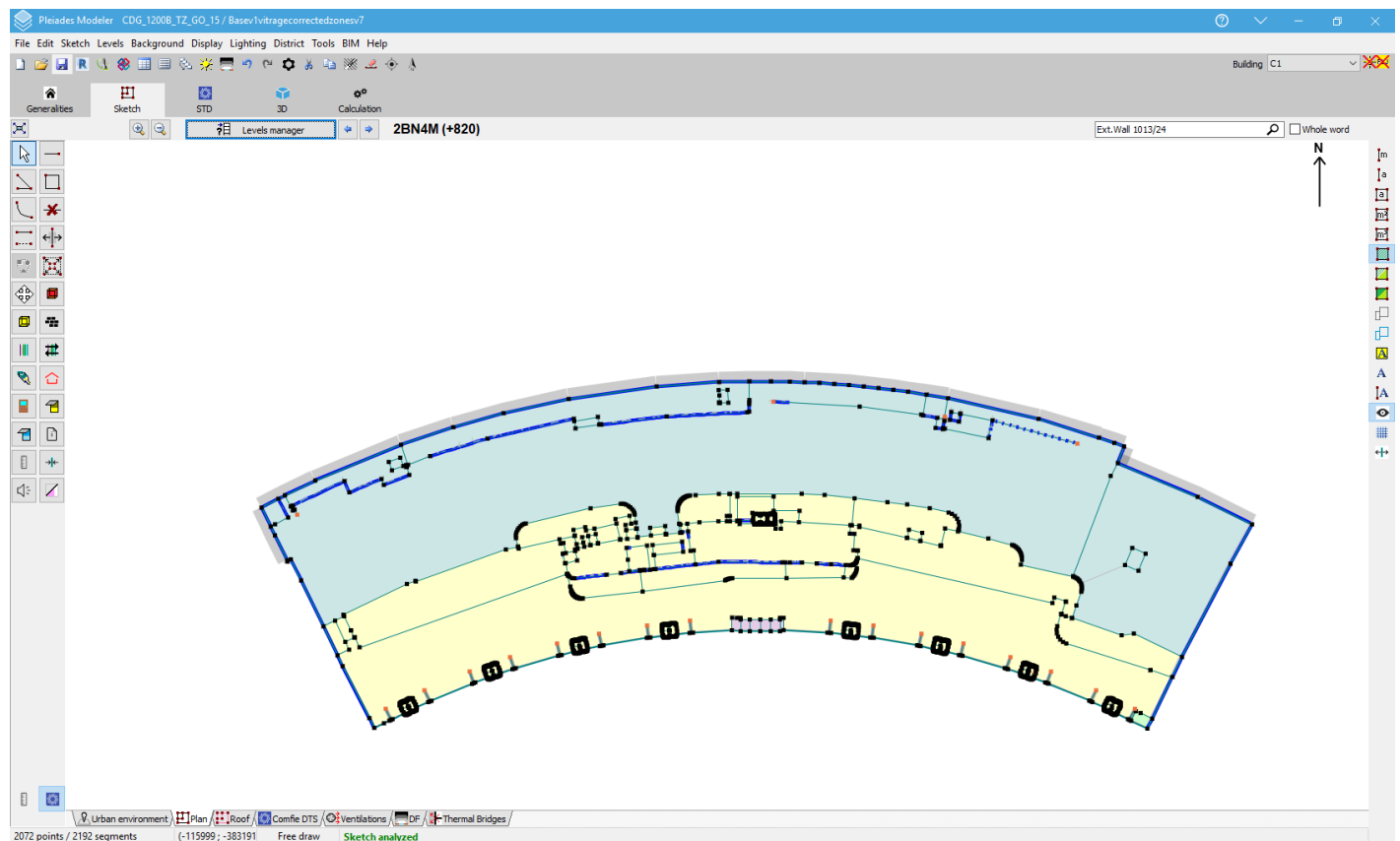
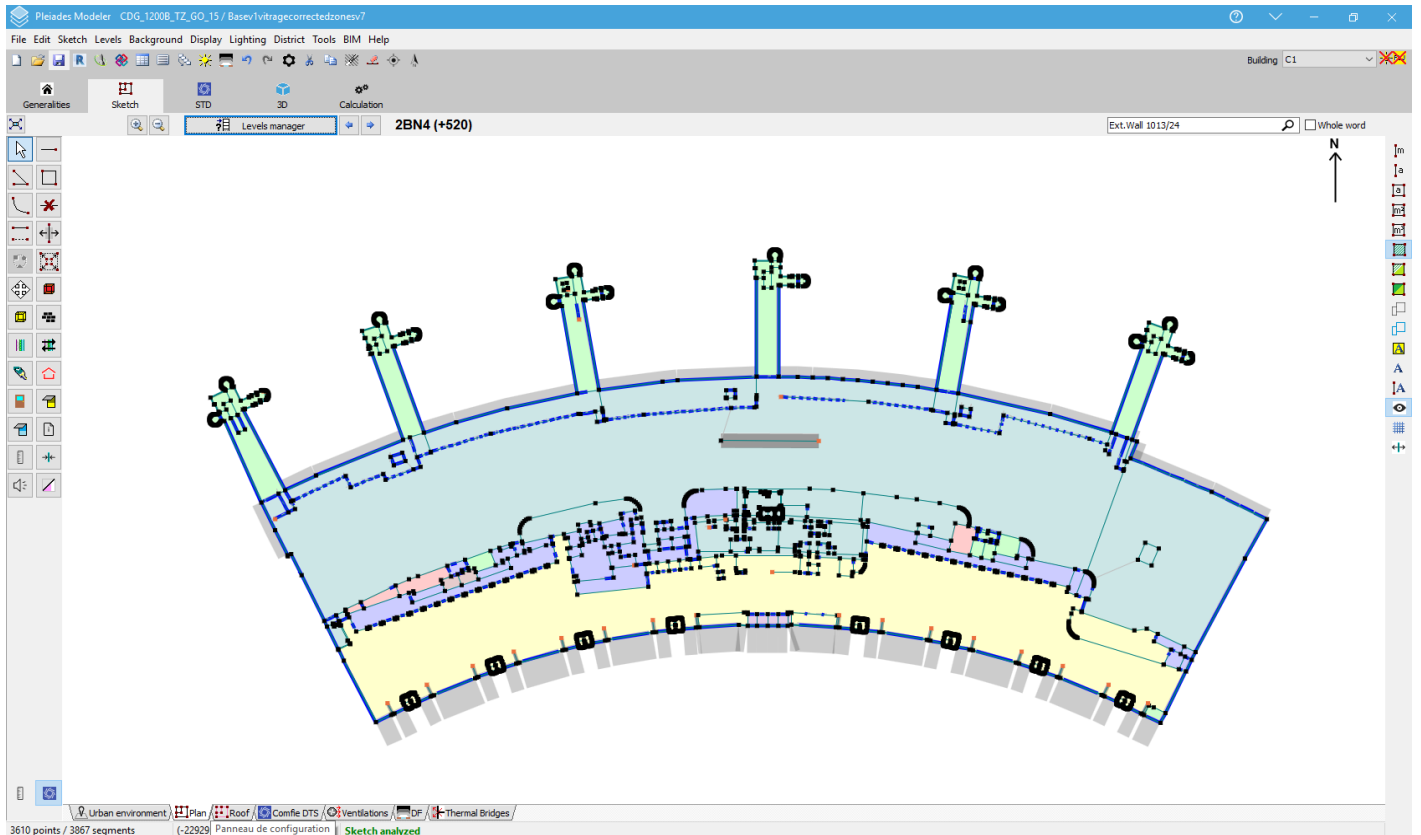
3.2.5 Floor maps and 3D model

After all the improvements for the imported model, the floor maps are completed, as shown in the figures below.



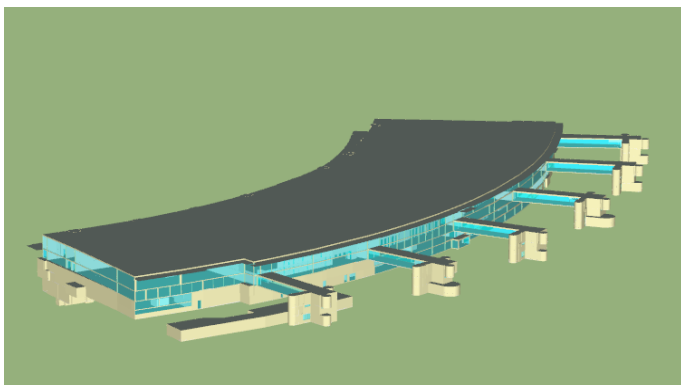
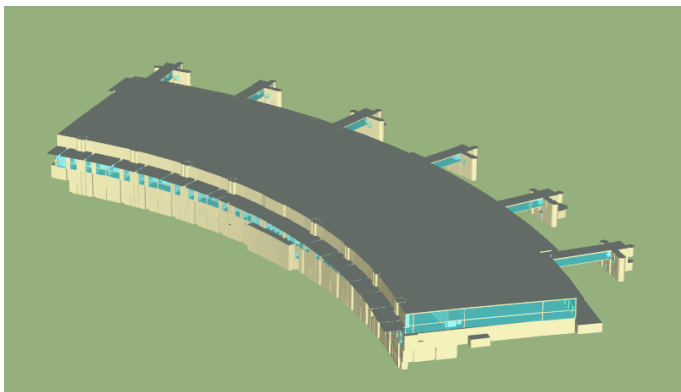
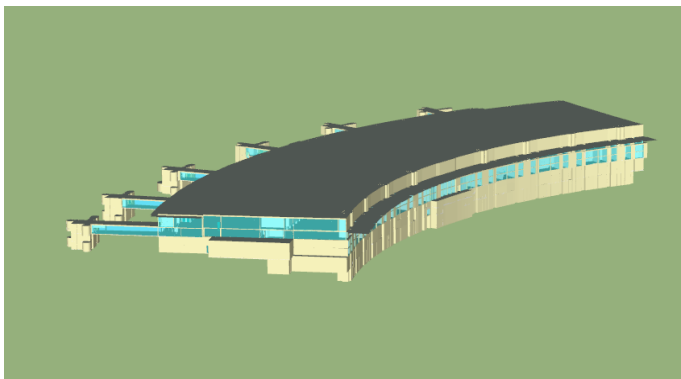
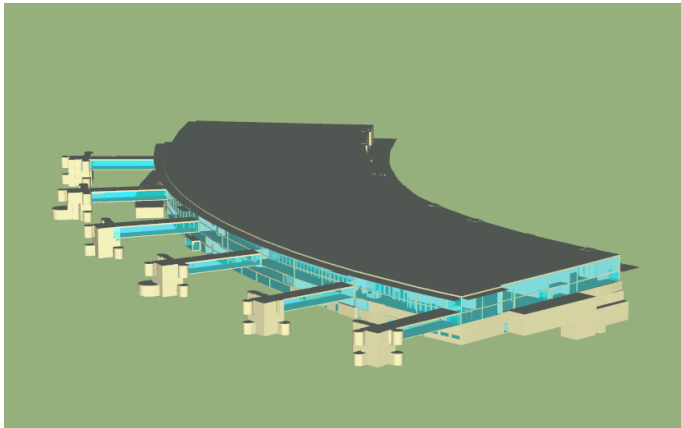








It takes around 5 minutes to get the 3D view, as shown in the figures below.



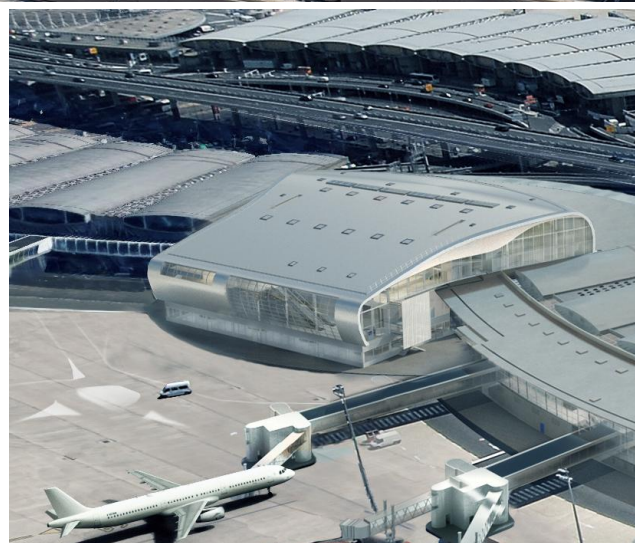
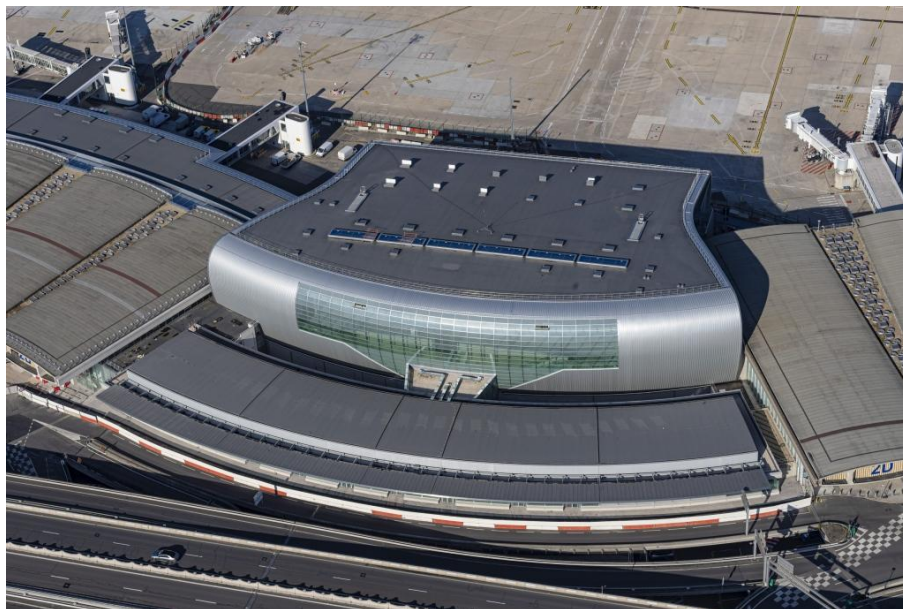


3.2.6 Generating a Pleiades model from AutoCAD files

In this section, we propose a second method to model an airport terminal in Pleiades: drawing the model based on AutoCAD (DWG) files. The principle of this method is to import the level plans in AutoCAD file format (.dwg) as background and then draw each level using Pleiades modeler. The glazing information of each façade can be obtained by verifying the façade plans in AutoCAD format. This method was tested for the link between terminal 2B and 2D (i.e. link BD).

❖ Link BD

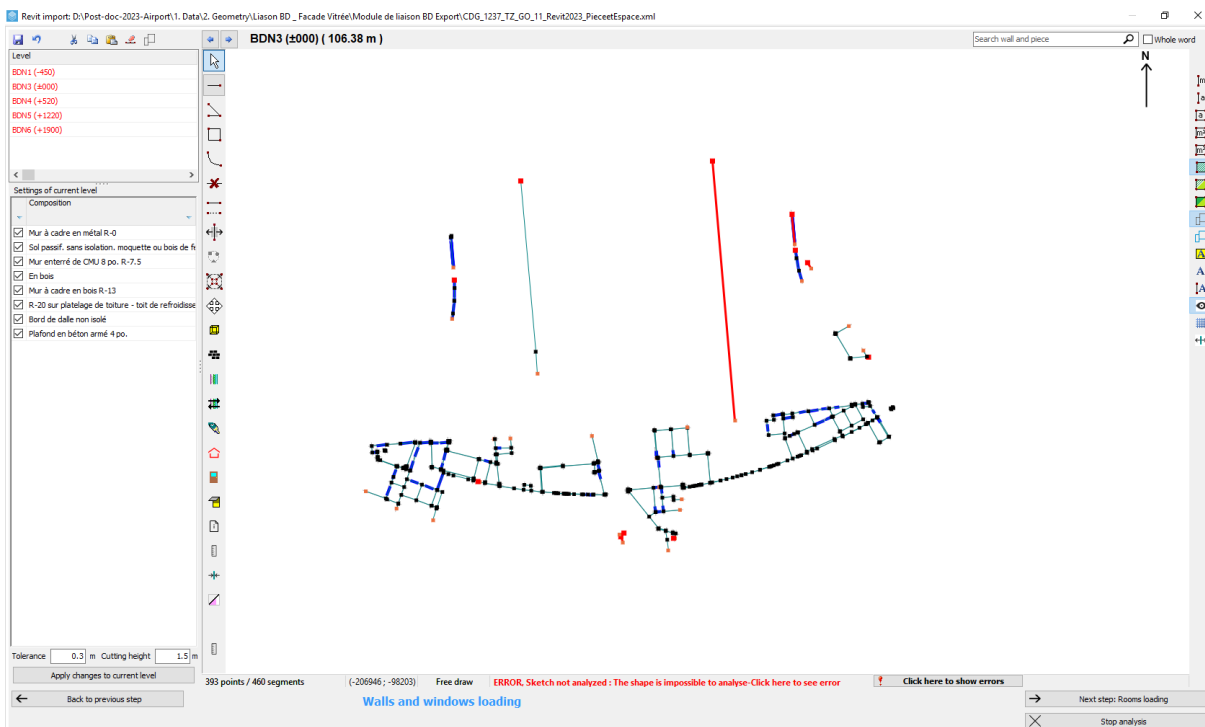
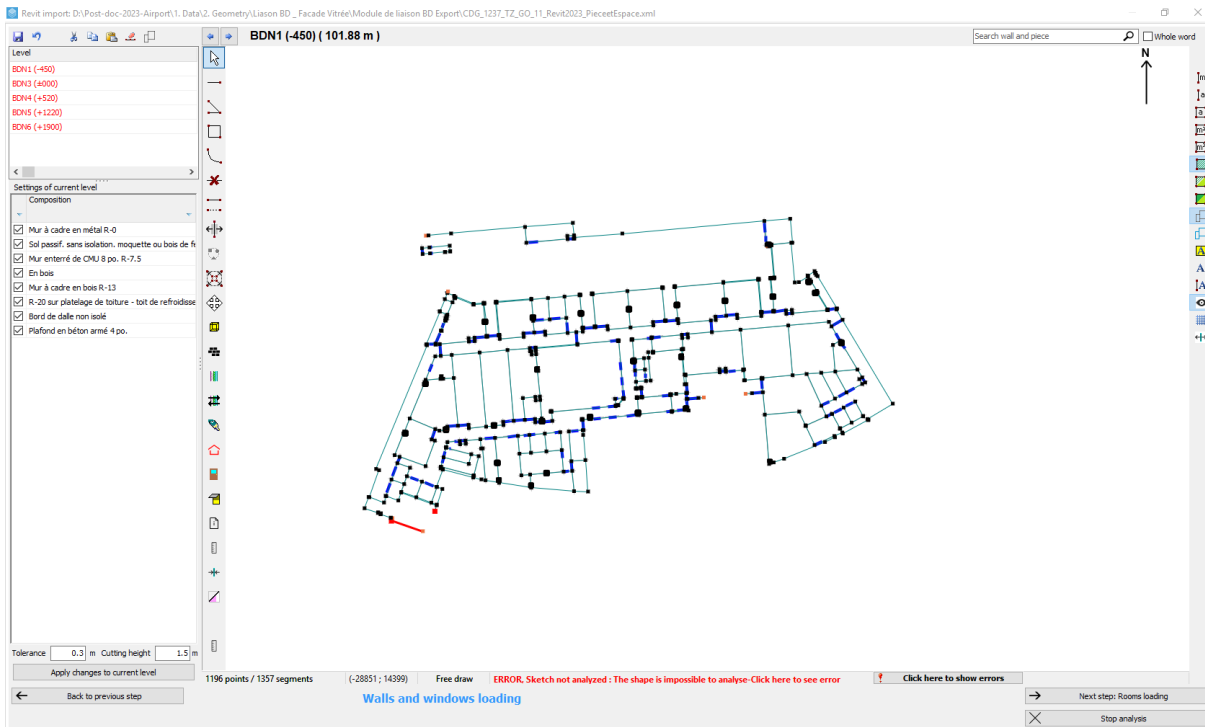
This is the building which links the terminals 2B and 2D (see the picture below). It has a sloped roof and the north and south façades are not vertical but with the shape of double curves. It is challenging to model these complex elements in Pleiades.

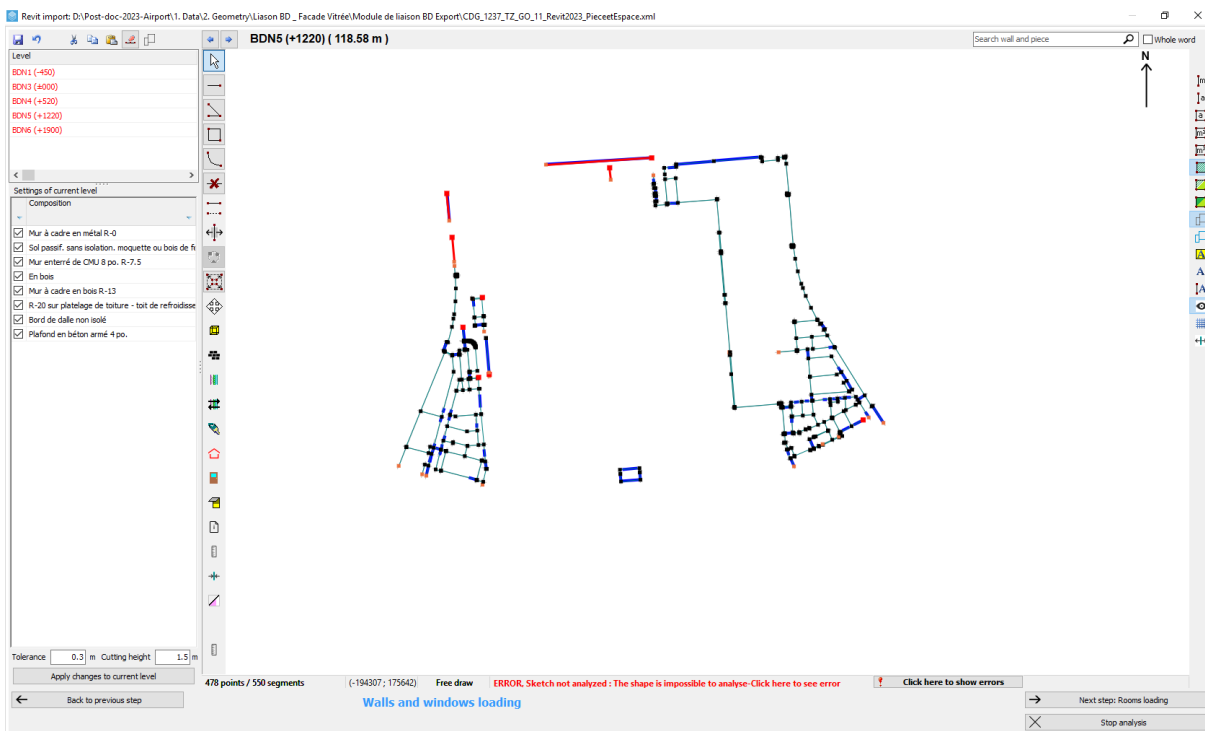
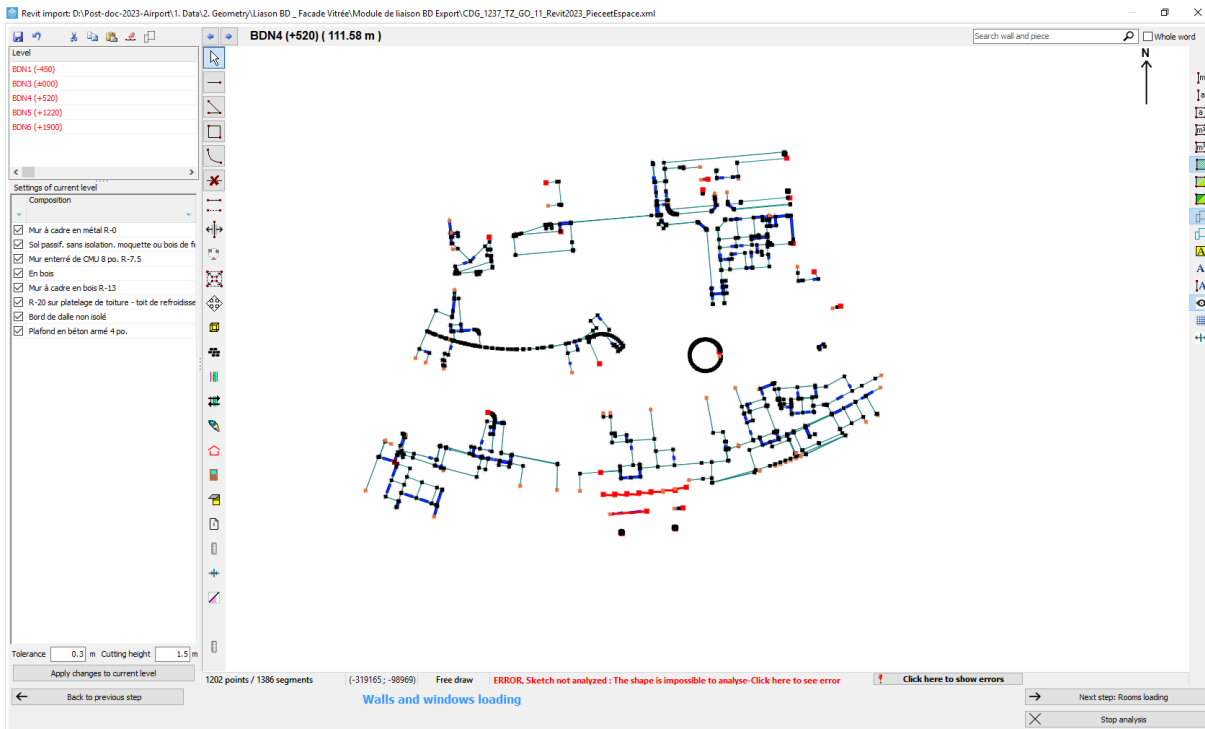


❖ Problems with the gbXML export

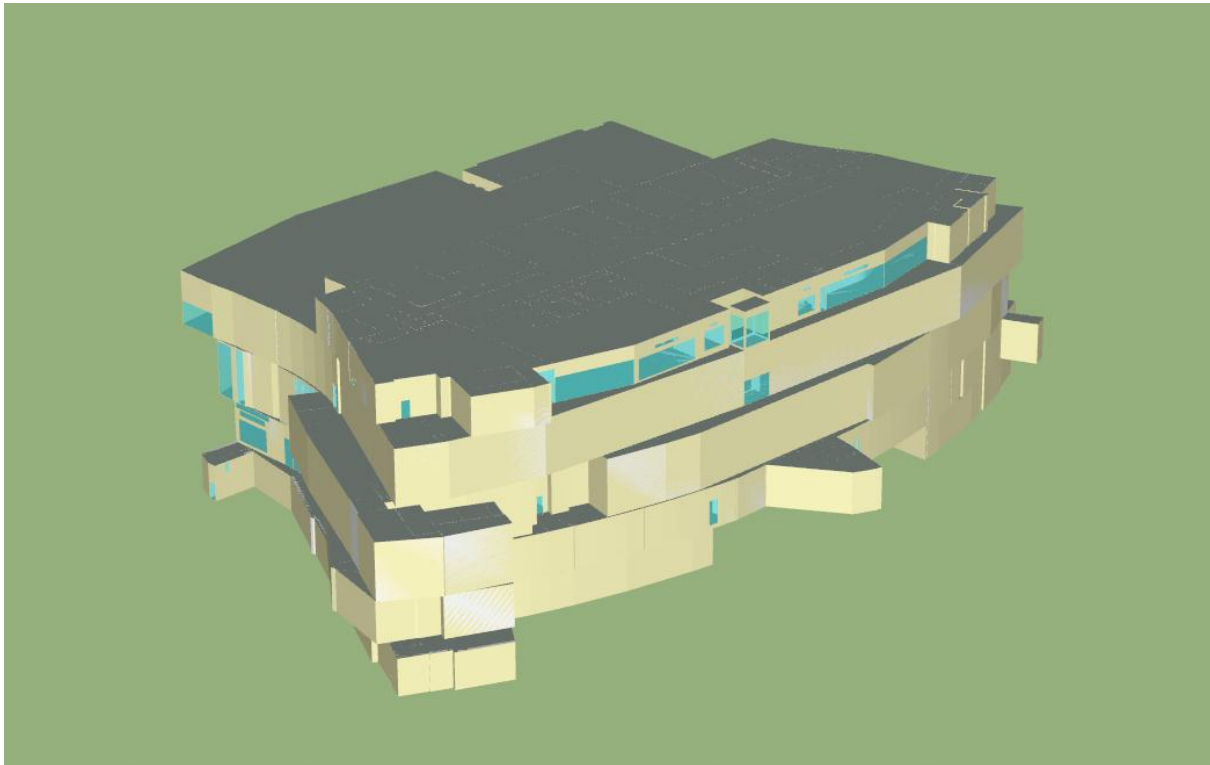


As described in section 3.2.2, the gbXML file generated from Revit file could not appropriately describe the link BD. When it is imported in Pleiades, the maps of each level are not complete and there are many errors, as shown in the figures below for the 4 levels.





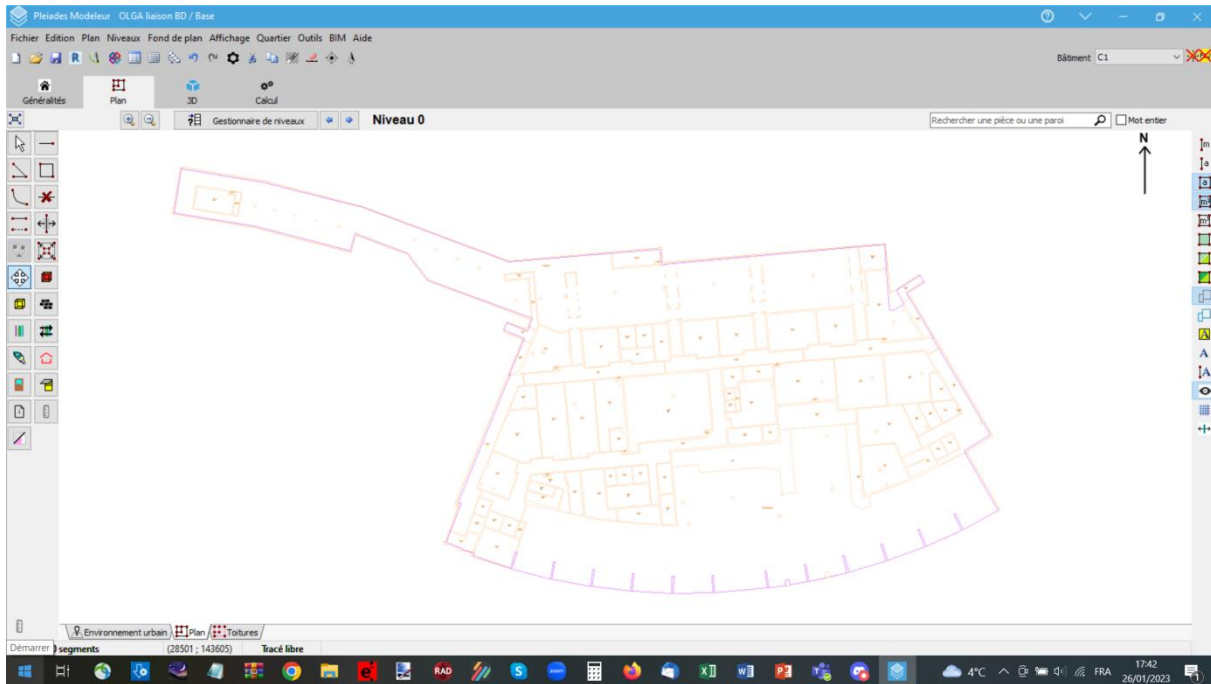
We modified and improved the levels roughly and quickly to generate a 3D model, as shown below.



The quality of the gbXML file of the link BD is poor, because the levels are not complete and there are many double walls. The sloped roof and curved façades are not modelled. For a model with a small or medium size such as the link BD, it seems that modelling based on AutoCAD files could be more efficient.

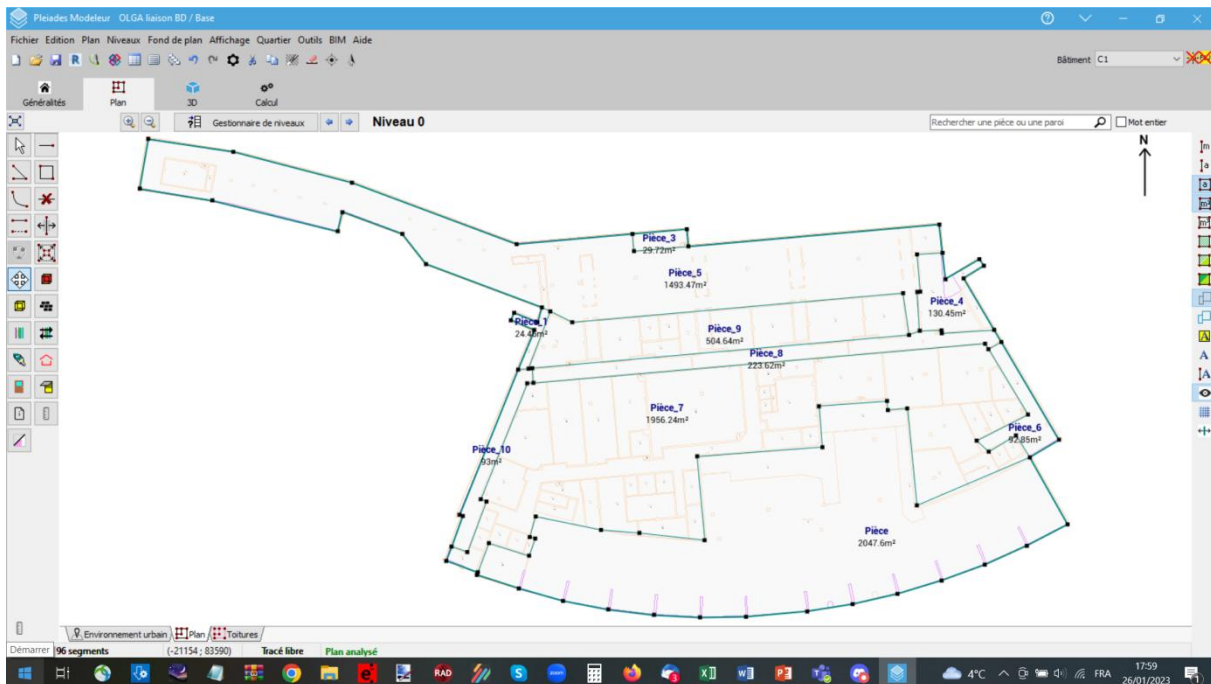
❖ Modelling based on AutoCAD files

1 AutoCAD files used as background for each floor, appropriate floor plans must be selected by the airport company.



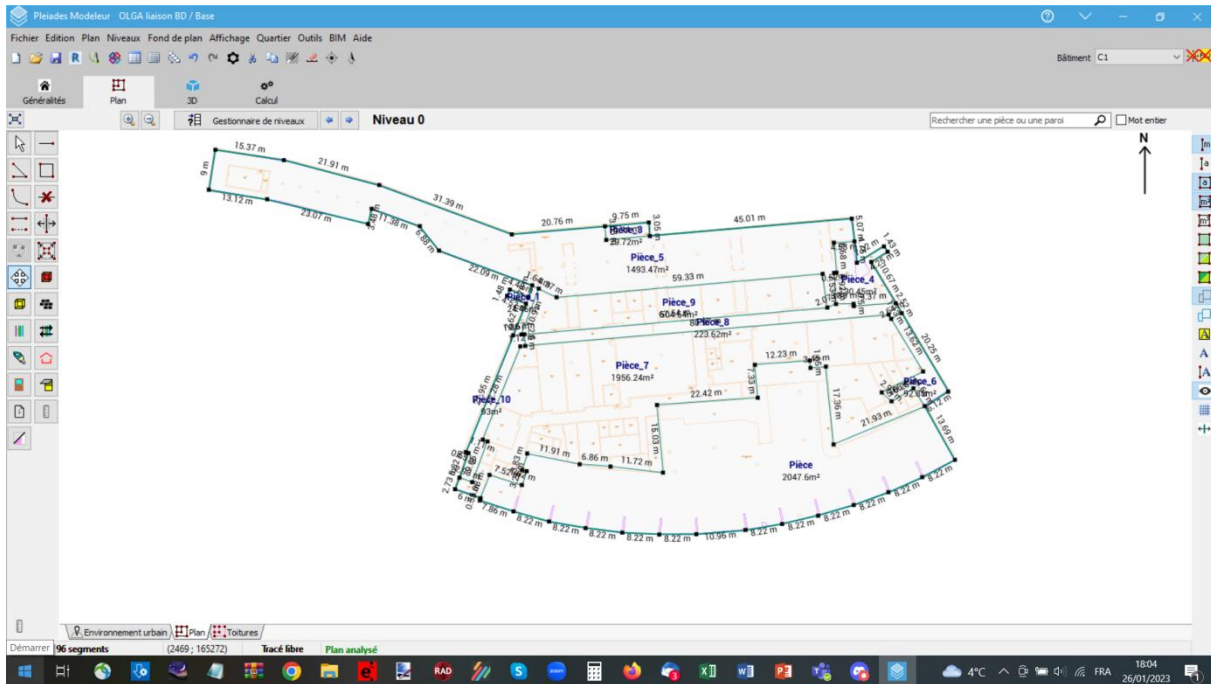
2 Walls have to be drawn

Some rooms with the same use (e.g. offices, passenger area...) and the same orientation (North, South...) can be grouped and in this case it is not needed to draw all connecting walls. This requires an exchange between the modeler and the airport company.

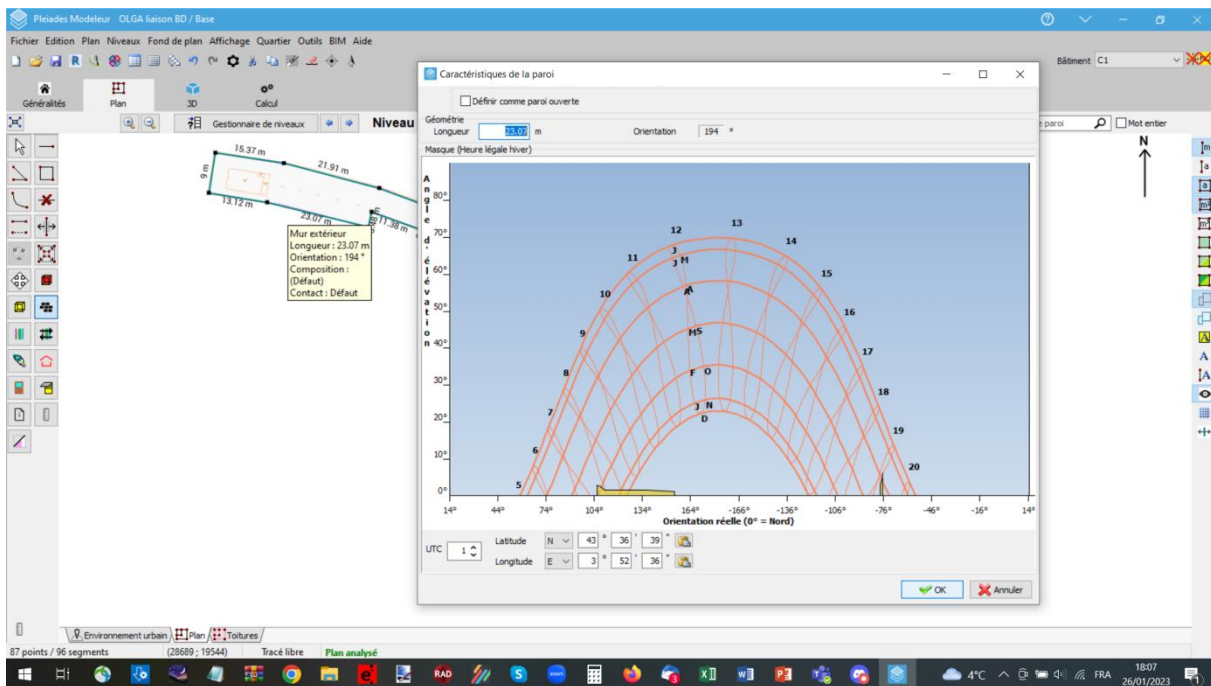


3 Scale

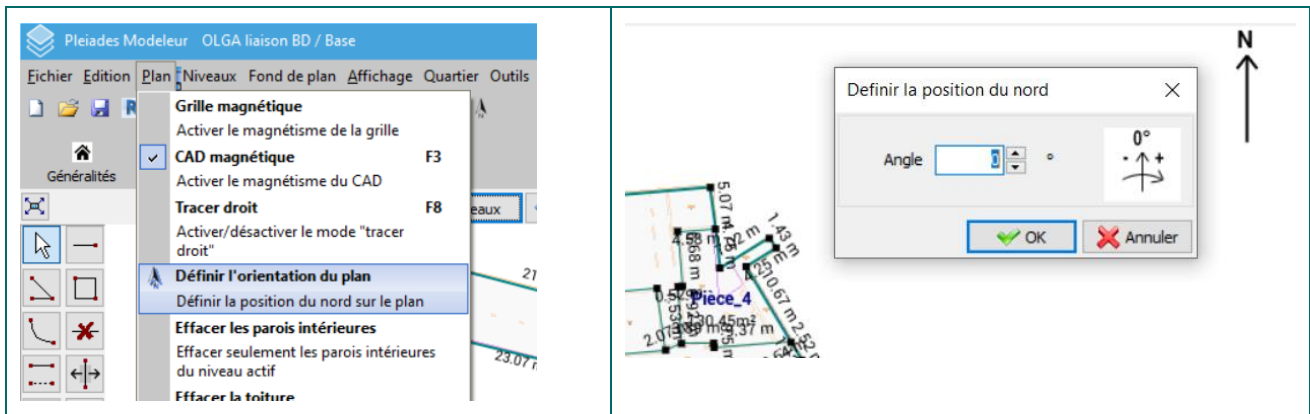
Lengths have to be checked.



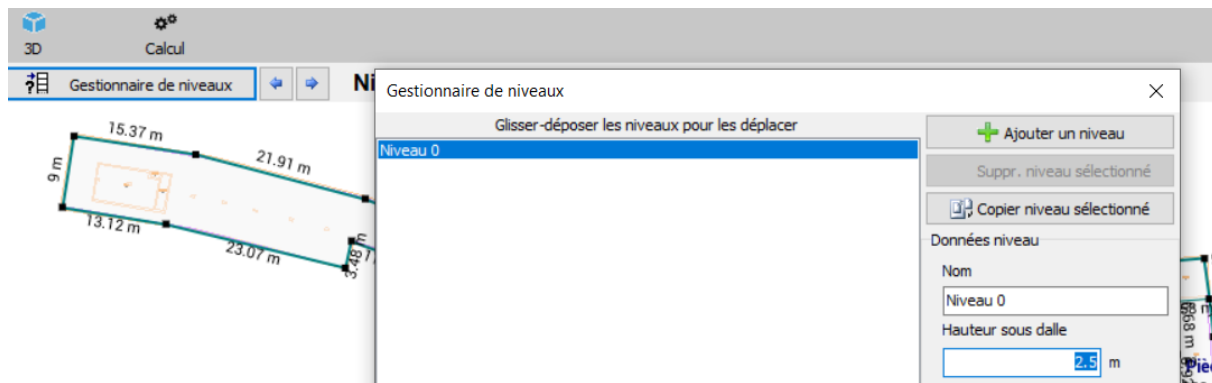
If needed one length must be changed and the whole model will be adapted.



4 Orientation has to be provided

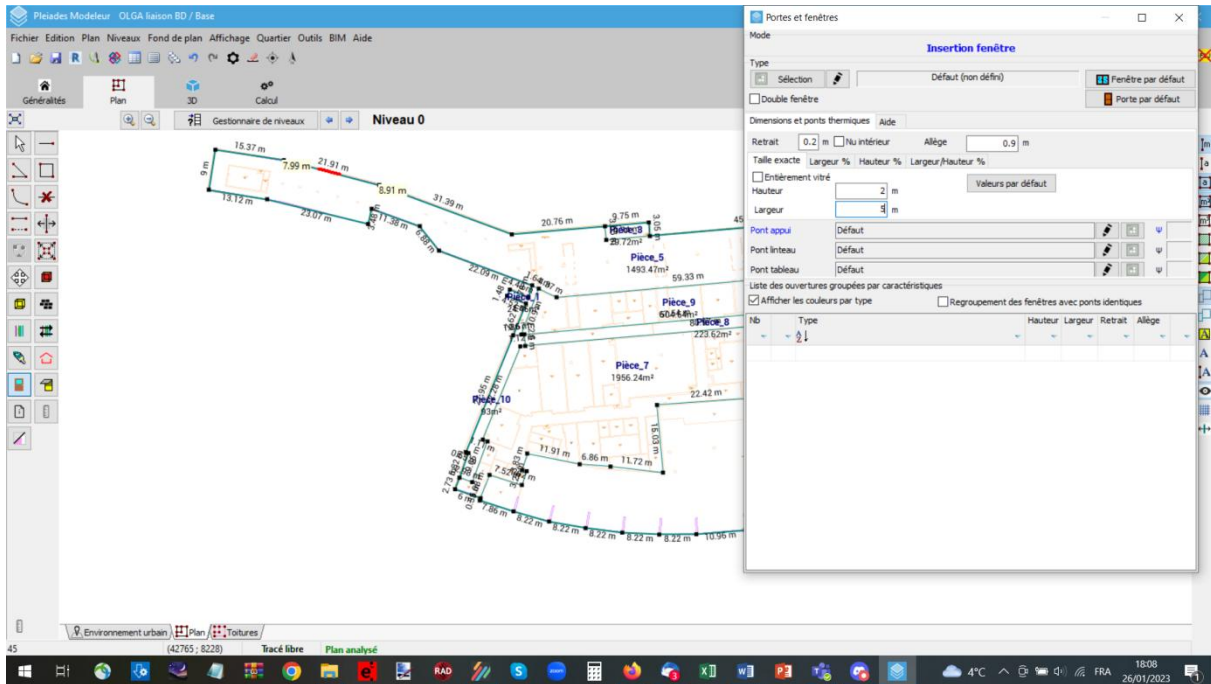


5 The height of each floor (between floor slab and ceiling, not accounting for slab thickness) must be provided

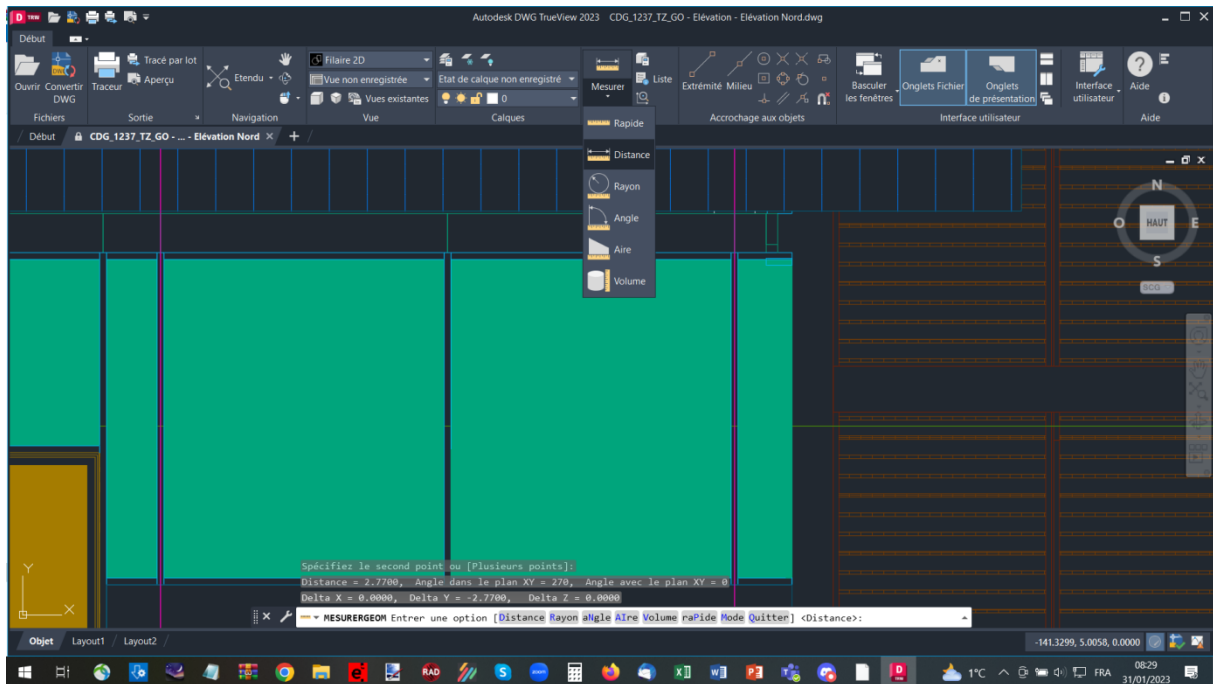


5 Glazed areas have to be included

This requires façade plans.

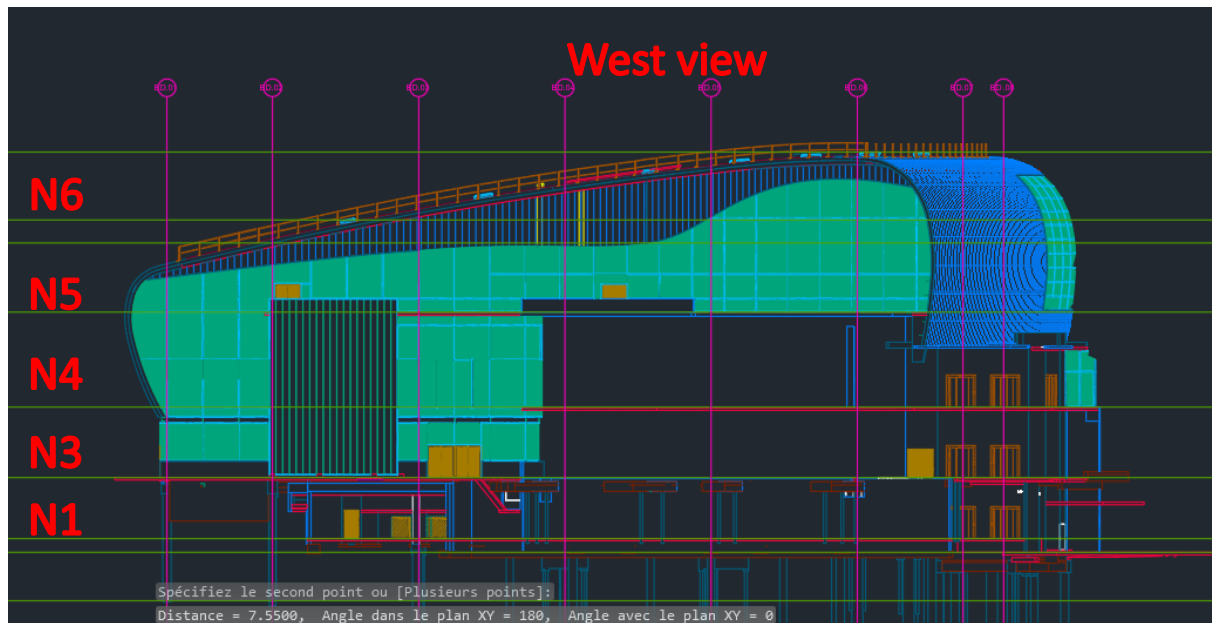


Glazing dimensions can be obtained from elevation plans (AutoCAD files):

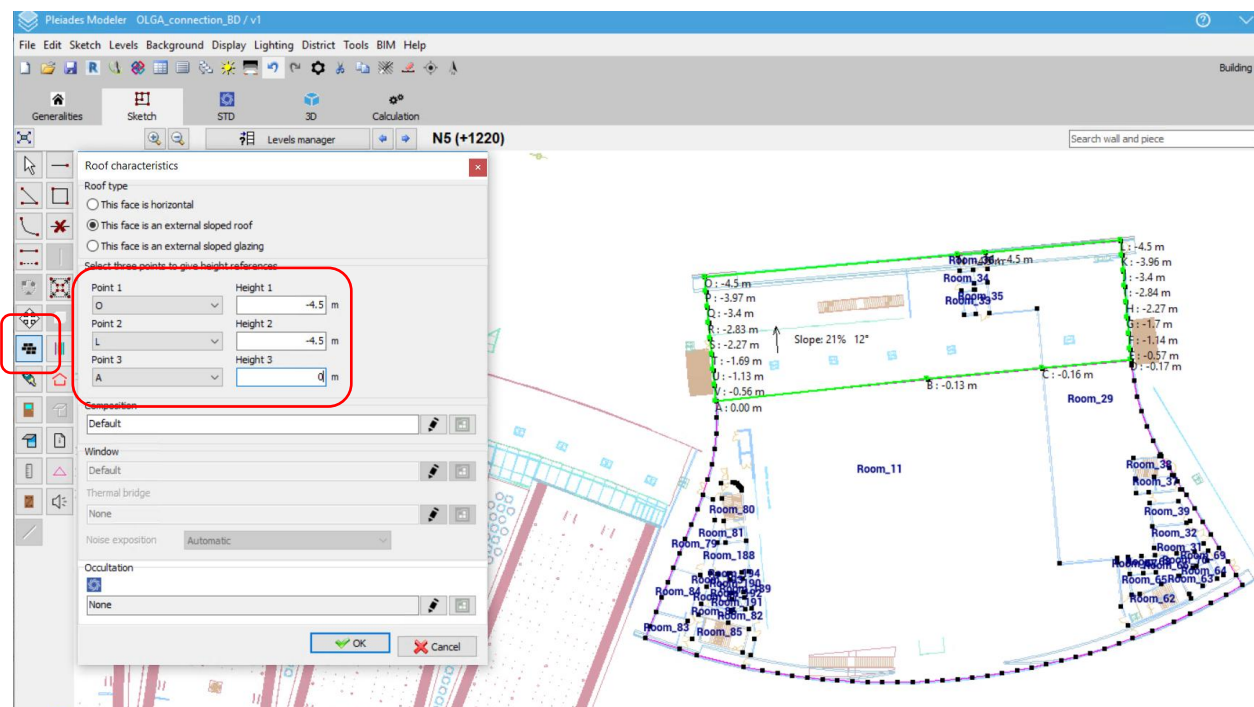
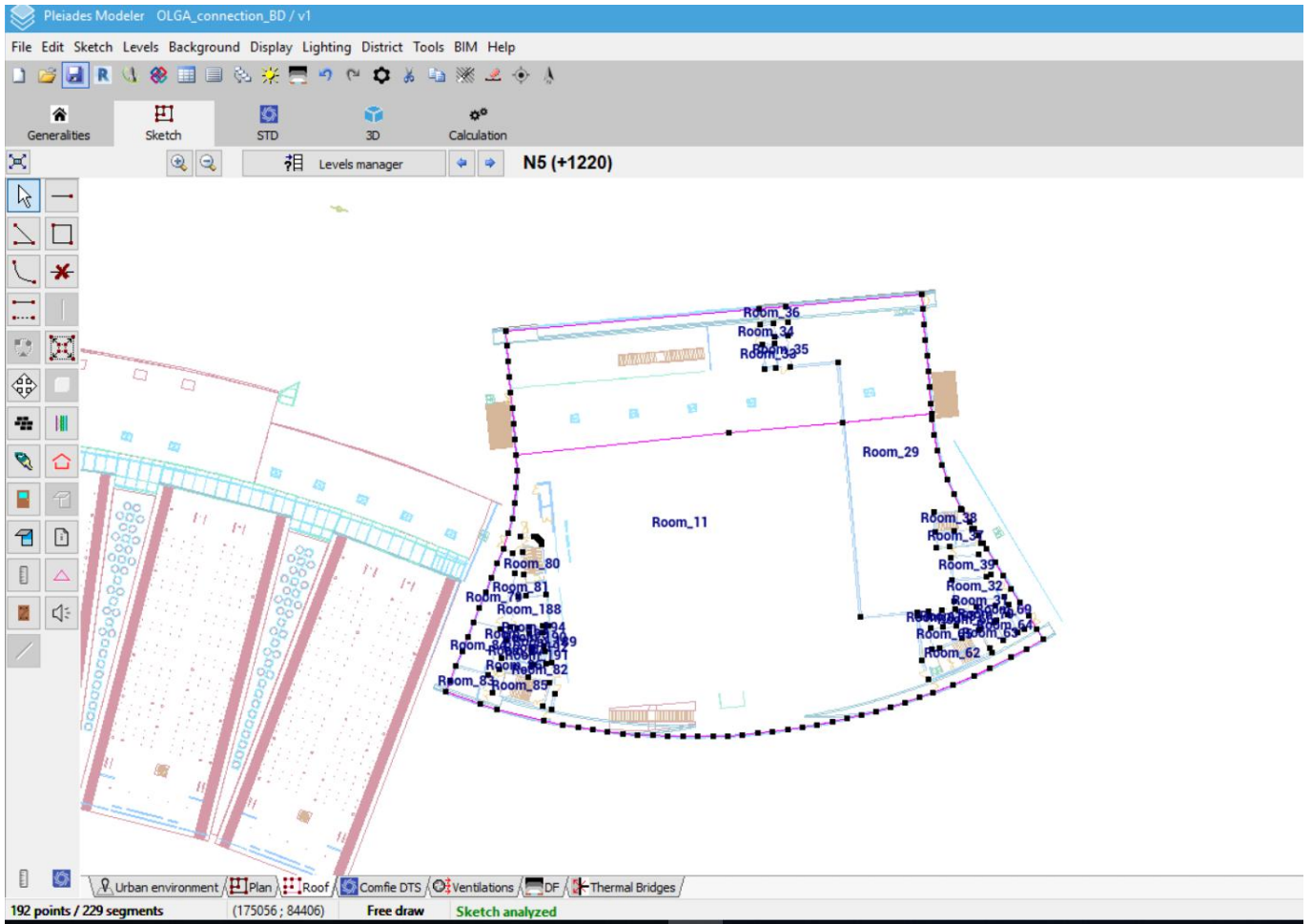


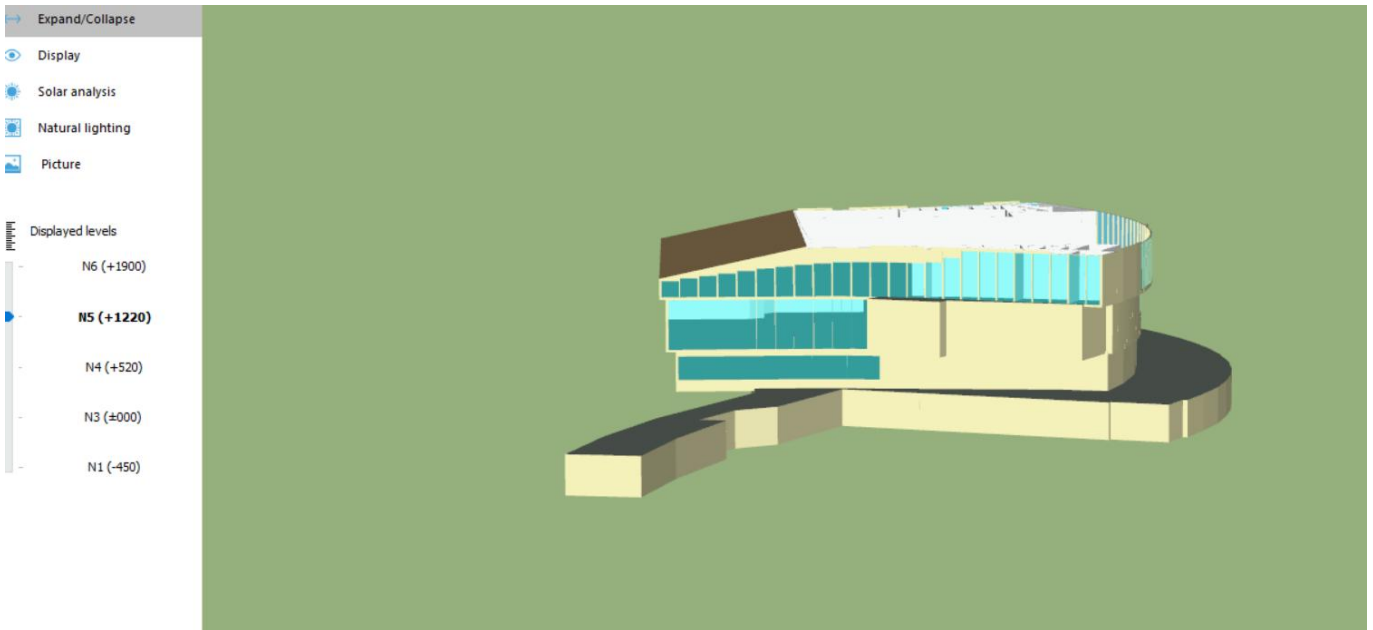
❖ Sloped roof modelling

To model the roof, we should check the façade view to determine to which level(s) belongs the roof. Considering the west view, as shown in the figure below, around 1/3 of the roof on the left belongs to level N5 and 2/3 of the roof on the right belongs to level N6.

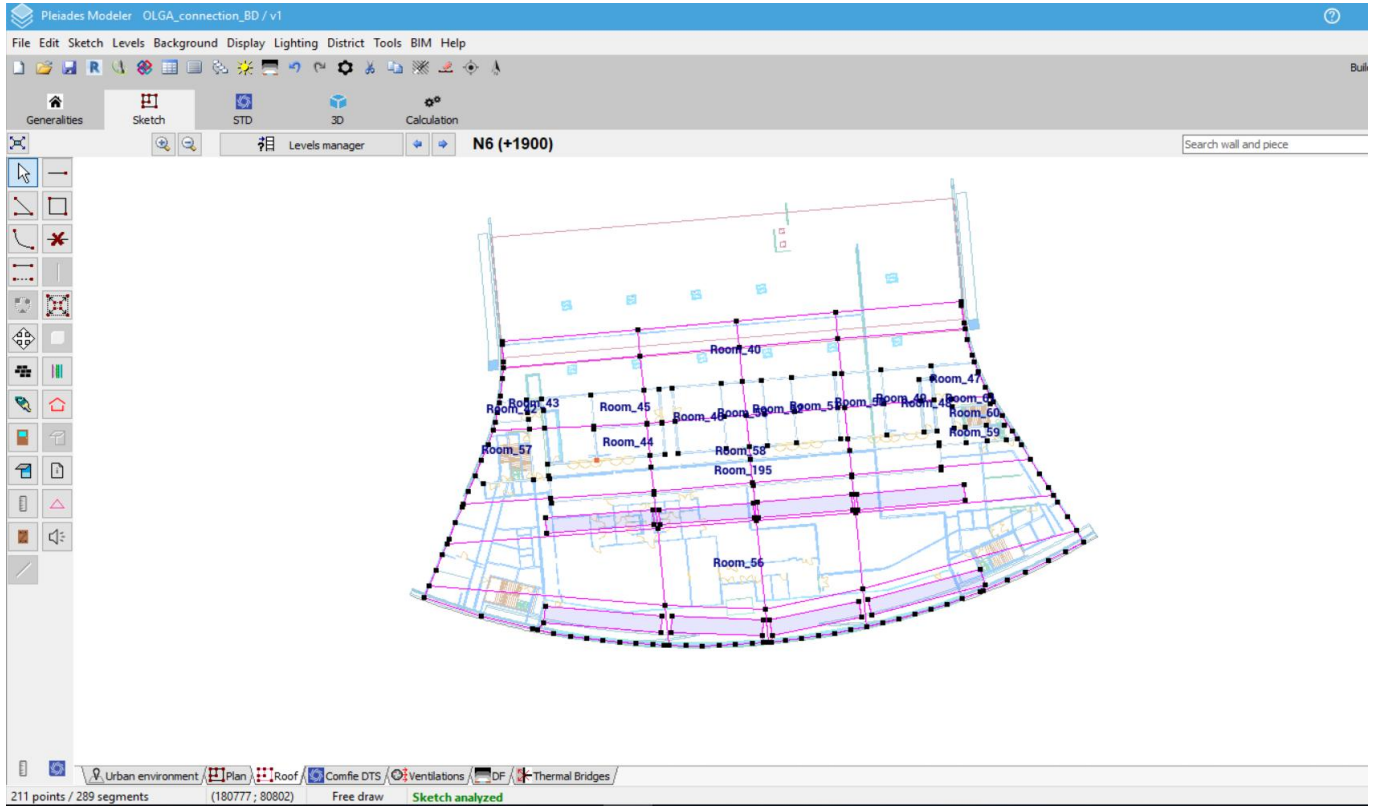


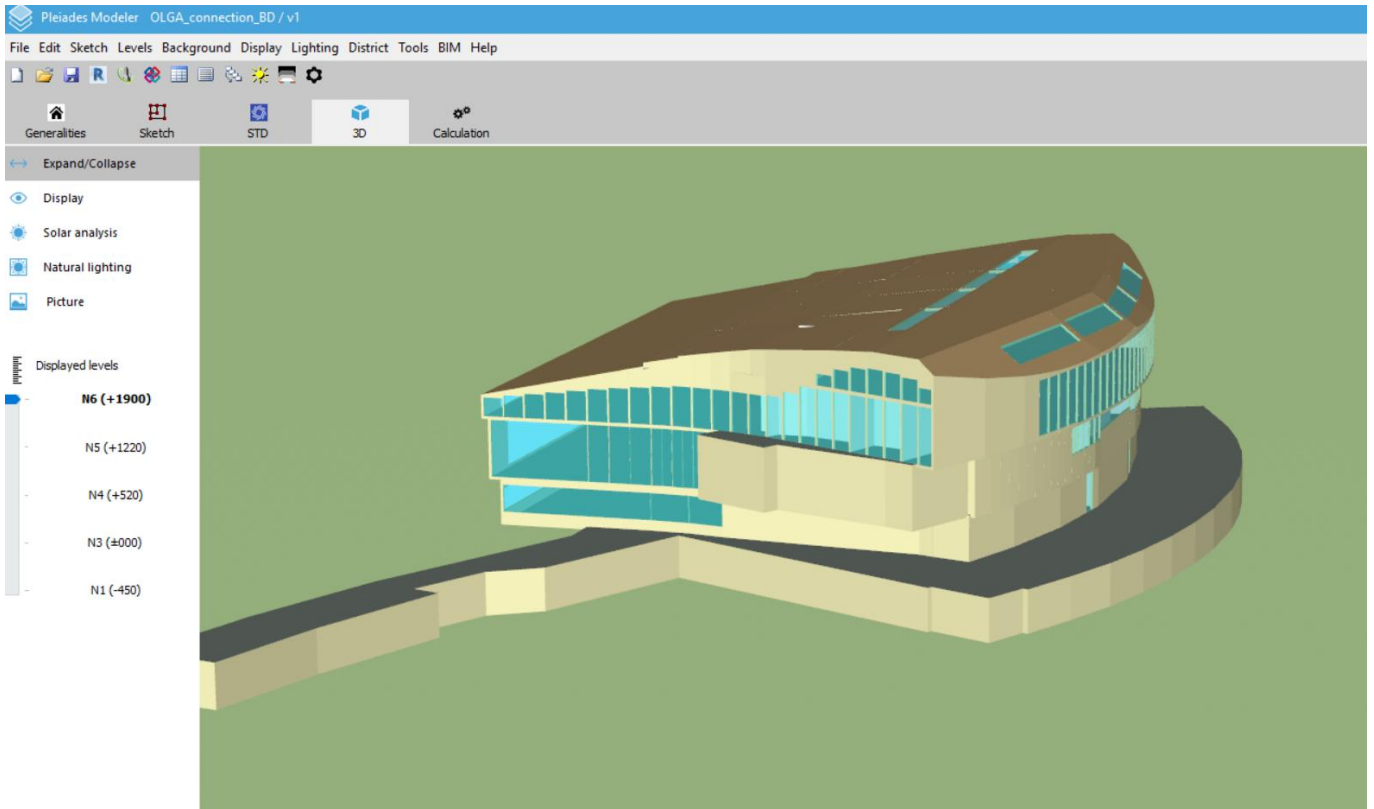
It is possible to measure the slope of the roof on level N5 in AutoCAD, including the heights of the lowest and highest points of the slope and the horizontal distance between them. The roof could be modelled by clicking the tab “Roof” at the bottom of the design interface, as shown below. The line in the middle represents the top of the sloped roof. Then it is possible to define the height of the different points of the slope by clicking the option “wall composition”, as shown in the figure below. For a sloped surface, the heights of three points should be defined. We can set the highest point A as the reference point and its height is 0m. Then the two lowest points are point O and L, with a relative height difference of -4.5m. The modelled slope of level N5 in 3D is shown below.





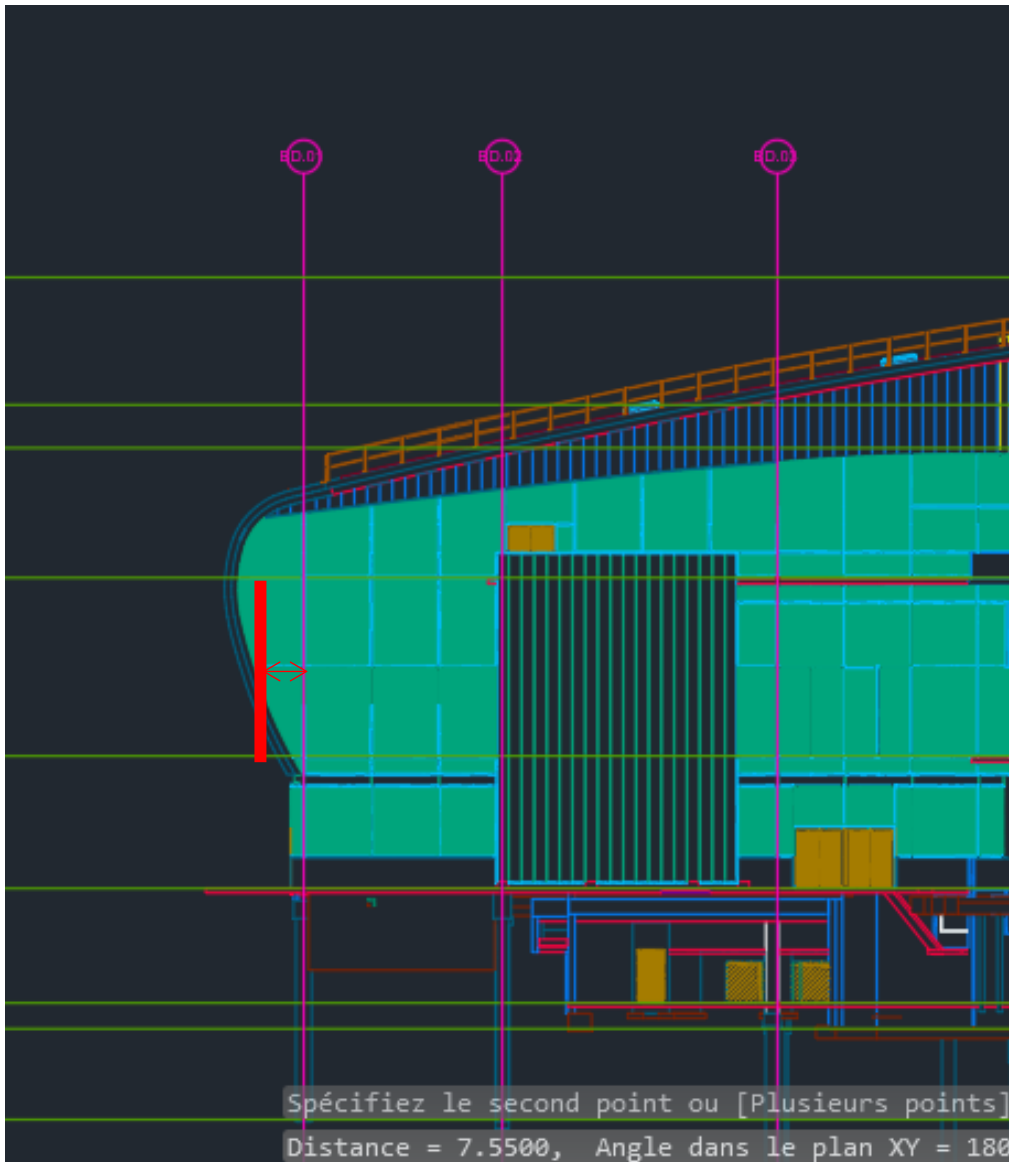
The roof of level N6 is more complex to model, due to its shape and the surface curve. We discretise the roof into several small cells, as shown in the figure below. We apply the same abovementioned method (using AutoCAD file to identify the relative height of each point) to each small cell. It should be noted that the south façade of level N6 is a curved surface which is modelled as roof in this model. The 3D model of this building at level N6 is shown below.





❖ Double curved façade modeling

The south and north external walls are curved on level N4 and N5. The slopes of the curved external wall are small, so we directly model them as vertical walls, but with a location in the middle of the slope, as shown in the figure below. The south façade of level N6 is modelled as the roof as abovementioned.

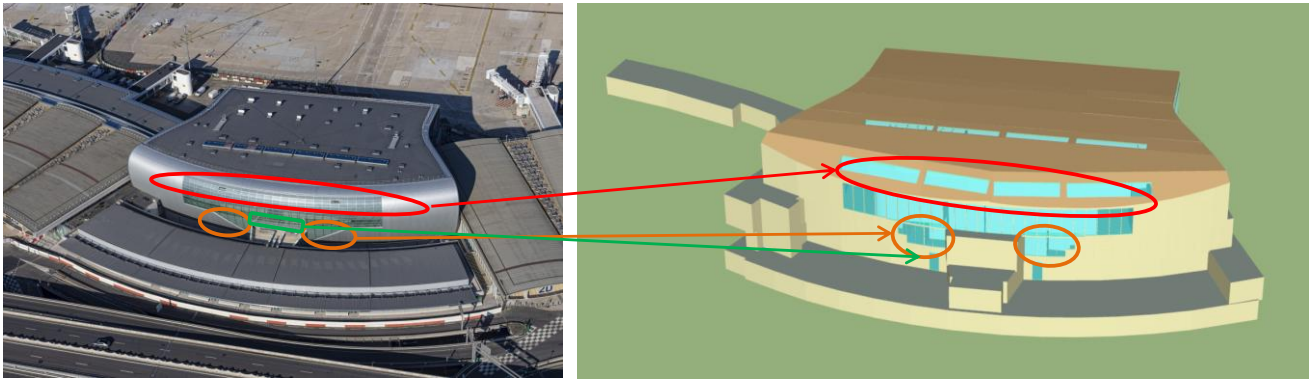


❖ Modelling of glazing

Glazing dimensions can be obtained from elevation plans (AutoCAD files), as explained above. Then we can model the glazing on each façade by inserting windows in Pleiades Modeler. It is also possible to define windows on a roof in Pleiades, which is used here to represent the glazing on the top of the curved external wall. It is difficult to model it exactly the same as the real construction due to the logic of Pleiades. The principle is then to minimize error on glazing and envelope areas so that heat losses and solar gains are the most precise as possible, as shown in the red circle in the figure below. Similarly, some glazings in triangle shape, which is not allowed in Pleiades, are converted into a rectangular shape with the same area, as shown in the brown circles. The glazing on level N4 in the green rectangular could not be modelled directly, because it

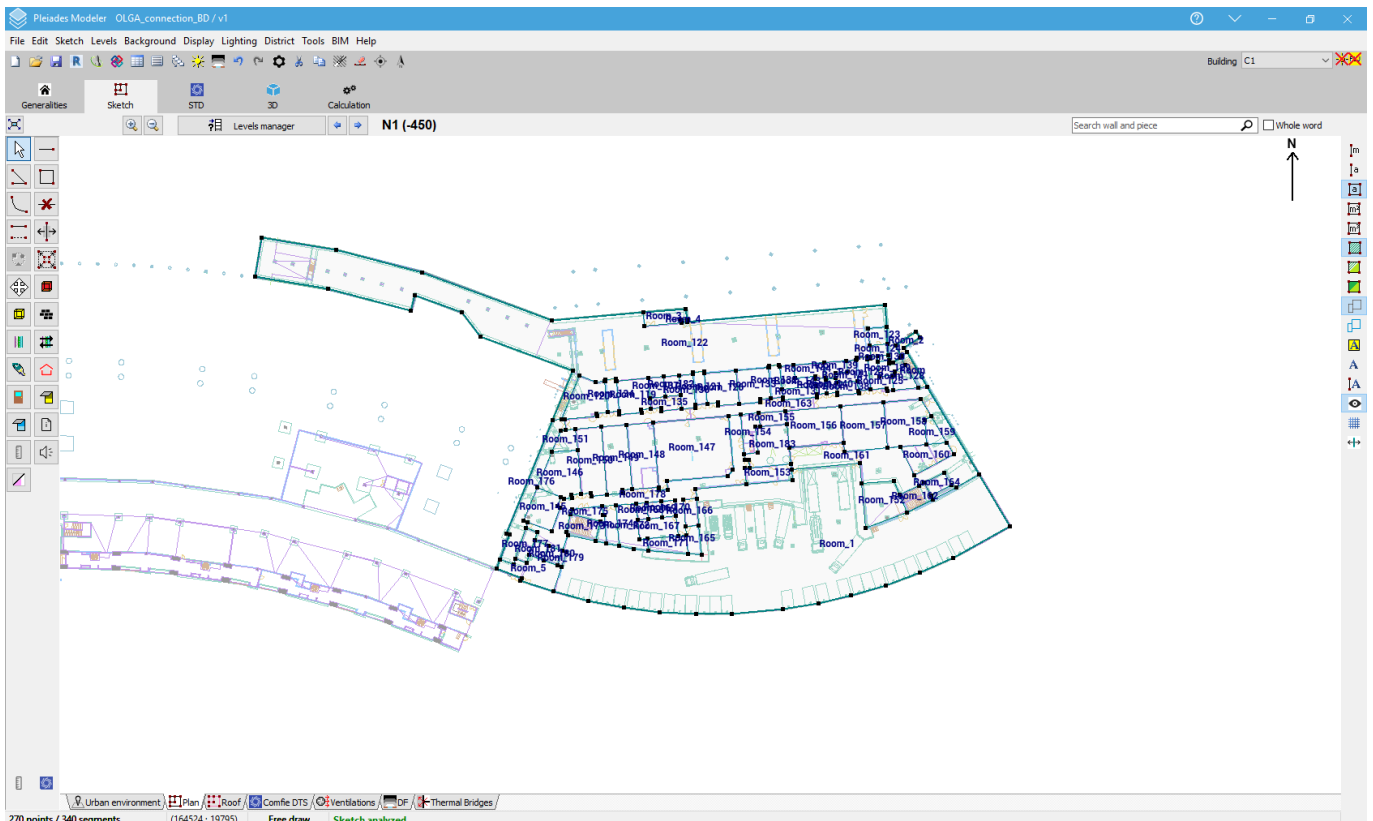


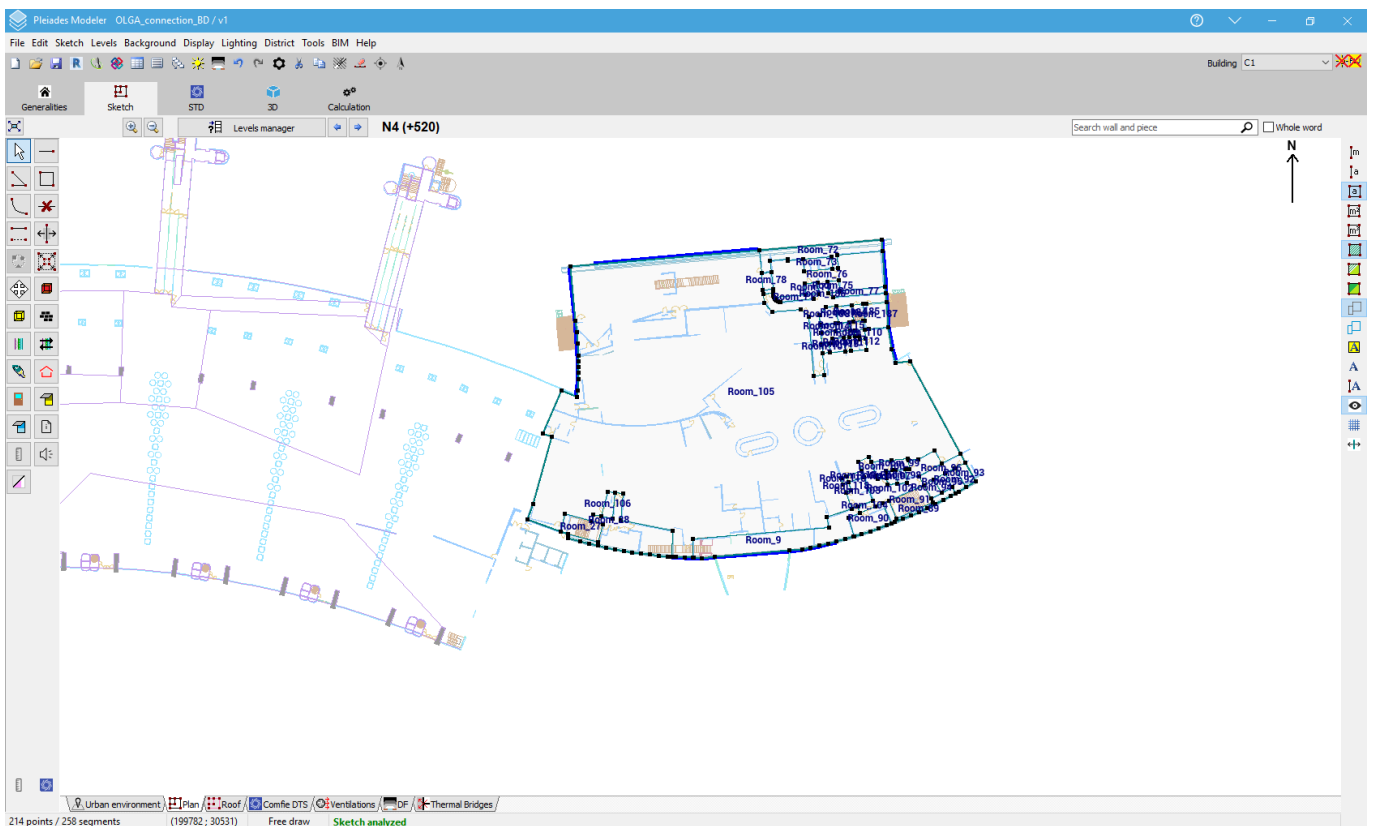
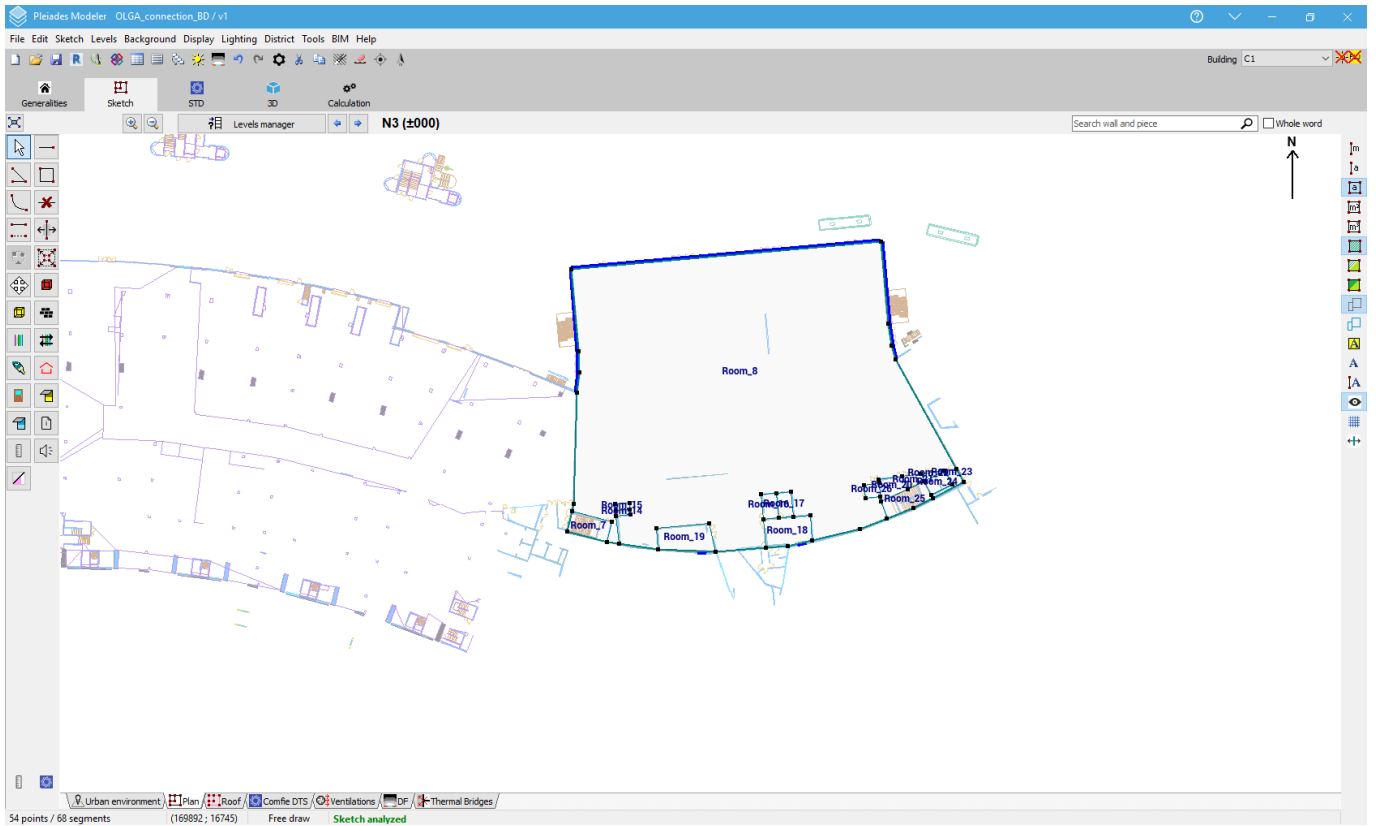
is occupied by a concrete structure in COMFIE. Therefore it is distributed to the areas in the brown circles next to it.

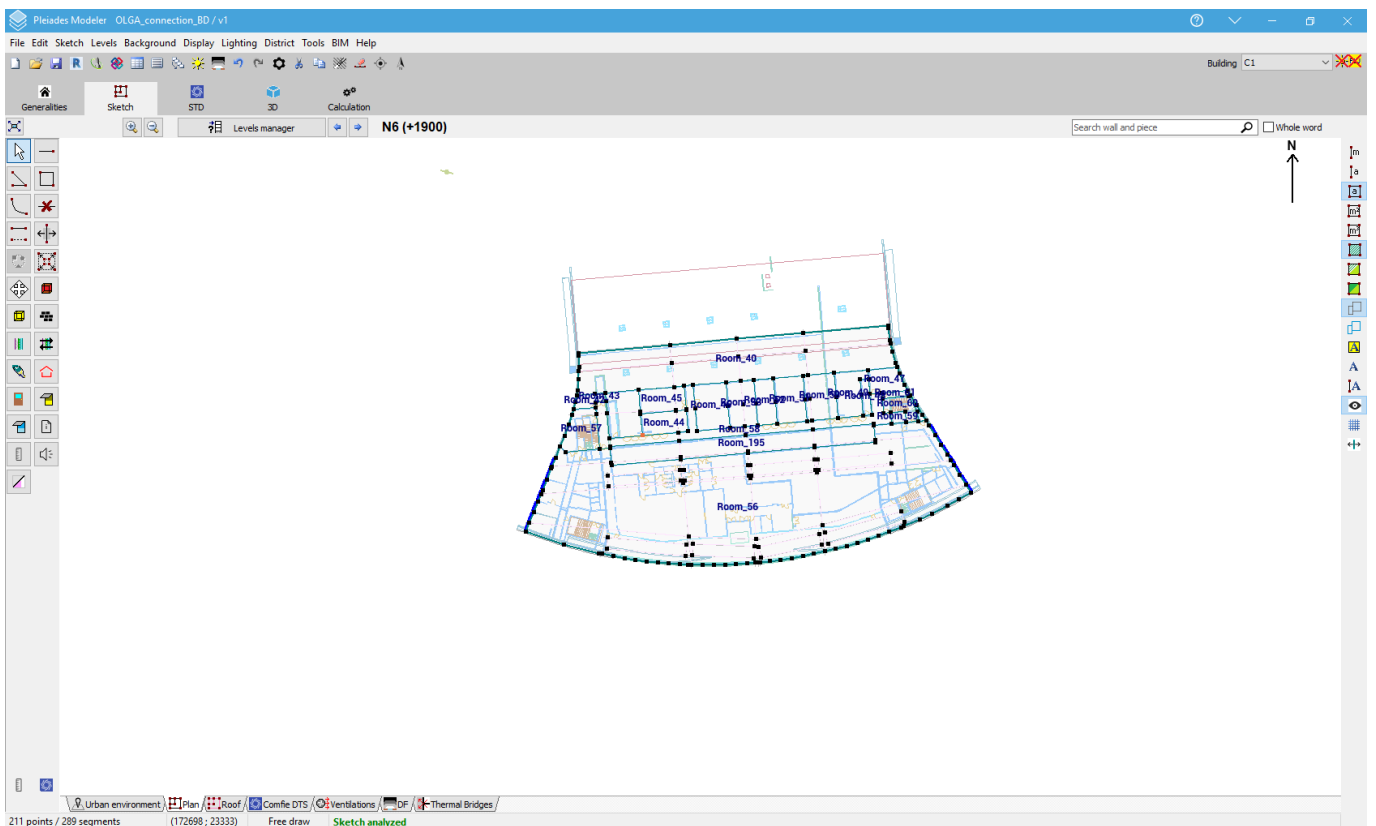
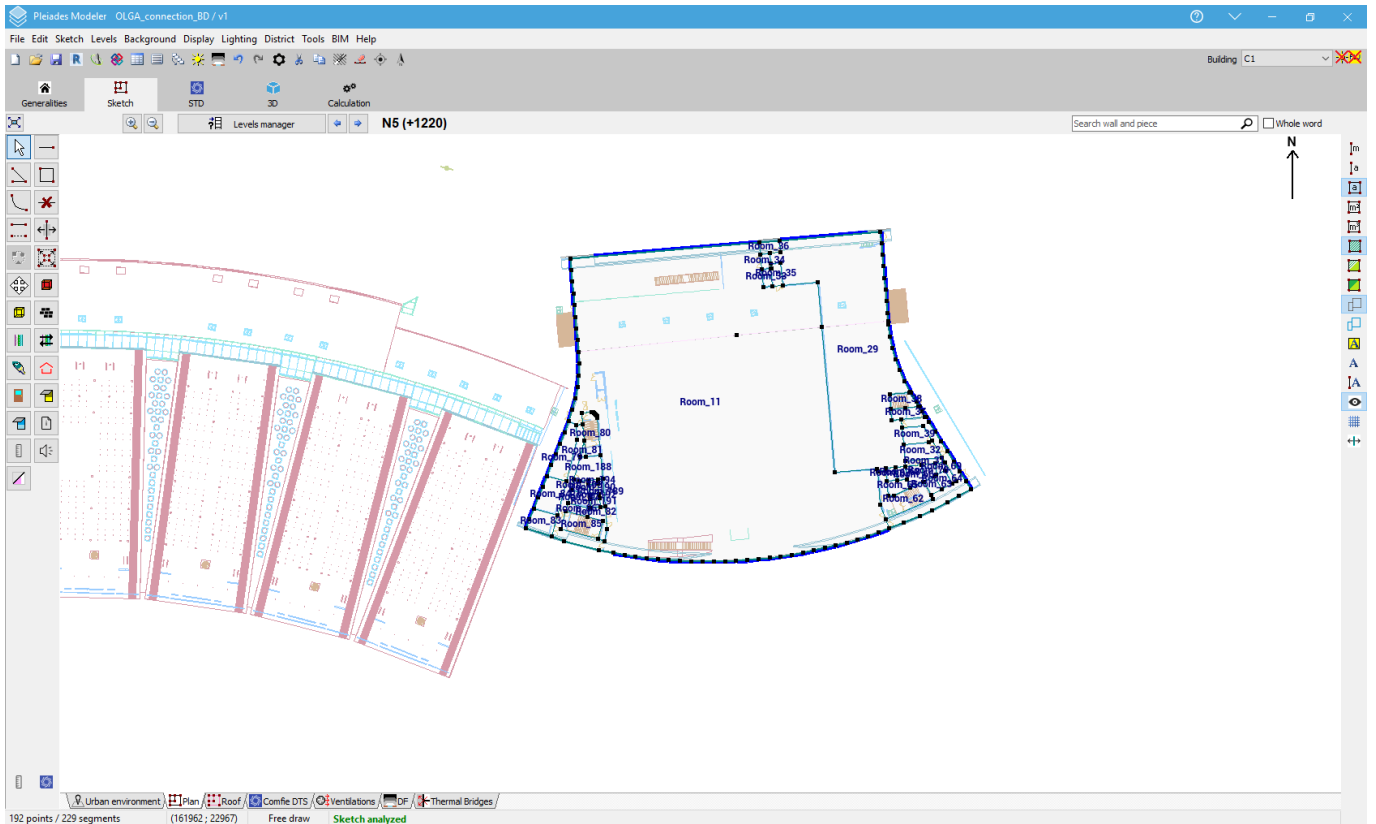


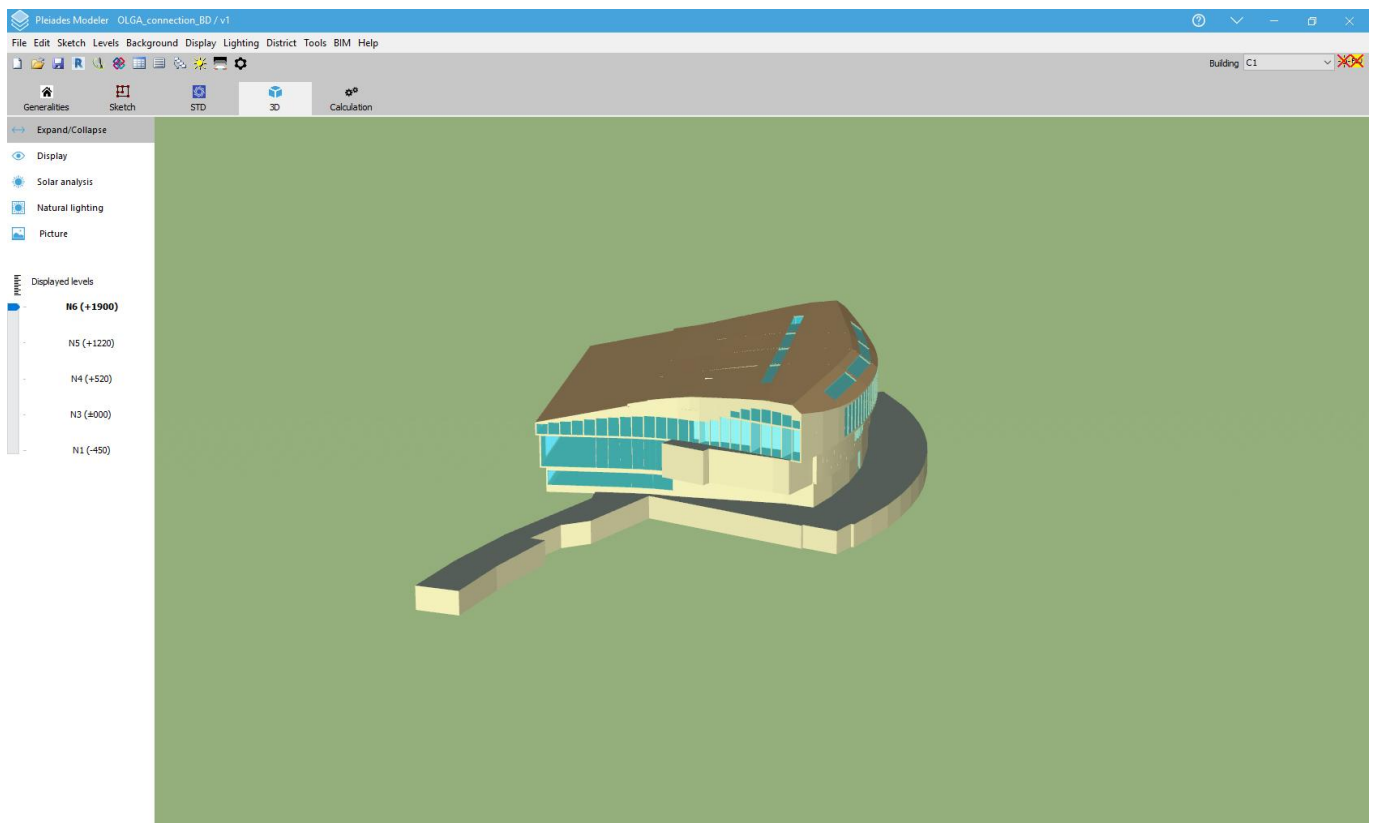
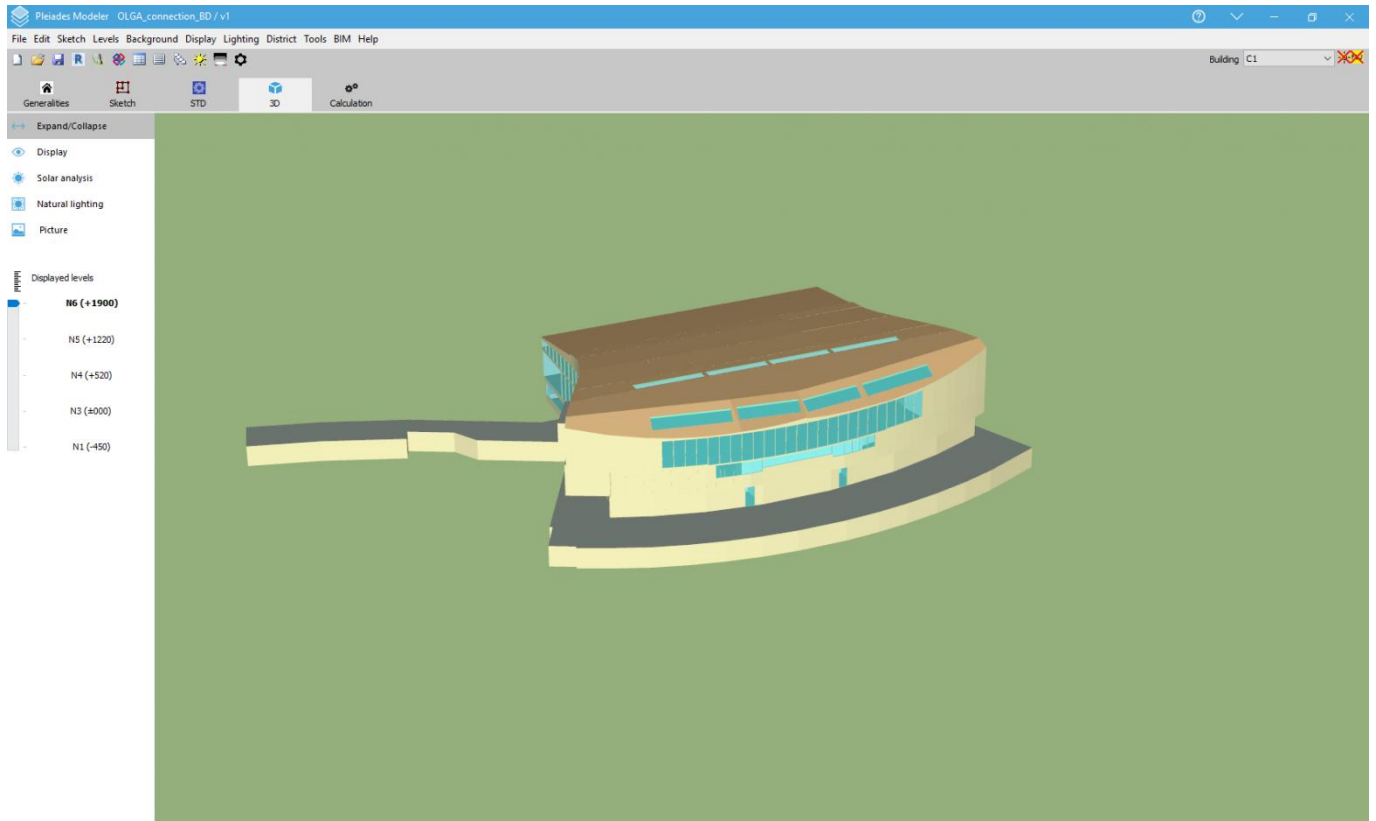
❖ Floor maps and 3D model

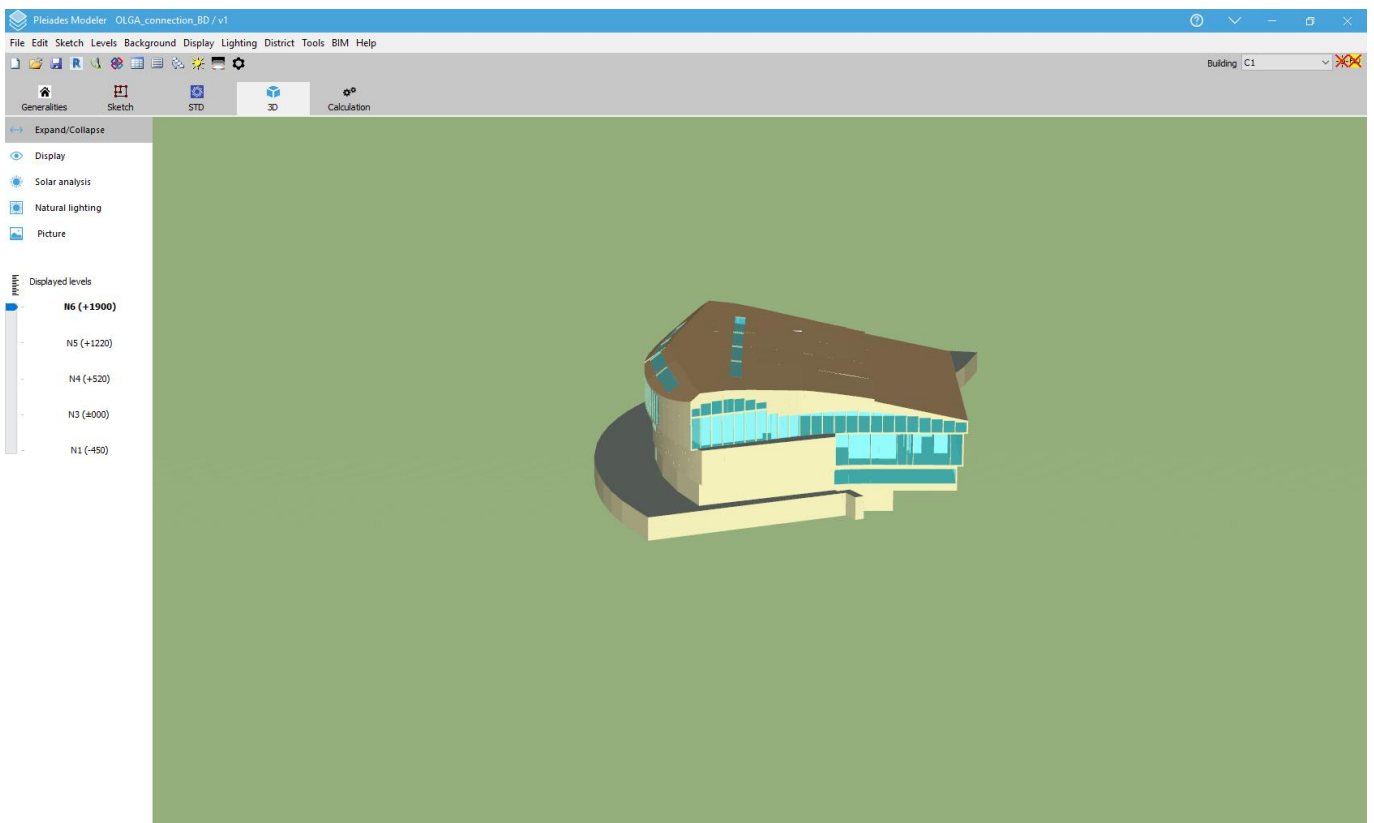
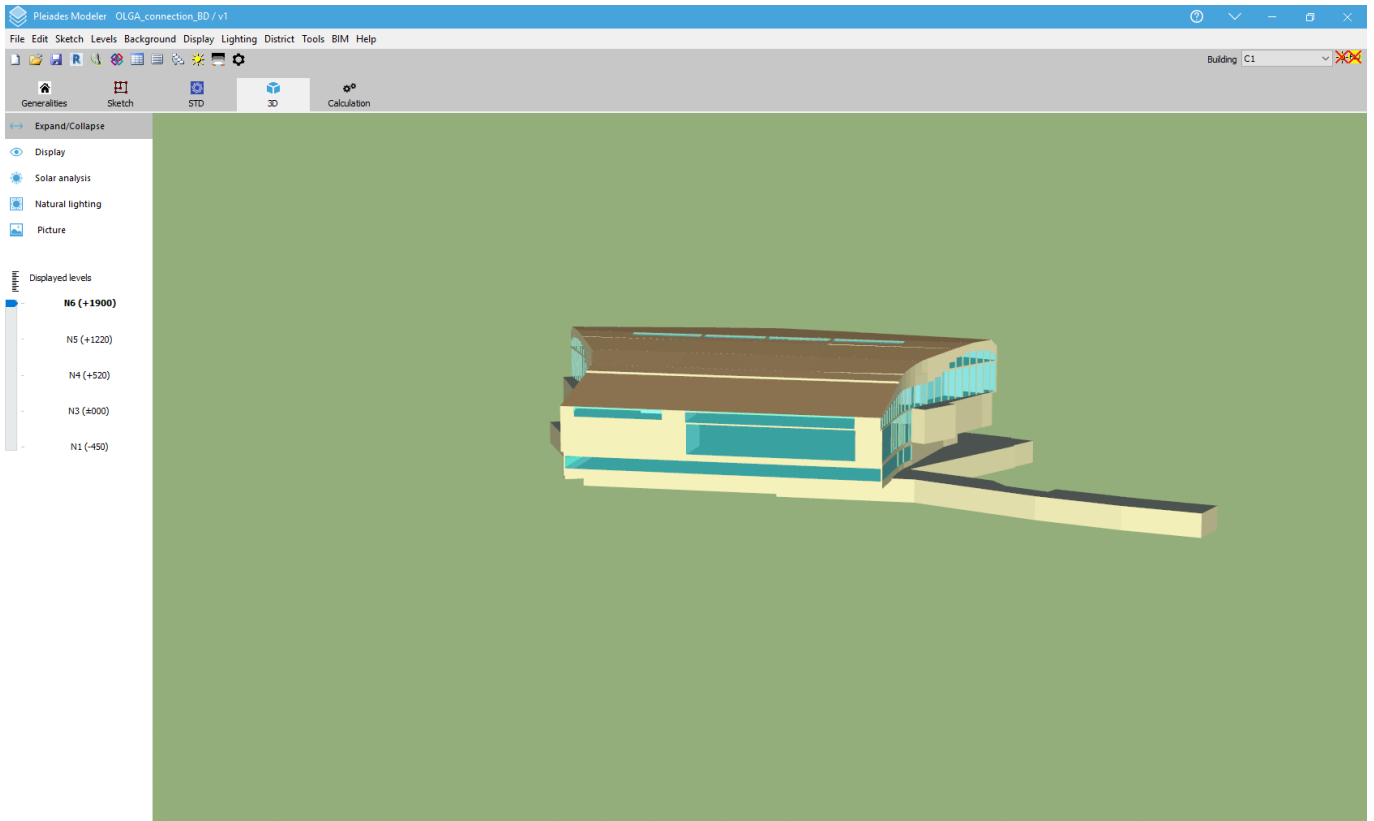
After all these improvements of the imported model, the floor maps are completed, as shown in the figures below.











❖ Benefits comparison between gbXML method and AutoCAD method



The benefits/ inconveniences are summarized in the table below.

Method	Benefit	Inconvenience
gbXML	<ul style="list-style-type: none"> • Very efficient if the model quality is good • Avoid drawing by hand • Internal walls and windows information is included in the model 	<ul style="list-style-type: none"> • Highly depends on the model quality • Numerous small errors could be generated, such as double walls, unreasonable shapes • Windows information could be wrong and needs to be corrected • Cannot deal with complex shapes and curves
AutoCAD	<ul style="list-style-type: none"> • Can deal with complex shapes and curves, such as sloped roof or curved façade • Efficient to model the building if its size is not very large • Double walls and strange shapes could be avoided 	<ul style="list-style-type: none"> • Not efficient for a very big and complex building • Windows, internal walls and doors have to be drawn by hand, which could be a heavy work

3.2.7 Collecting data on occupancy

Default number of persons according to uses (offices, shops, passengers halls...) were refined as much as possible using monitored data.

3.3 Configuration of the dynamic thermal simulation

3.3.1 Choice of the climatic data

Various hourly climate data regarding the external ambient air temperature, global horizontal solar radiation, diffuse horizontal and direct normal solar radiation, relative humidity and wind speed and direction were collected by the measurement equipment in the CDG airport. A typical year corresponding to the period 2007-2021 is considered except for the air temperature, which uses the hourly data collected by the MétéoFrance in 2022. This is to calibrate the occupancy scenarios based on the heating and cooling consumption of 2022. These data were converted into a weather station file which could be used in the BES tool Pleiades STD, as shown in the figure hereunder.

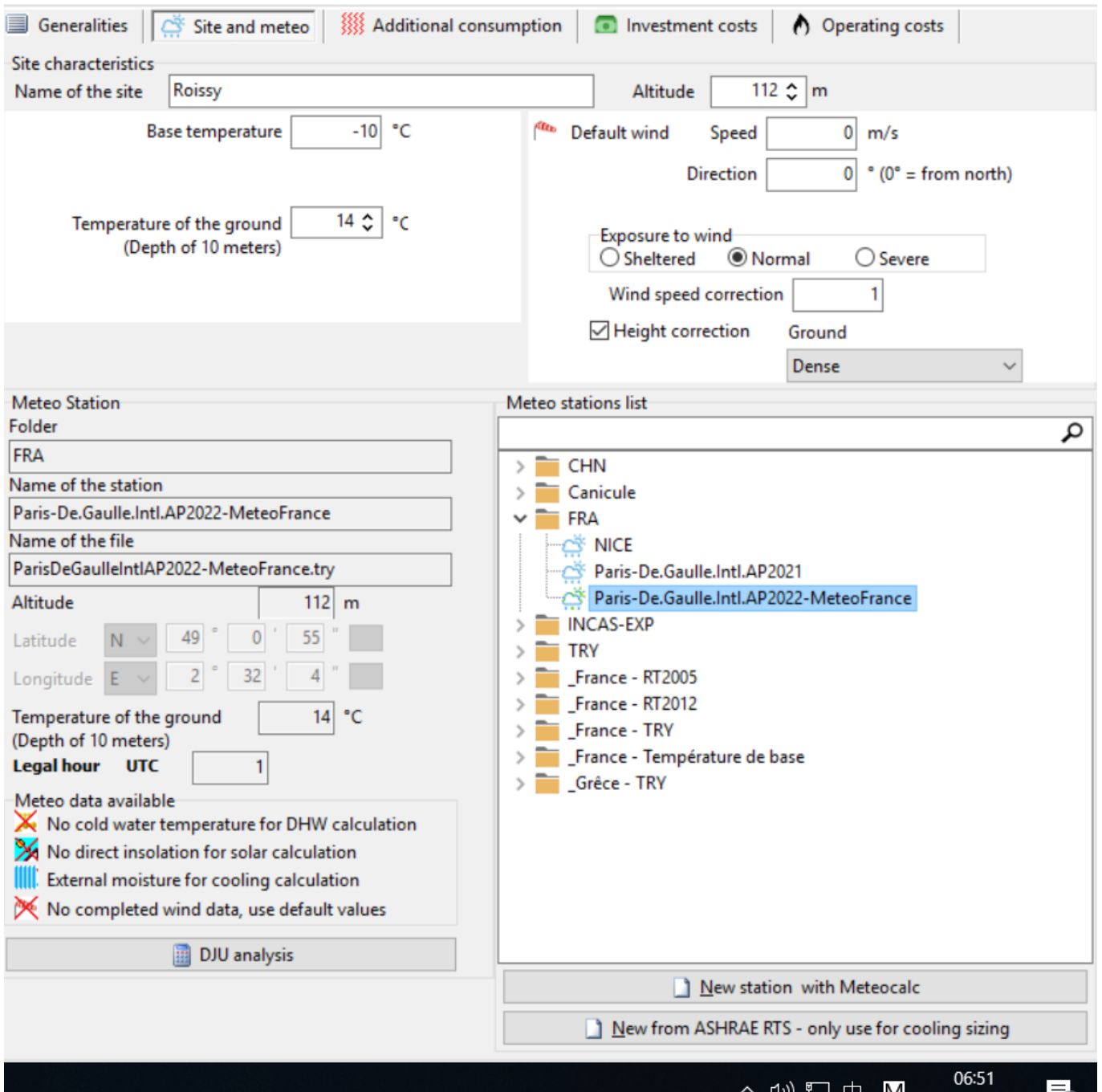


Figure: Meteorological file in Pleiades

The air temperature and total horizontal radiation (unit: J/cm²) are shown in the figures below:

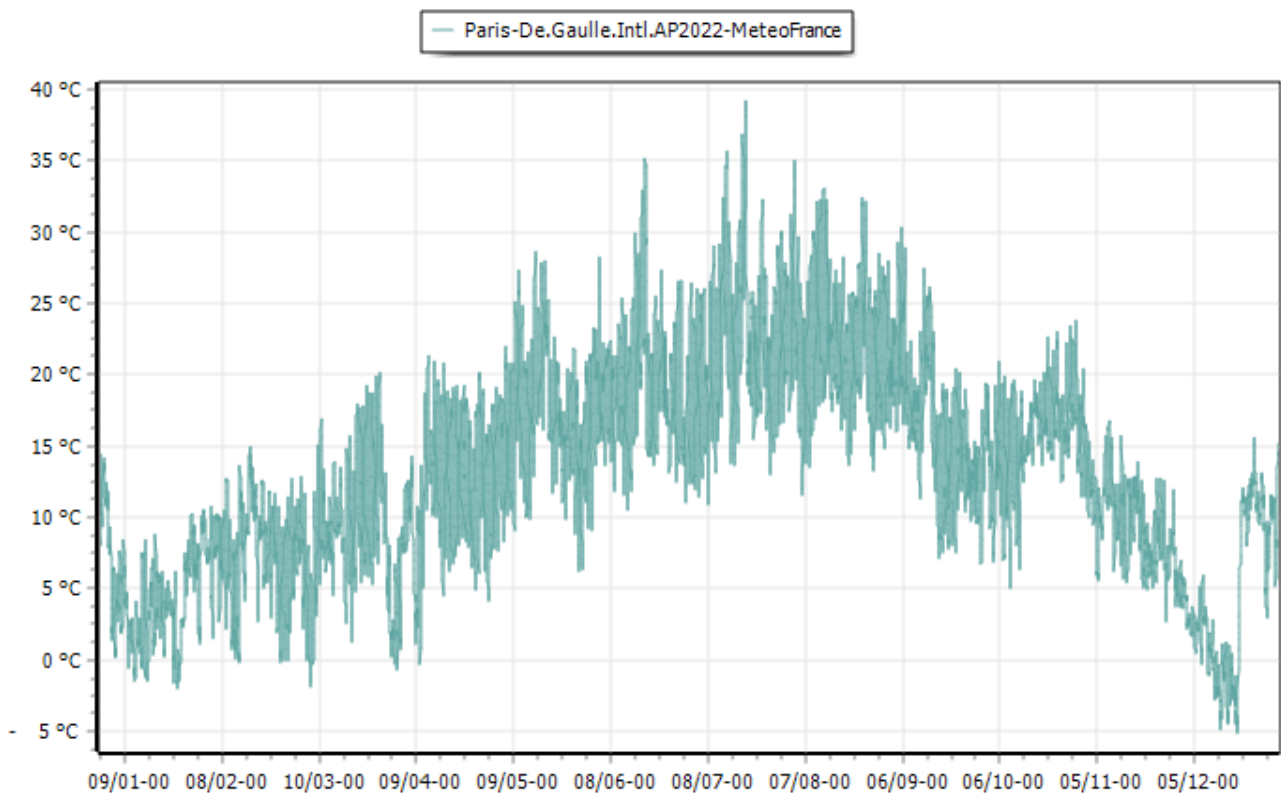


Figure: Air temperature collected by MeteoFrance in 2022

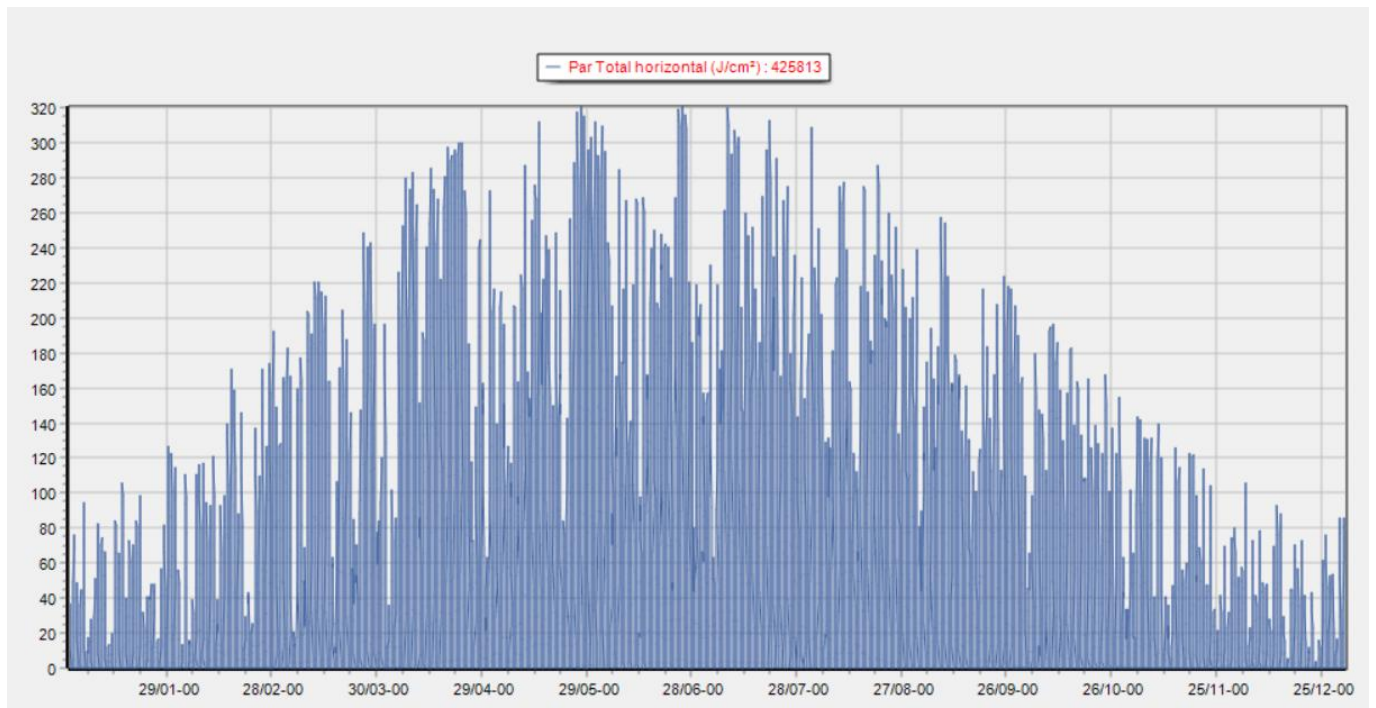


Figure: Total horizontal radiation from a typical year corresponding to the period 2007-2021



3.3.2 Zone definition

3.3.2.1 Terminal 2B

In Pleiades STD, a building is decomposed into several thermal zones for the software to calculate its thermal performance. A zone is a volume with a homogeneous thermal behavior e.g. temperature evolution and energy load. The temperature is identical in all rooms of a zone. Criteria such as the use of a room and the corresponding occupancy, the location of the room (orientation and level), internal gains and control systems are often used to divide the zones. All rooms must be allocated to thermal zones (e.g. departure hall, arrival hall, offices, shops, unheated luggage zone...).

As a first version, the model of terminal 2B was divided into 52 thermal zones, based on the following principle:

- The zones are divided based on levels and use;
- The adjacent rooms are grouped into one zone if they have the same use and the same occupancy scenarios;
- Gangways are combined into one zone;
- Vertical connections (e.g. vertical stairs) on different levels are combined to one thermal zone.
- The mezzanine levels are separately divided into zones.
- The open floors of a mezzanine level are combined with the zones of the level below.

This model was tested and the simulation time is around 3 hours and 30 minutes, which is too long, especially if the optimization process is involved. Then we regrouped the zones if they have the same temperature setting points scenarios (average the internal gain and ventilation scenarios if necessary) to minimize the number of zones in order to reduce the simulation time. After a test, the number of zones is reduced to 19, and one simulation takes around 2 hours and 3 minutes. The zones of each level are shown in different colours in the figures below. The detailed zone information of link BD is shown in the table in section 3.3.3.

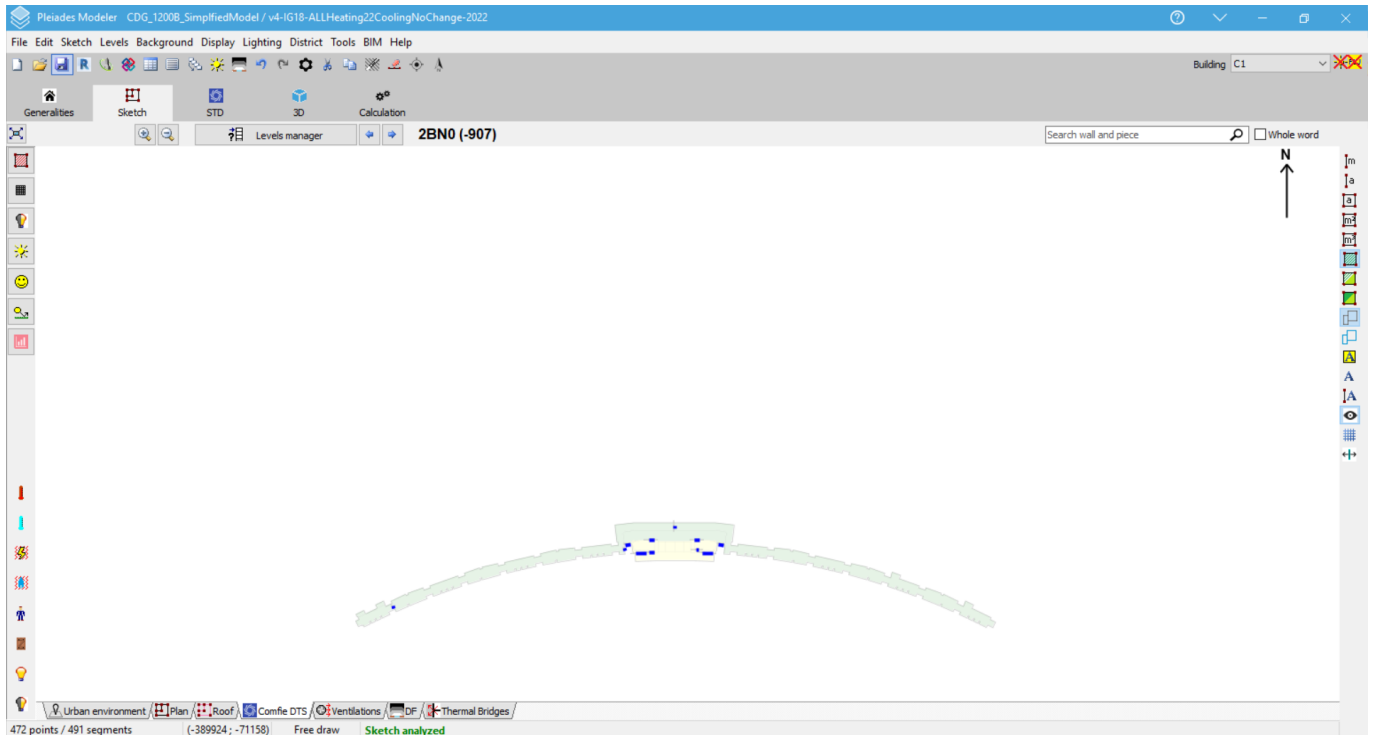


Figure: Zone definition of level N0 of Terminal 2B

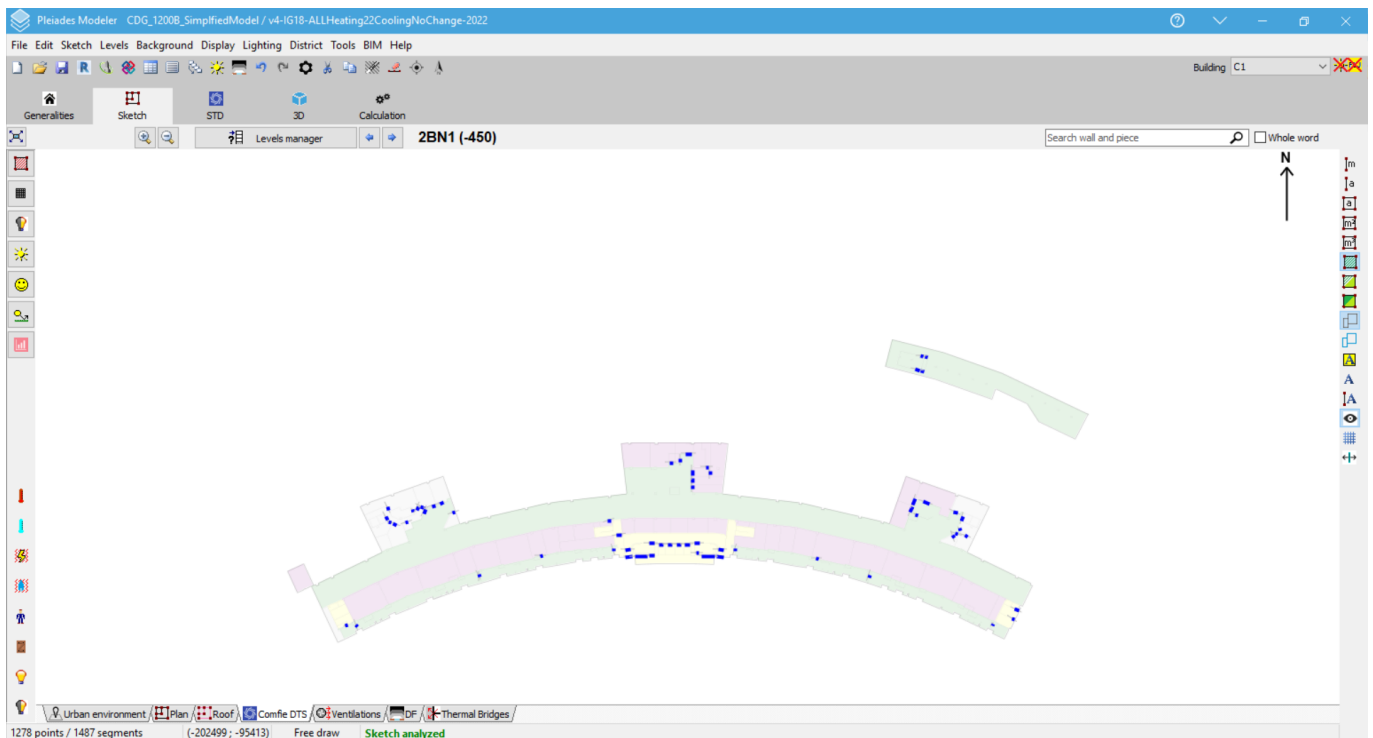


Figure: Zone definition of level N1 of Terminal 2B

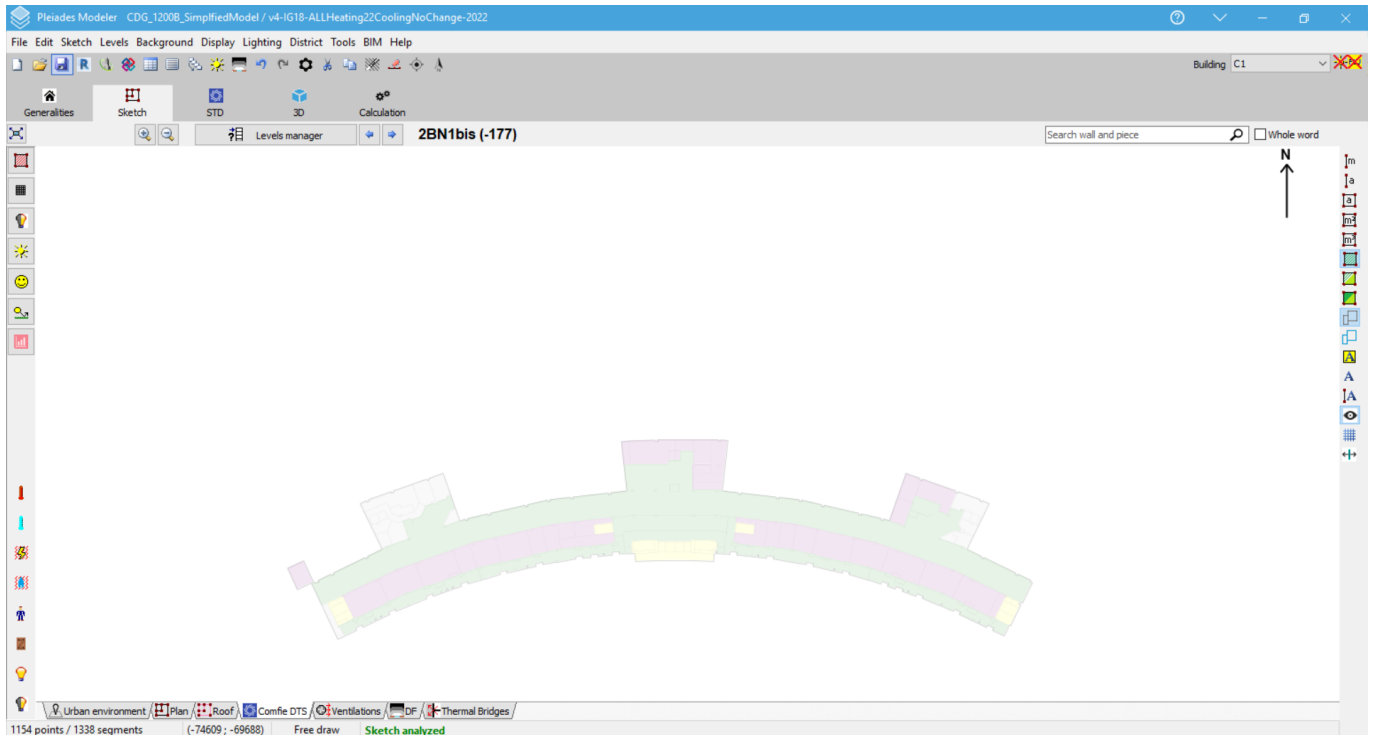


Figure: Zone definition of level N1bis of Terminal 2B

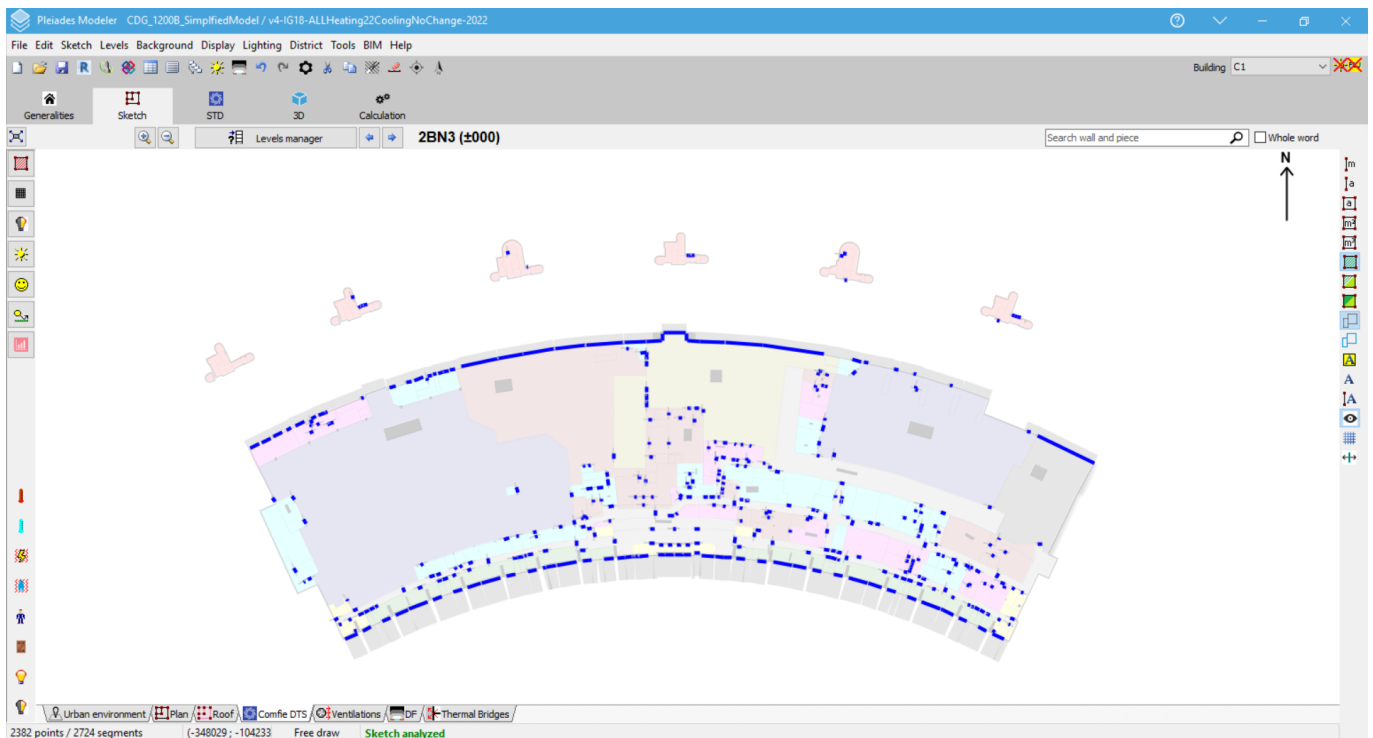


Figure: Zone definition of level N3 of Terminal 2B

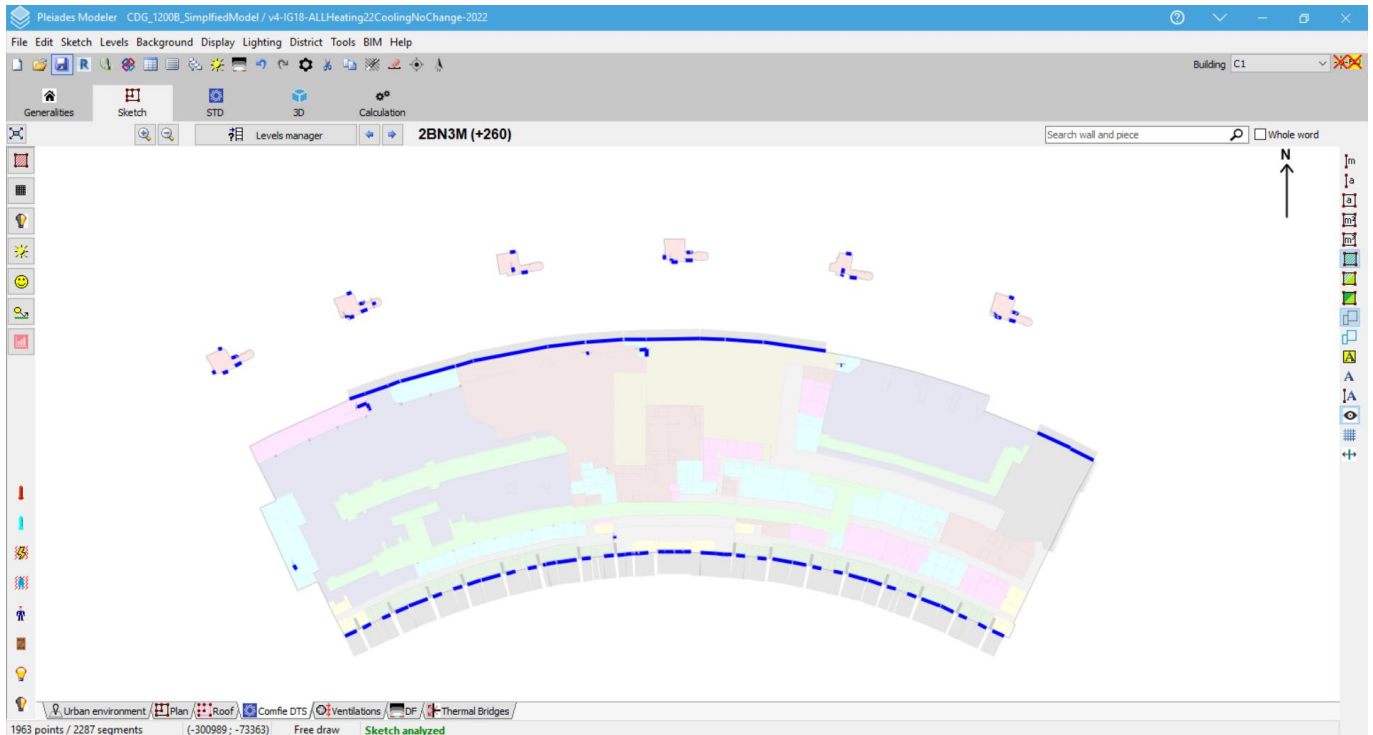


Figure: Zone definition of level N3M of Terminal 2B

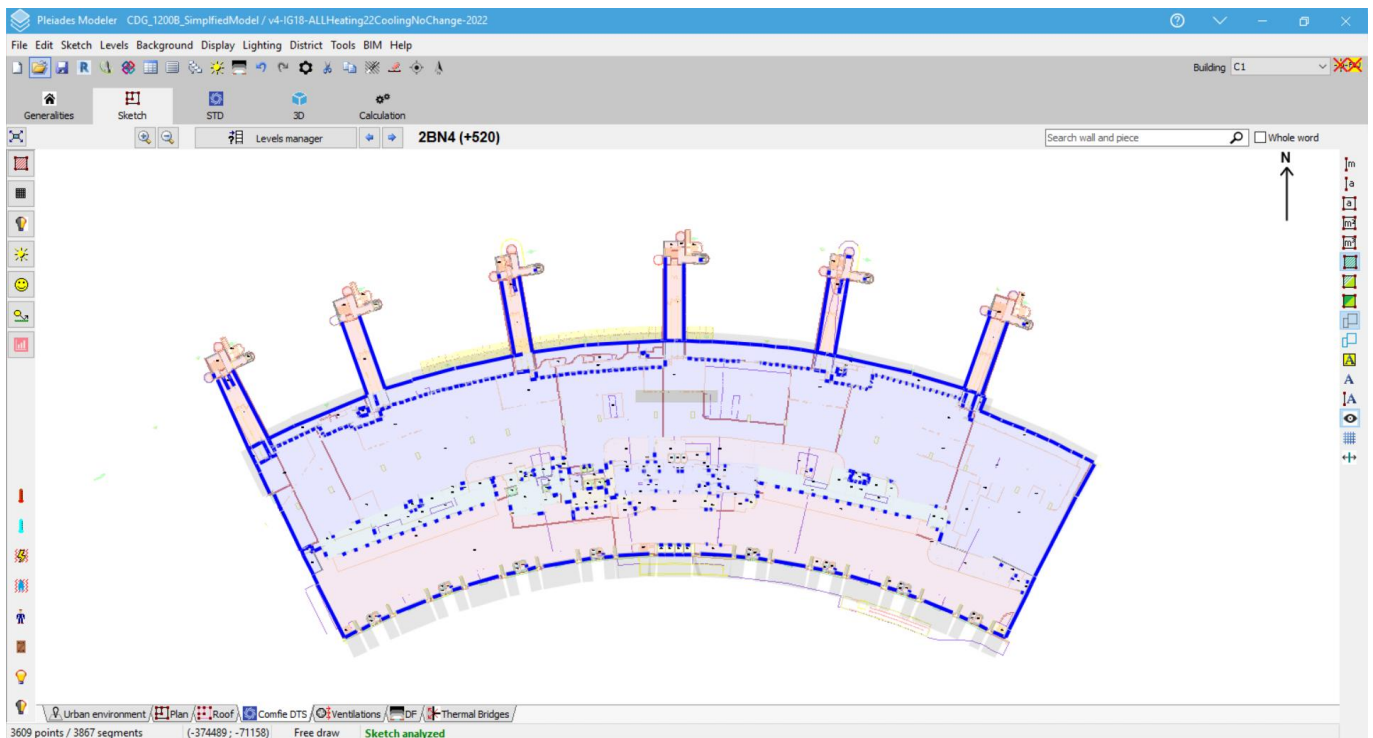


Figure: Zone definition of level N4 of Terminal 2B

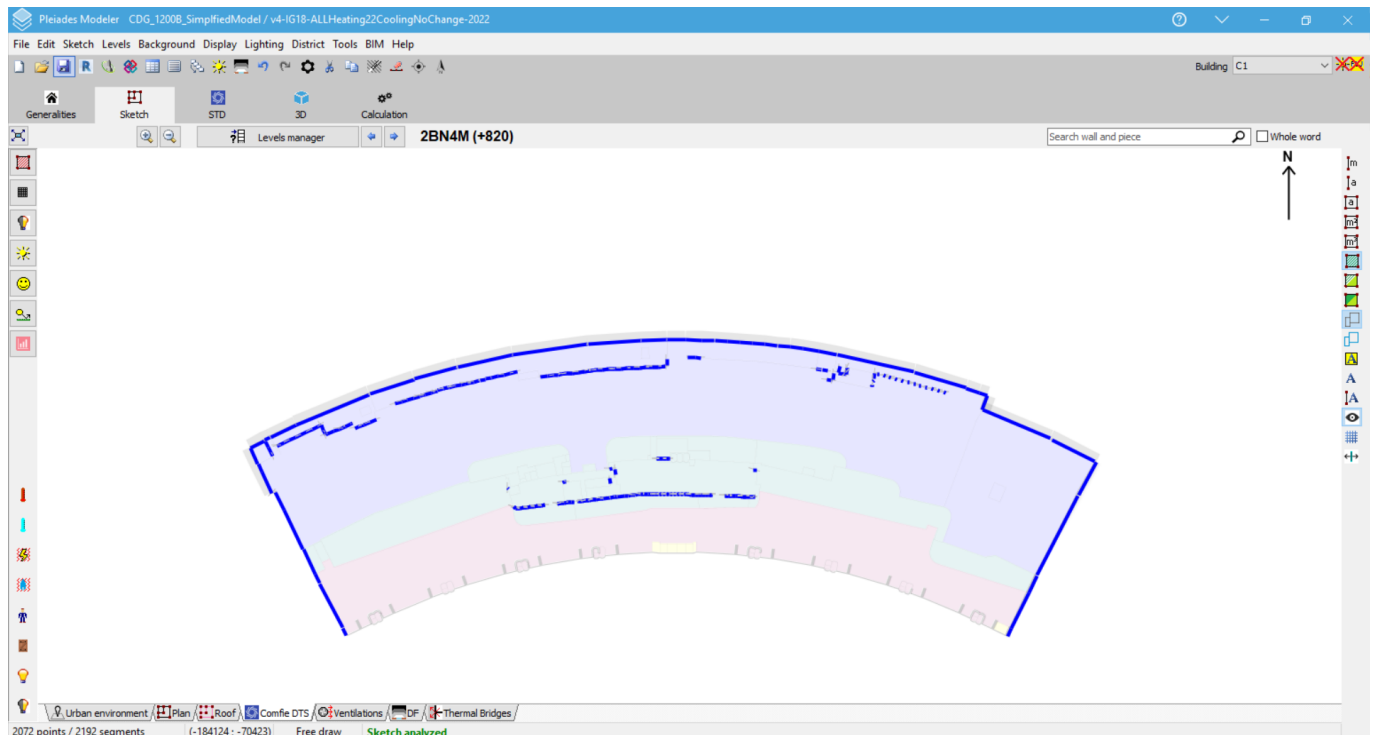


Figure: Zone definition of level N4M of Terminal 2B

3.3.2.2 Link BD

The zone definition of link BD is based on the similar criteria as terminal 2B. The zone definitions of all floors are shown in the following figures. In fact, the model of link BD is generated from the CAD plan, it contains much less details regarding the internal walls and doors. This largely reduces the computation time of Pleiades COMFIE simulations. Therefore a zone definition with more details is possible in this model. There are 44 zones in total. The detailed zone information of link BD is shown in the table in section 3.3.3.

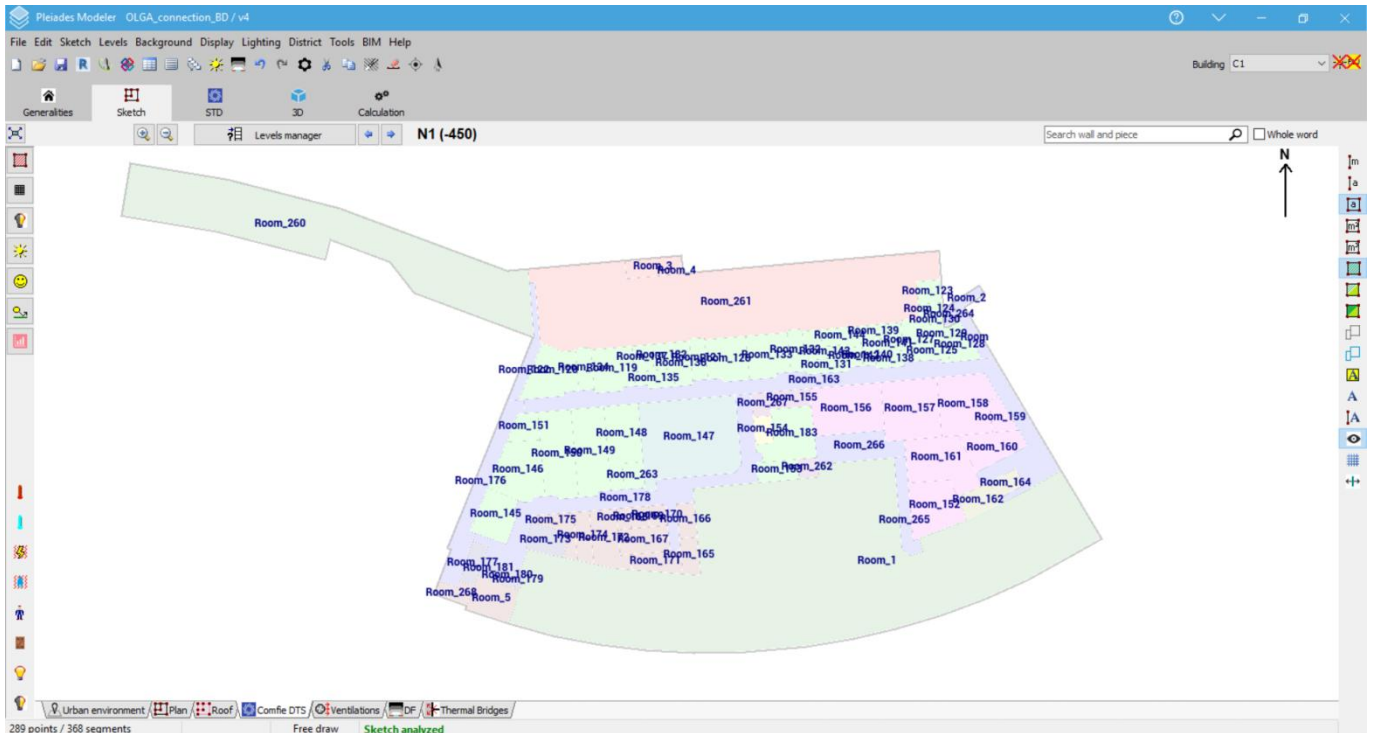


Figure: Zone definition of level N1 of link BD

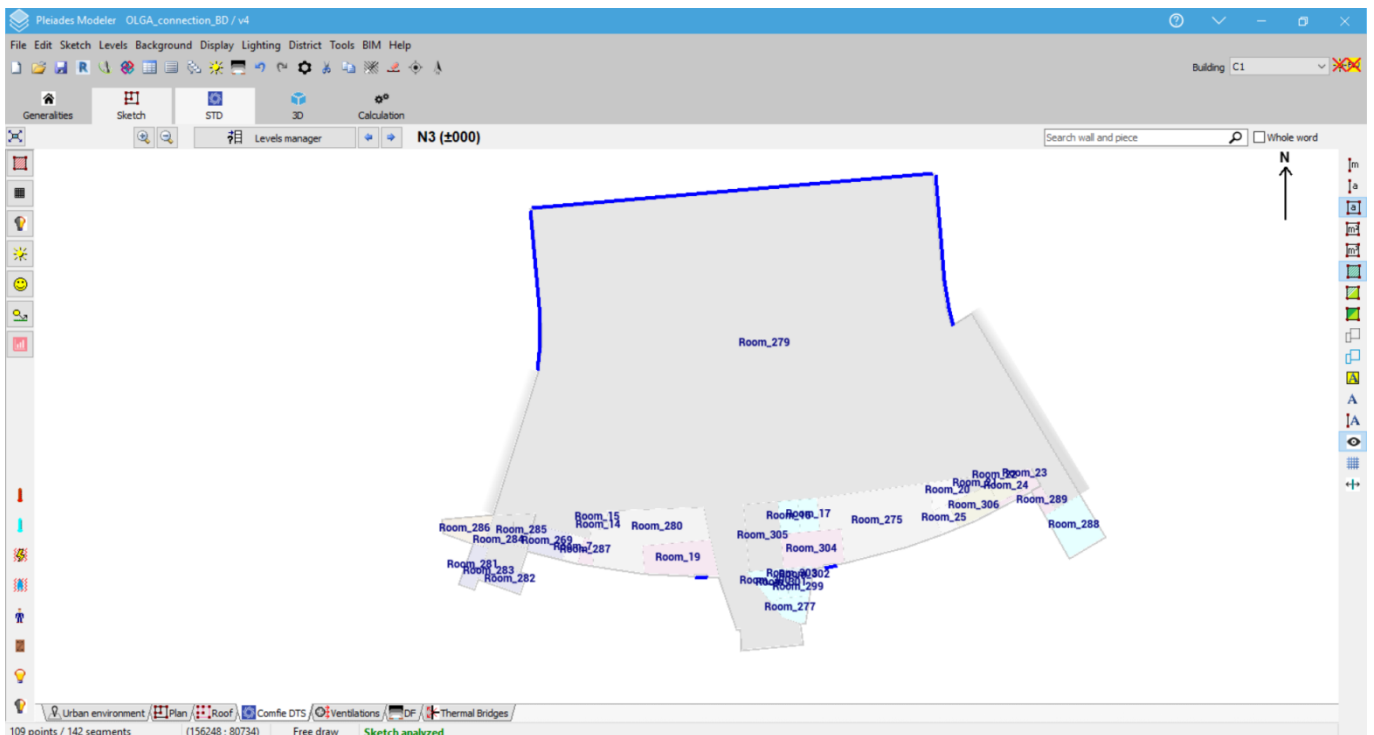


Figure: Zone definition of level N3 of link BD

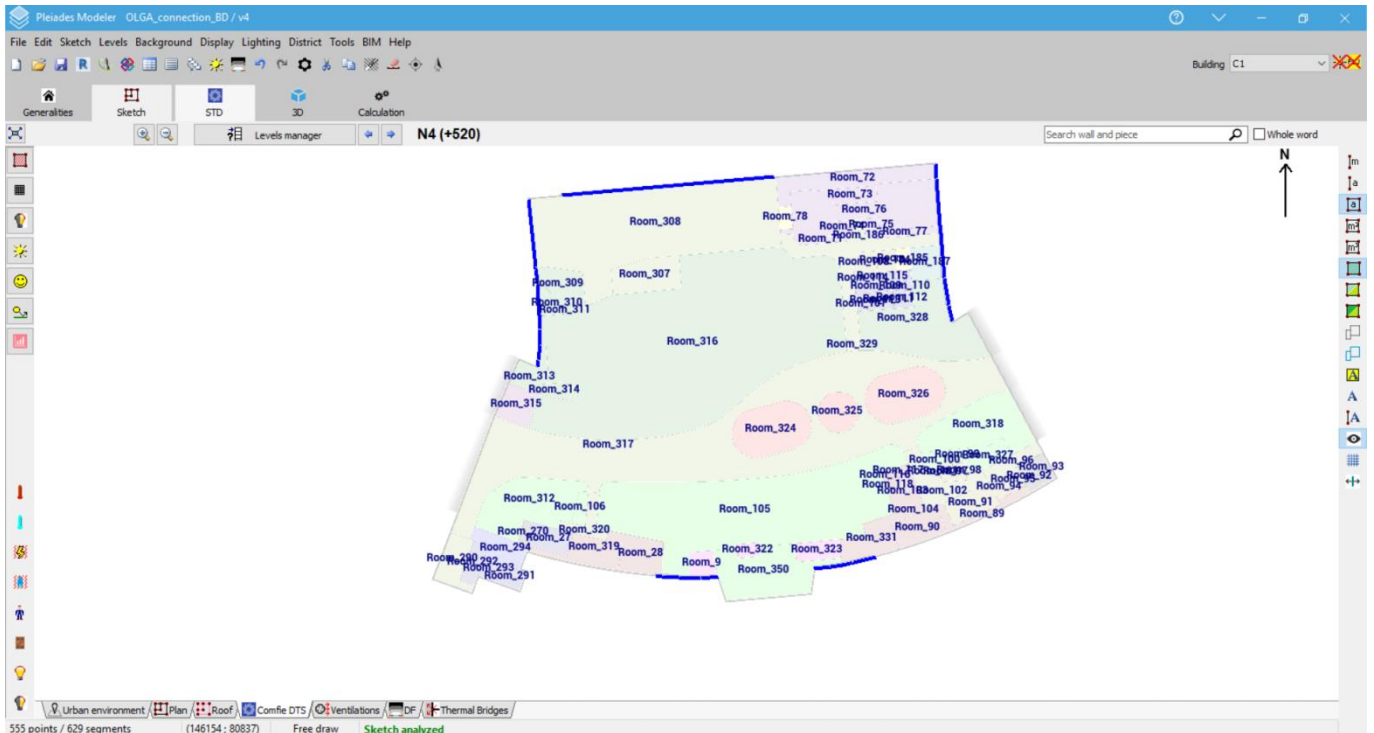


Figure: Zone definition of level N4 of link BD

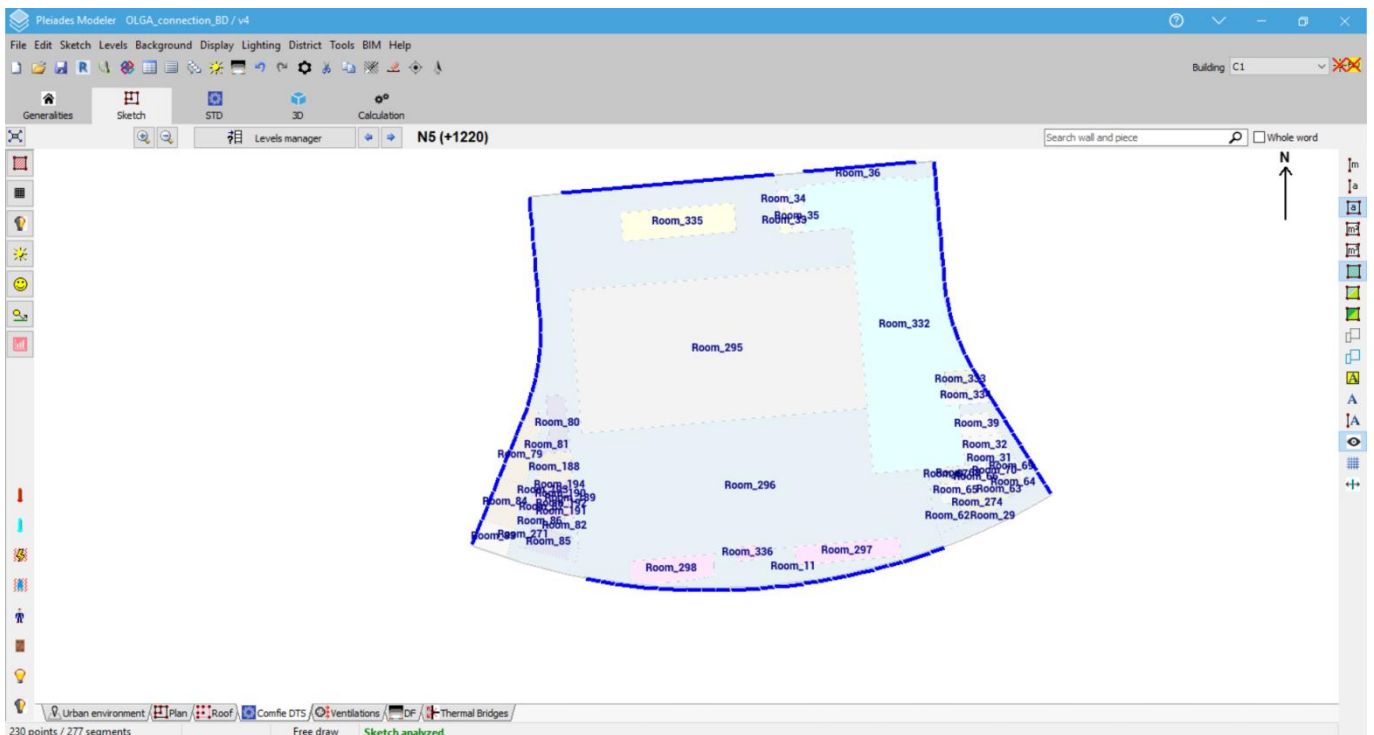


Figure: Zone definition of level N5 of link BD

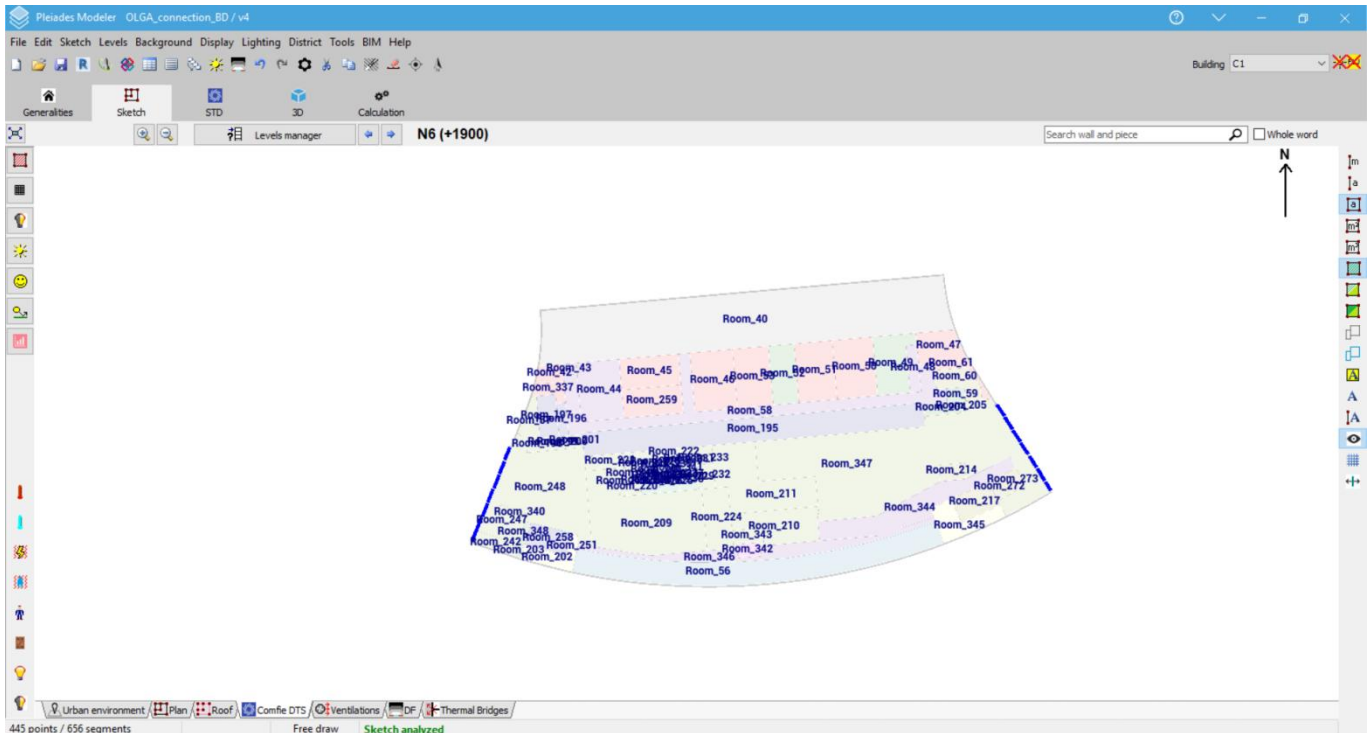


Figure: Zone definition of level N6 of link BD

3.3.3 Occupancy scenario

3.3.3.1 Scenario calibration

The scenarios strongly influence the simulation results. The heating and cooling consumptions were collected for terminal 2B and link BD. Therefore the calibration was done for the scenarios such as the heating set point, internal gain, based on the comparison between simulation results and the measurements.

The total heating and cooling loads of terminal 2B and the link BD were collected for different years, as shown in the figures below. In fact, only the year 2022 is appropriate for calibration, because other years are either incomplete or during COVID, which is not representative. The separate heating and cooling loads for terminal 2B and link BD could be estimated by distributing the total load according to their heating and cooling areas, which are 47000 m² (heating) and 36000 m² (cooling) for terminal 2B and 22800 m² (heating) and 16400 m² (cooling) for link BD

The electricity consumption is 208 kWh/m² heating area for terminal 2B and 232 kWh/m² heating area for link BD.

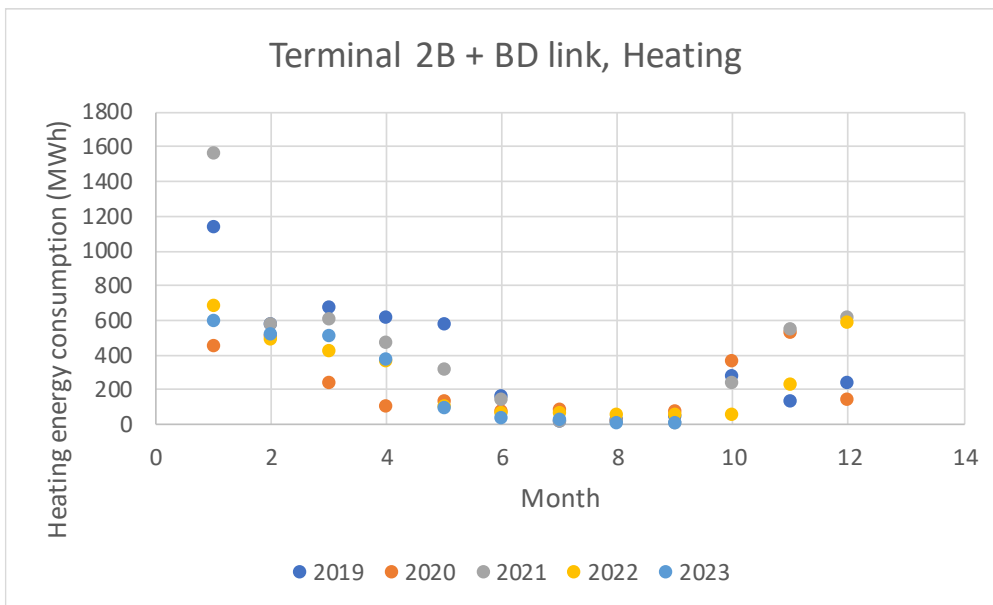


Figure: Heating need measurements in terminal 2B and link BD

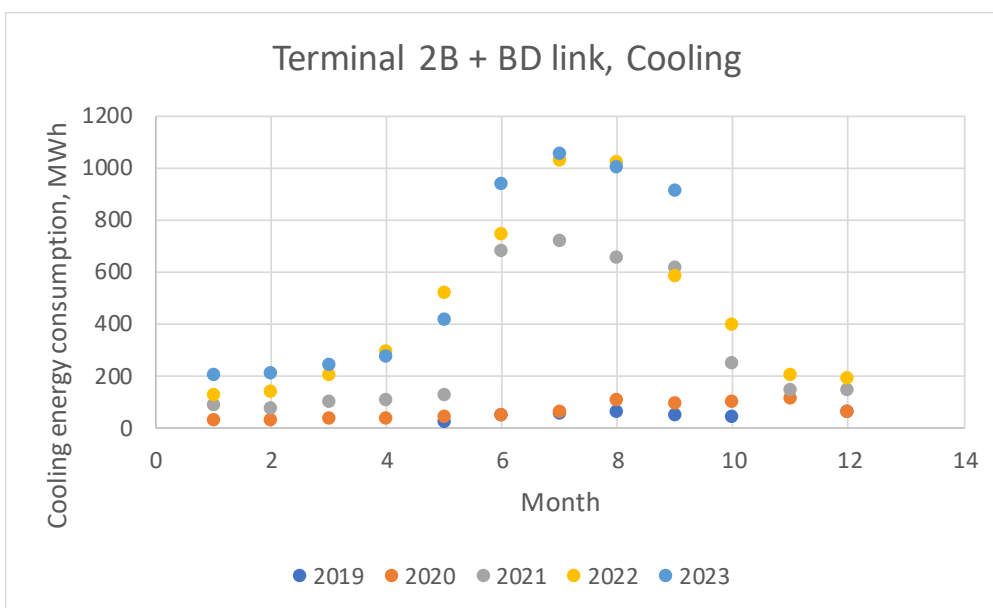


Figure: Cooling need measurements in terminal 2B and link BD

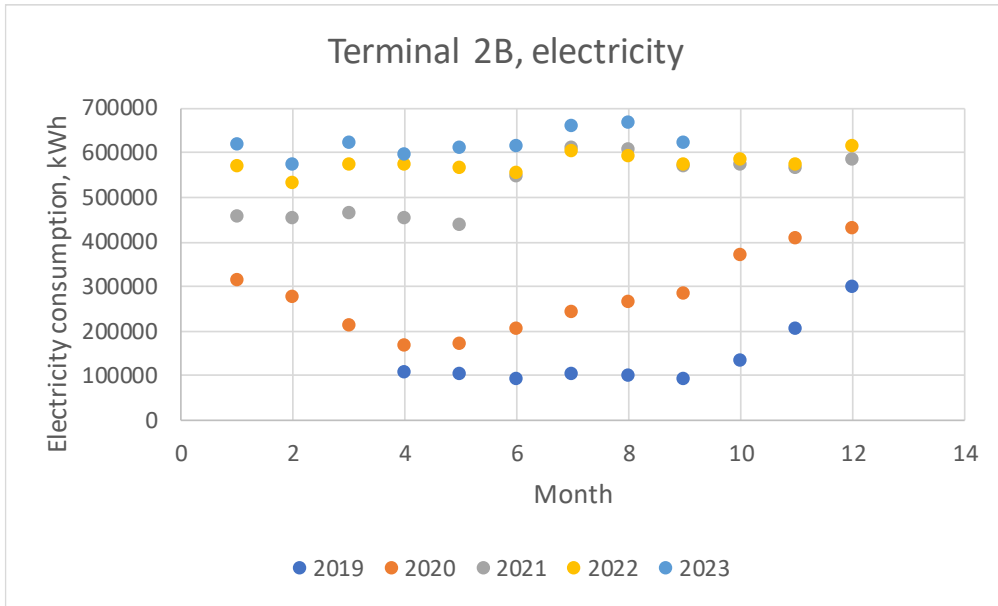


Figure: Electricity consumption measurements in terminal 2B

For the terminal 2B, the simulated heating load is 1631 MWh, which is 22% smaller than the measurements of 2022. Meanwhile the cooling load is 12% smaller and the electricity consumption is 3% is larger. For the link BD, the heating load is 695 MWh, which is 31% smaller than the measurements of 2022. Meanwhile the cooling load is 6% larger and the electricity consumption is 25% is smaller. Considering the high uncertainties regarding the climate data and occupancy scenarios, the simulation results and the scenarios in the simulation are considered acceptable. Gaps between simulation and measurements may be due to differing indoor temperatures, internal gains (e.g. related to electricity consumption in shops, offices etc.), ventilation air flow-rates, and climatic data. The details about the scenarios are listed in the sections below.

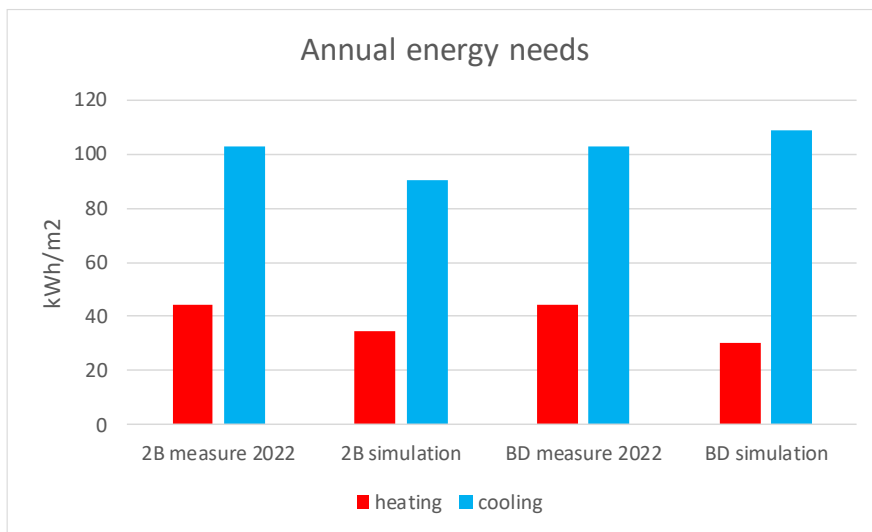




Figure: Annual needs comparison for terminal 2B and link BD

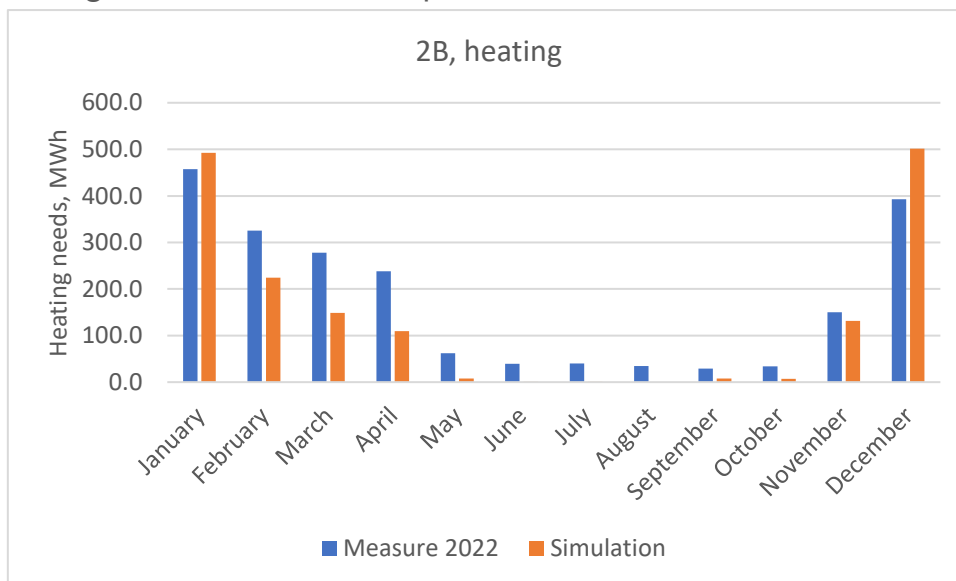


Figure: Heating needs comparison in terminal 2B

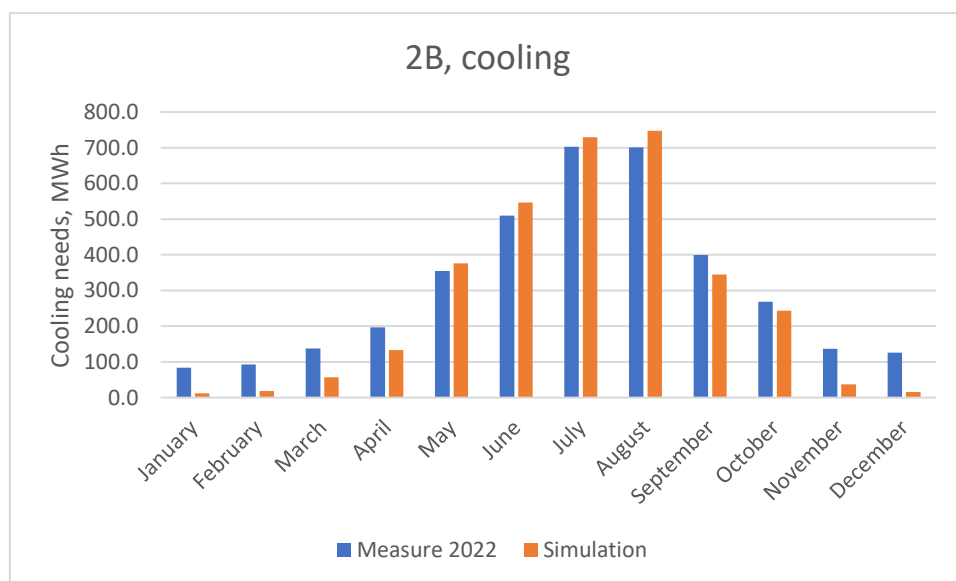


Figure: Cooling needs comparison in terminal 2B

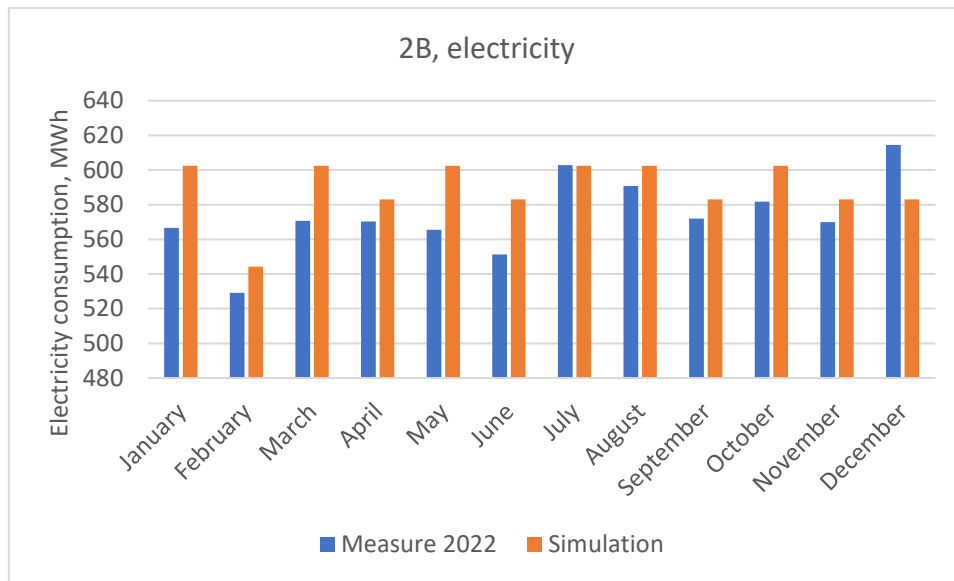


Figure: Electricity consumption comparison in terminal 2B

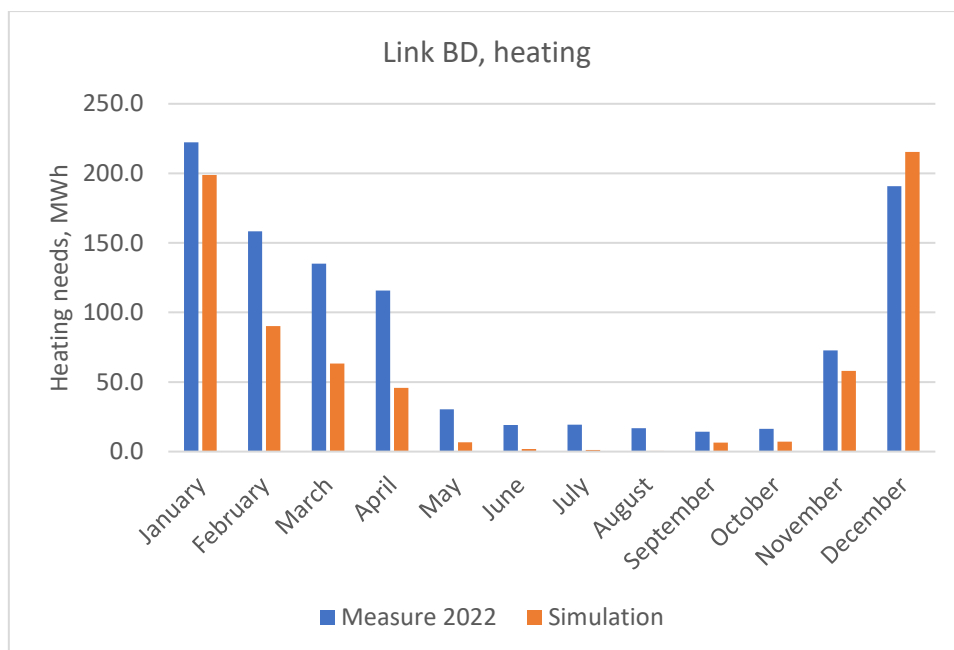


Figure: Heating needs comparison in link BD

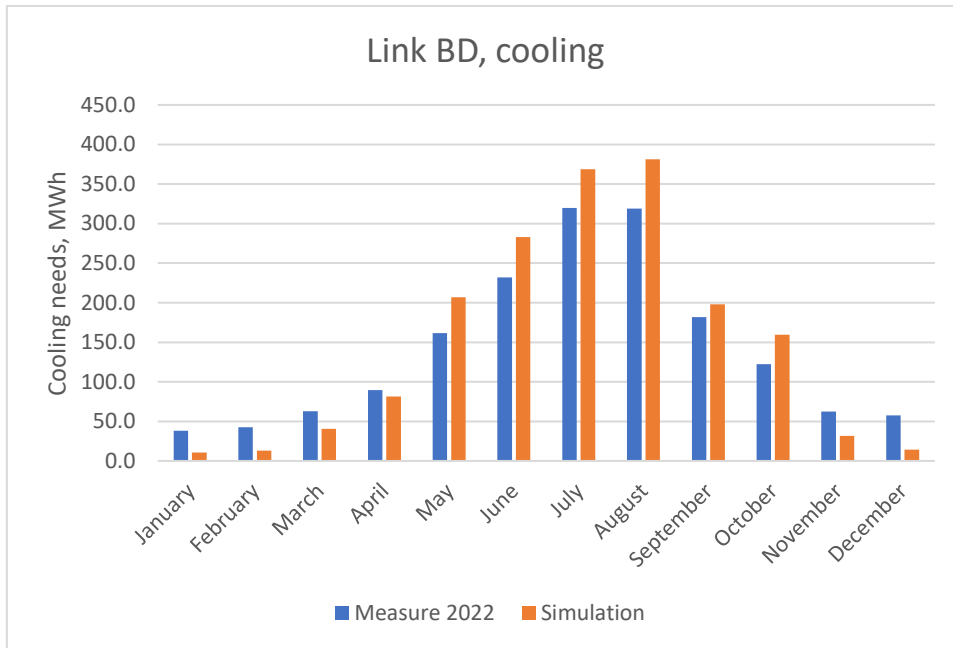


Figure: Cooling needs comparison in link BD

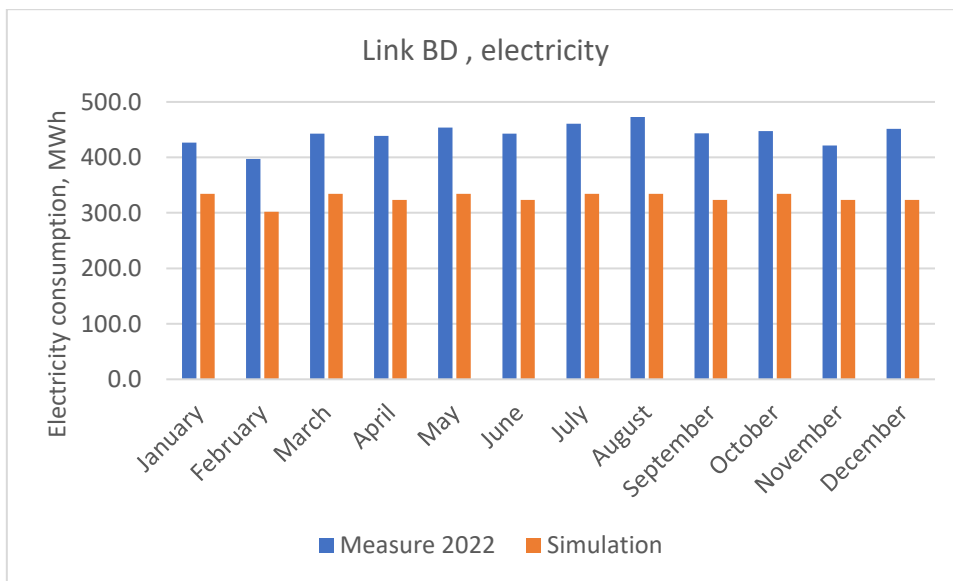


Figure: Electricity consumption comparison in link BD

3.3.3.2 Terminal 2B

The occupancy scenarios mainly include four types: heating and cooling, internal gain, occupancy and ventilation. They are summarized as scenario numbers for each zone of terminal 2B in the table below.

Table: Zone definition and their scenarios for terminal 2B



Zone number	Zone name	Heating scenario	Cooling scenario	Internal gain	Occupancy	Ventilation
1	Unheated space	-	-	IG2	O8	V2
2	Gangways	22°C all year	C4	IG13	O4	V2
3	N3M	22°C all year	C2	IG13	O5	V2
4	N4-Boarding Hall	22°C all year	C4	IG13	O4	V2
5	N4M	22°C all year	C2	IG13	O5	V2
6	Vertical connection	22°C all year	C4	IG1	O6	V2
7	N1-Technical rooms	22°C all year	C5	IG13	O7	V1
8	N3-Bagage-sorting hall	22°C all year	-	IG13	O8	V2
9	N3-Security and border check	22°C all year	C3	IG13	O2	V2
10	N3-Boarding hall	22°C all year	C4	IG13	O6	V2
11	N3-Offices	22°C all year	C2	IG13	O5	V2
12	N3-Bagage delivery hall	22°C all year	C1	IG13	O4	V2
13	N3-Horizontal circulation	22°C all year	-	IG1	O6	V2
14	N3-Technical rooms	22°C all year	C5	IG13	O7	V1
15	N4-Technical rooms	22°C all year	C5	IG13	O7	V1
16	N4-Offices	22°C all year	C2	IG13	O5	V2
17	N4-Check-In Zone	22°C all year	C4	IG13	O3	V2
18	N1-Offices	22°C all year	C2	IG13	O5	V2
19	N4-Shops	22°C all year	C4	IG13	O4	V1

The details of each scenario are presented in the table below. It should be noted that heating, cooling, internal gain, occupancy and ventilation scenarios are applied for the whole year.

3.3.3.3 Link BD

The scenarios for link BD are summarized as scenario numbers for each zone in the table below.

Table: Zone definition and their scenarios for link BD

Zone number	Zone name	Heating scenario	Cooling scenario	Internal gain	Occupancy	Ventilation
1	N1-Outside	-	-	-	-	-
2	N1-Bagage-sorting-hall	22°C all year		IG8	O8	V2
3	N1-Shops	22°C all year	C4	IG6	O4	V2
4	N1-Horizontal circulation	22°C all year		IG1	O6	V2
5	N1-Security and border check	22°C all year	C3	IG3	O2	V2
6	N1-Private toilets	22°C all year		IG2	O6	
7	N1-Office	22°C all year	C2	IG4	O5	V2
8	Vertical connection-West	22°C all year	C4	IG1	O6	V2
9	Vertical connection-East	22°C all year	C4	IG1	O6	V2
10	N1-Electricity room-West	22°C all year	C6	IG9	O7	V1
11	N1-Electricity room-East	22°C all year	C6	IG9	O7	V1
12	N3-Bagage delivery hall	22°C all year	C1	IG3	O4	V2



13	N3-Shops	22°C all year	C4	IG6	O4	V2
14	N3-Office	22°C all year	C2	IG4	O5	V2
15	N3-Private toilets	22°C all year		IG2	O6	-
16	N3-Smoking lounge	22°C all year	C4	IG1	O1	V4
17	N3-HVAC room	22°C all year		IG1	O7	-
18	N3-Electricity room	22°C all year	C6	IG9	O7	V1
19	N4-Public toilets	22°C all year	C4	IG9	O6	-
20	N4-Horizontal circulation	22°C all year		IG1	O6	V2
21	N4-Shops-North	22°C all year	C4	IG6	O4	V2
22	N4-Shops-Middle	22°C all year	C4	IG6	O4	V2
23	N4-Shops-South	22°C all year	C4	IG6	O4	V2
24	N4-Smoking lounge-South	22°C all year	C4	IG1	O1	V4
25	N4-Smoking lounge-North	22°C all year	C4	IG1	O1	V4
26	Vertical connection-North	22°C all year	C4	IG1	O6	V2
27	N4-Restaurant technical room-West	22°C all year	-	IG2	O7	-
28	N4-Restaurant technical room-East	22°C all year	-	IG2	O7	-
29	N4-Electricity room-North	22°C all year	C6	IG9	O7	V1
30	N4-Electricity room-South	22°C all year	C6	IG9	O7	V1
31	Vertical connection-Middle	22°C all year	C4	IG1	O6	V2
32	N4-HVAC room	22°C all year		IG1	O7	-
33	N5-Security check	22°C all year	C3	IG3	O2	V2
34	N5-Shops	22°C all year	C4	IG6	O4	V2
35	N5-Horizontal circulation	22°C all year		IG1	O6	V2
36	N5-Office	22°C all year	C2	IG4	O5	V2
37	N5-Private toilets	22°C all year		IG2	O6	-
38	N5-Electricity room	22°C all year	C6	IG9	O7	V1
39	N6-Horizontal circulation	22°C all year		IG1	O6	V2
40	N6-Shops	22°C all year	C4	IG6	O4	V2
41	N6-Private toilets	22°C all year		IG2	O6	-
42	N6-Electricity room-South	22°C all year	C6	IG9	O7	V1
43	N6-HVAC room	22°C all year		IG1	O7	-
44	N6-Electricity room-North	22°C all year	C6	IG9	O7	V1



Scenario	Hour																								
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Cooling scenario (°C)	C1						26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	
	C2					26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
	C3			26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26		
	C4			26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
	C5	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
	C6	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Internal gain scenario (W/m ²)	IG1	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	
	IG2	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
	IG3	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
	IG4	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	
	IG6	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	
	IG8	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	
	IG9	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	
	IG11	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	
	IG12	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	176	
IG13	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18		
Occupancy scenario (person/m ²)	O2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25		
	O3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2		
	O4	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17		
	O5	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14		
	O6	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10		



	O7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	O8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ventilation scenario (vol/h)	V1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	V2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	V4	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10



3.4 Results of the dynamic thermal simulation

3.4.1 Terminal 2B

A simulation was performed for the model of terminal 2B. The time for analyzing the file during the pre-calculation period is around 30 minutes. The calculation time of this model for one simulated year is around 2 hours 30 minutes.

The Sankey diagram of the yearly balance of terminal 2B is shown in the figure below.

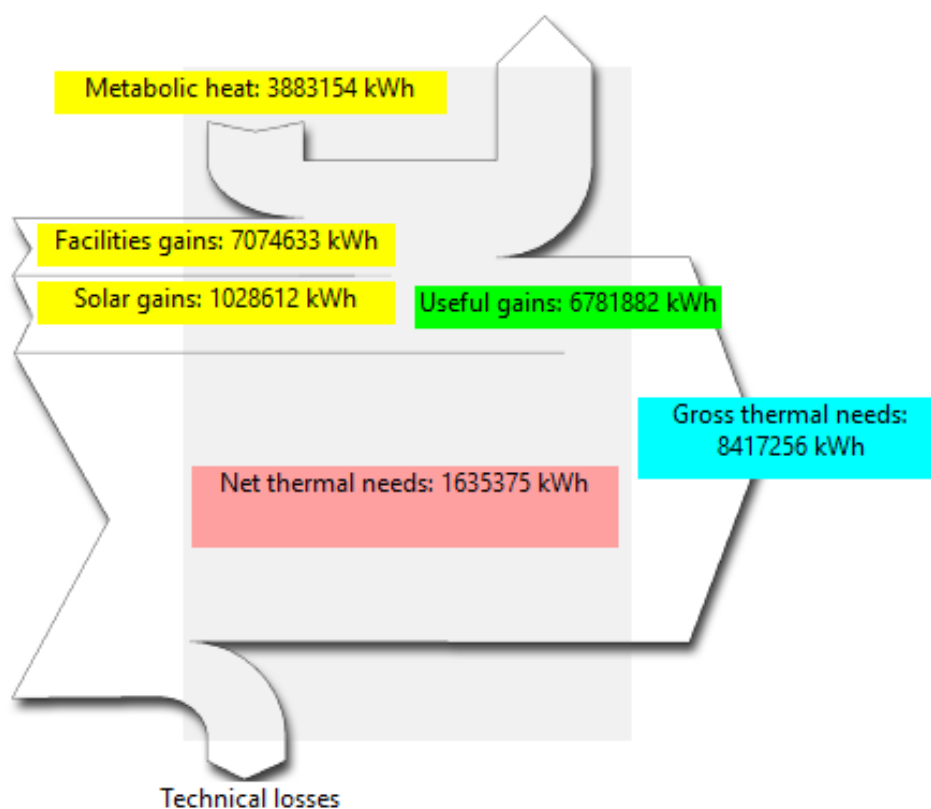


Figure: Sankey figure for the simulation of terminal 2B

The net heating area is 44 200 m² and the net cooling area is 36 000 m². The total annual heating and cooling loads are 1 635 375 kWh and 3 271 009 kWh, respectively, which corresponds to 37 kWh/m² and 91 kWh/m². The heating and cooling powers are shown in the figure below. The maximal heating power is 1728 kW and the maximal cooling power is 2743 kW. These values may be reduced by considering a slower temperature variation when starting heating or cooling in the early morning. The main contribution of the heating load comes from the boarding hall on level N4, which is around 28% of the total heating load. The boarding hall on level N4 still contributes the most cooling load (22% of the total cooling load), with a cooling load of 74 kWh/m².

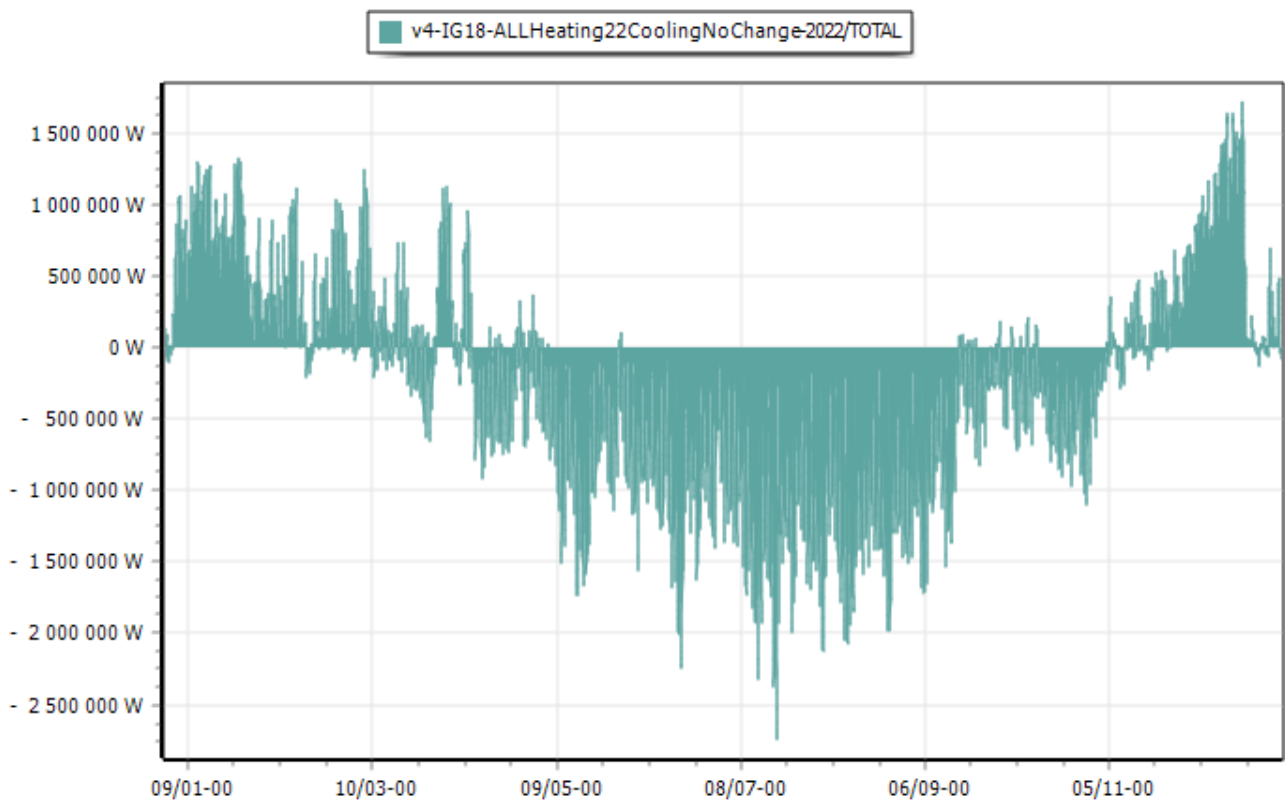


Figure: Hourly heating and cooling power in the simulation of terminal 2B

The temperature and heating/cooling power of the boarding hall on level N4 are shown in the figure below. During the heating season, the temperature is always above 22°C. In summer, the temperature could be higher than 26°C because during night the cooling systems are off for three hours between 23h and 2h. The highest temperature is 30.4°C. The maximal heating and cooling power are 516 kW and 885 kW, respectively (again, these values may be reduced by considering a slower temperature variation when starting heating or cooling in the early morning). The discomfort rate is 2%. Its annual solar gain is 321 618 kWh and internal gain is 1 547 775 kWh.

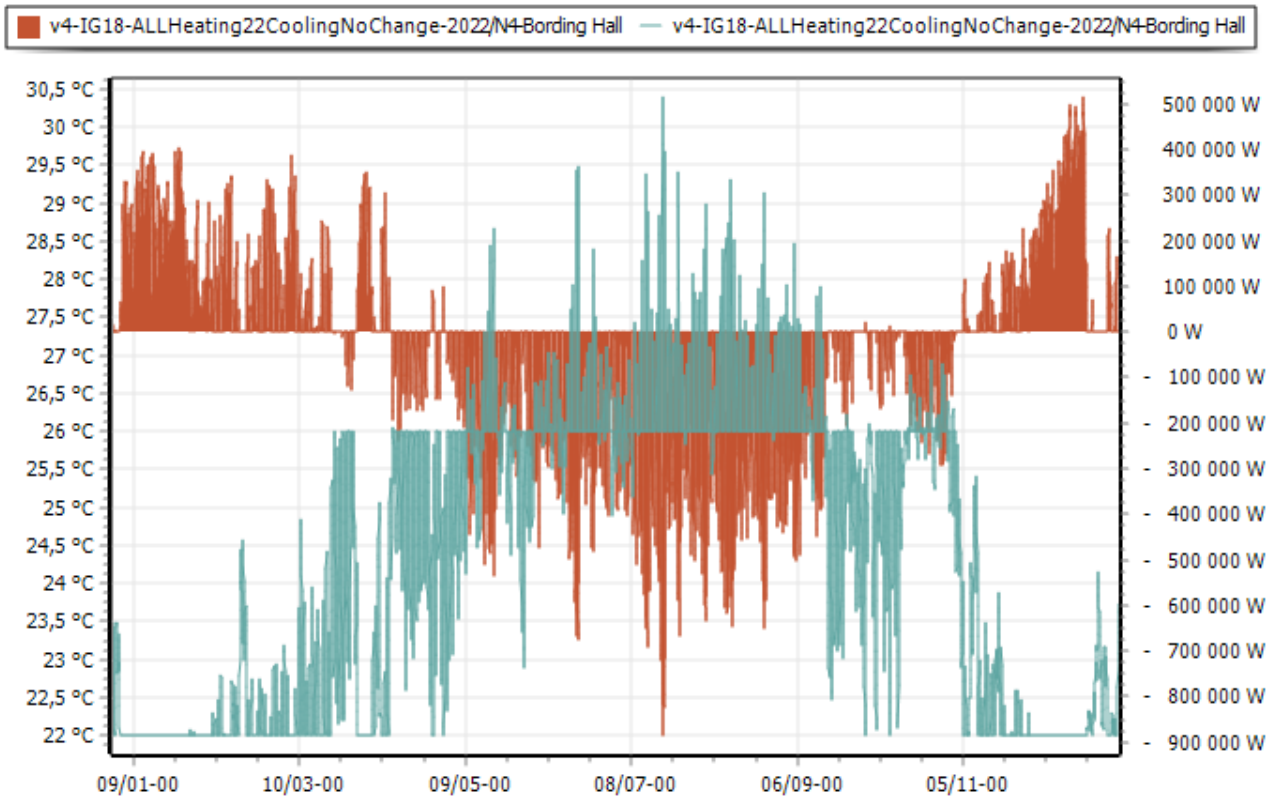


Figure: Temperature and heating/cooling power of the boarding hall on N4 in the simulation of terminal 2B

3.4.2 Link BD

The Sankey diagram of the yearly balance of BD link is shown in the figure below. The net heating area is 23 230 m² and the net cooling area is 16 300 m². The total annual heating and cooling loads are 696 900 kWh and 1 793 600 kWh, respectively, which corresponds to 30 kWh/m² and 110 kWh/m². The heating and cooling powers are shown in the figure below. The maximal heating power is 783 kW and the maximal cooling power is 1273 kW (again, these values may be reduced by considering a slower temperature variation when starting heating or cooling in the early morning).

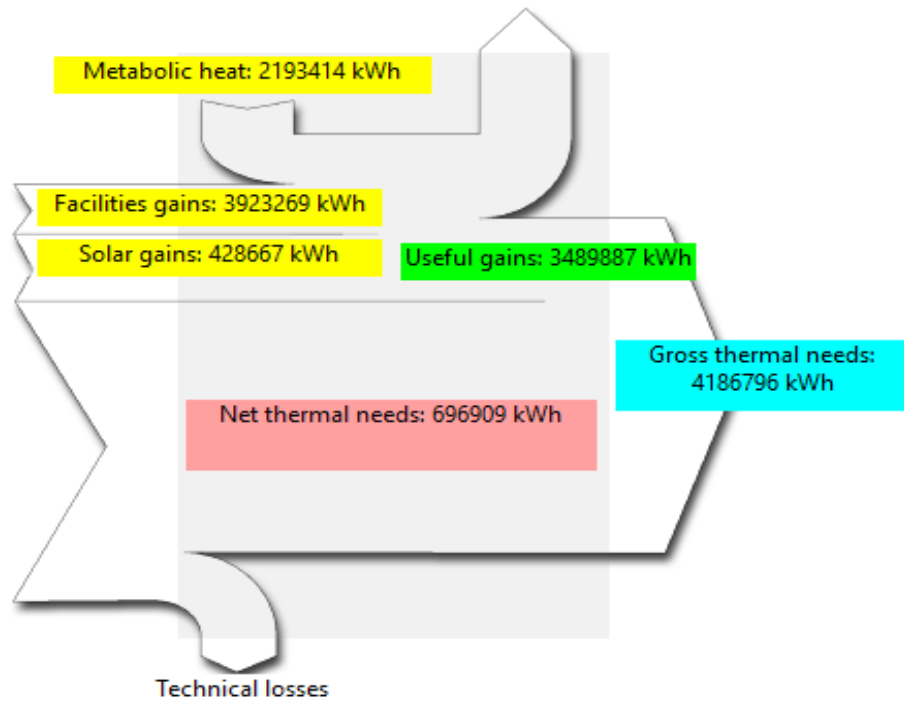


Figure: Sankey figure for the simulation of link BD

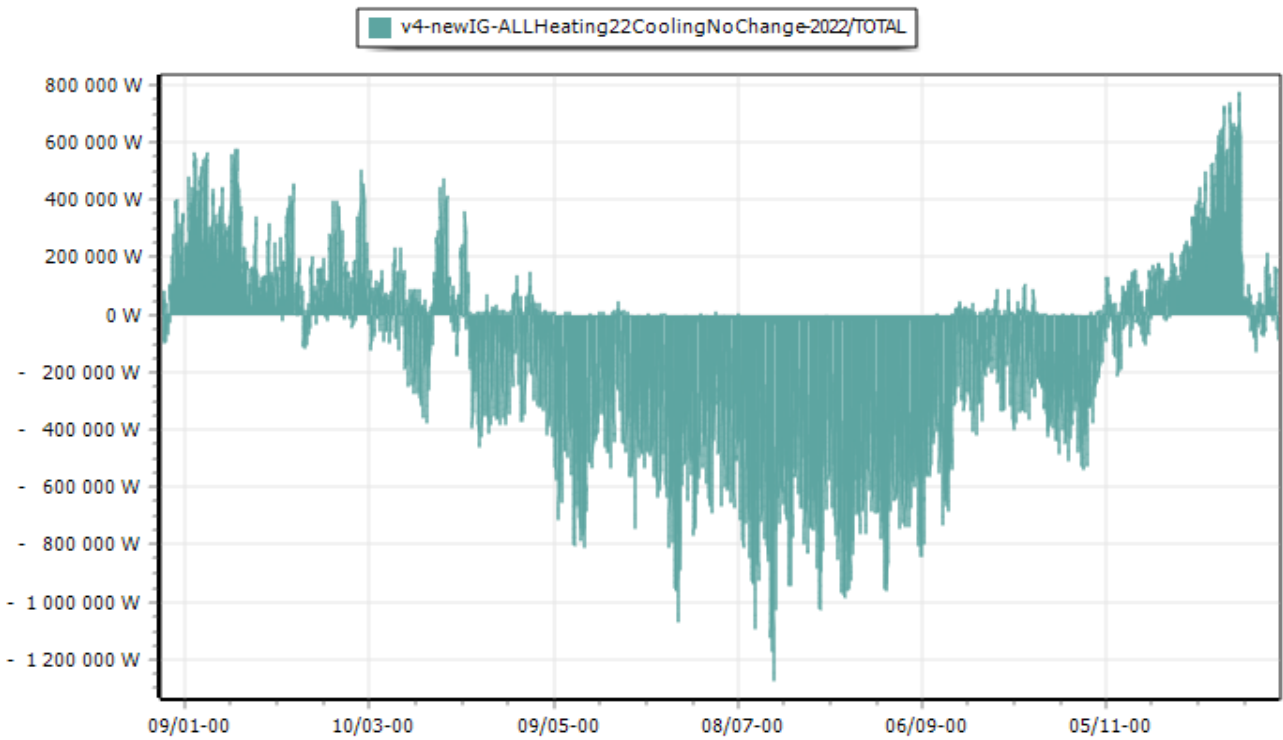


Figure: Hourly heating and cooling power in the simulation of link BD



The main contribution of the heating load comes from the zone N5-horizontal circulation, which is around 30% of the total heating load. The temperature and heating/cooling power of the zone N5-horizontal circulation are shown in the figure below. During the heating, the temperature is always above 22 °C. In summer, there is no cooling setpoint for this area. The highest temperature is 36.3 °C. The maximal heating power is 116 kW (again, this value may be reduced by considering a slower temperature variation when starting heating or cooling in the early morning). The discomfort rate is 25 %. Its annual solar gain is 187 297 kWh and internal gain is 131 288 kWh.

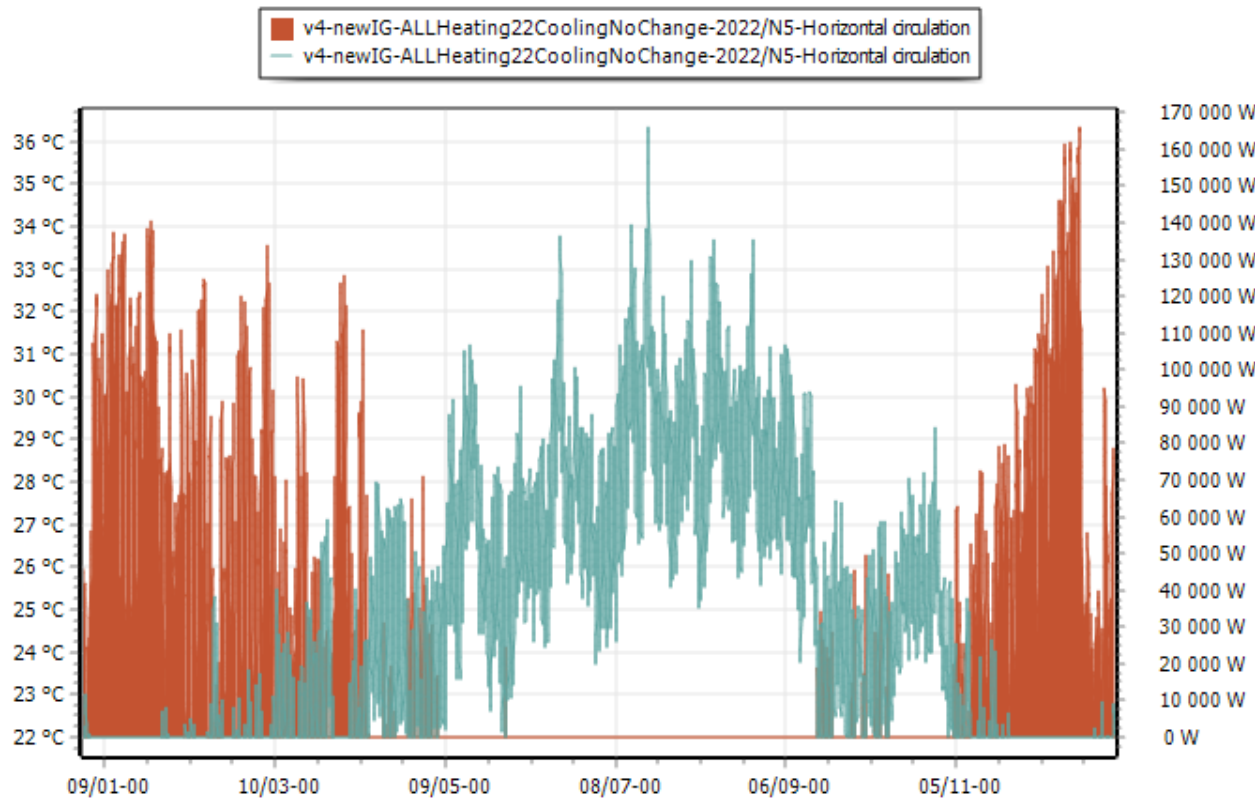


Figure: Temperature and heating/cooling power of N5-horizontal circulation in the simulation of link BD

The zone N3-bagage delivery hall contributes 25.3% of the cooling load, which is the most, with a cooling load of 97 kWh/m². The temperature and heating/cooling power of the zone N3-bagage delivery hall are shown in the figure below. During the heating, the temperature is always above 22 °C. In summer, the cooling temperature is maintained at 26 °C but it could be higher because the cooling system is switched off during night. The highest temperature is 32.1 °C. The maximal heating and cooling power are 111 kW and 395 kW, respectively (again, these values may be reduced by considering a slower temperature variation when starting heating or cooling in the early morning). The discomfort rate is 10 %. Its annual solar gain is 48 765 kWh and internal gain is 817 469kWh.

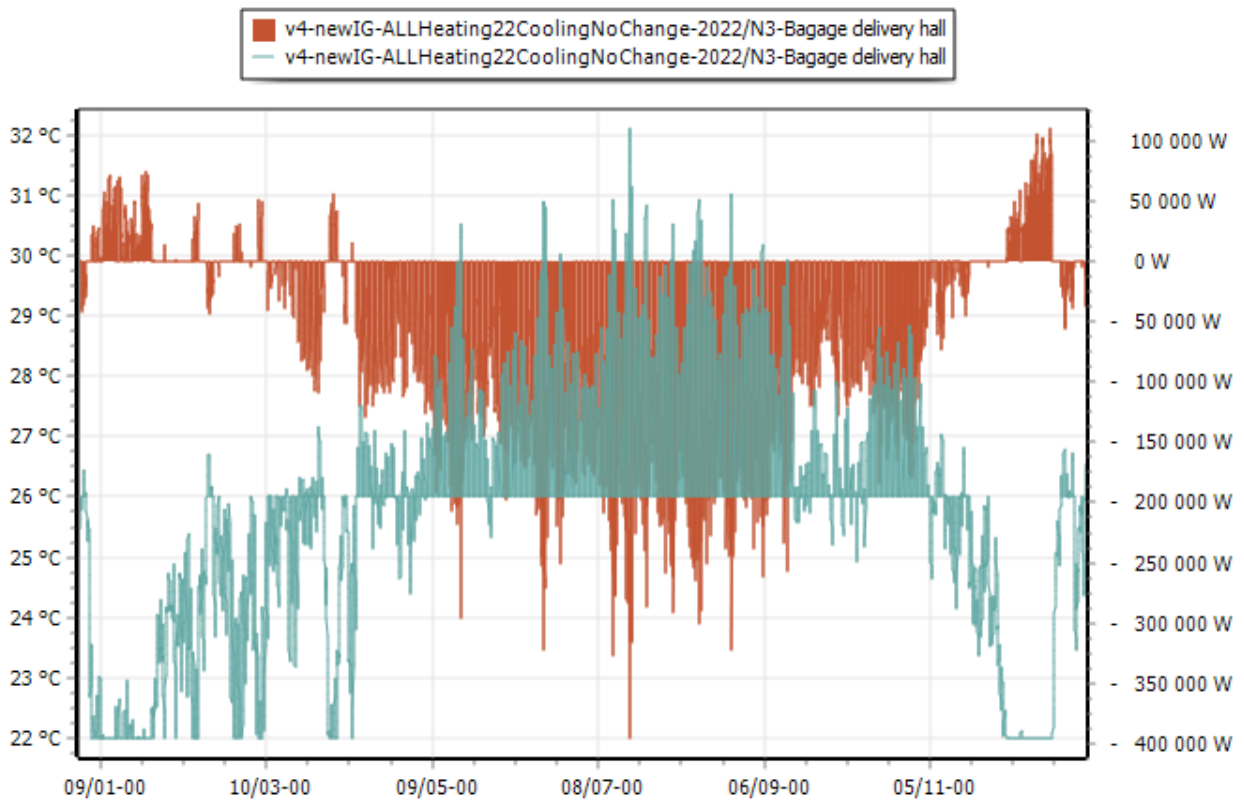


Figure: Temperature and heating/cooling power of N3-baggage delivery hall in the simulation of link BD

3.5 Results of the life cycle assessment

3.5.1 Goal and scope definition

The main goal of LCA for this study is to evaluate the environmental impacts such as CO₂ emission and primary energy consumption of the airport terminal 2B and the link BD, then compare the impacts of the existing buildings to the optimized proposals.

The evaluation scope covers the entire life cycle (which is assumed to be 50 years) of the building, consisting of the construction stage, the use stage, the renovation stage (depending on the lifespan of building materials and components) and the deconstruction stage. The system boundaries include the processes related to building operation, e.g. district heating using gas and wood for heating and domestic hot water (DHW), upstream processes (e.g. materials fabrication) and downstream processes (e.g. landfill or recycling of materials at end-of-life). Because the project is related to renovation of terminals, materials corresponding to foundations are not accounted for, and neither equipment like computers nor other devices. Focusing on the environmental impacts



of the building, the daily transportation of the persons and waste generation by users are not considered.

The functional unit is 1 m² over one year based on a lifespan of 50 years for the terminal 2B and link BD of airport CDG located near Paris.

3.5.2 Inventory analysis

The amount of each material is calculated using the LCA tool EQUER of Pleiades and the corresponding element in the ecoinvent⁵ database is used in the evaluation. For instance, if a manufacturer name is used for the insulation in the model (e.g. PSE therm TH32), the corresponding element has to be identified in ecoinvent (here, polystyrene). Version 3.4 of ecoinvent is used in this study. The amounts of materials of link BD are summarised in the following table.

Table: Materials in link BD and corresponding LCI items in ecoinvent

<i>Name</i>	<i>LCI item in ecoinvent</i>	<i>Masse</i>	<i>Unit</i>
Acier (générique)	Acier fortement allié	38 602.36	kg
Béton lourd	Béton B25	13 933 484.98	kg
Default	_default	125 242.06	m ²
Enduit extérieur	Enduit extérieur minéral	97 055.30	kg
Isolant PSE Therm TH32	Polystyrène expansé	8 642.04	kg
Isolant ROCKFEU	Laine de roche	34 321.14	kg
Laine de bois	Laine de roche	284 472.48	kg
Laine de verre	Laine de verre	10 621.80	kg
Lame d'air > 1.3 cm	Aucune association	344.72	kg
OLGA-Glazing-V200	Aluminium double vitrage	292.14	m ²
OLGA-Glazing-V202	Aluminium double vitrage	531.47	m ²
OLGA-Glazing-V204	Aluminium double vitrage	69.81	m ²
OLGA-Glazing-V205	Aluminium double vitrage	395.82	m ²
OLGA-Glazing-V209	Aluminium double vitrage	1 052.23	m ²
OLGA-Glazing-V210	Aluminium double vitrage	377.13	m ²
Parpaing de 20	Parpaing de béton cellulaire	140 782.94	kg
Placoplatre BA 13	Plâtre - plaque	507 887.74	kg
Weber therm Ultra 22	Polyuréthane - mousse	2 776.23	kg

In the assumptions, the weights of fabricated materials are 5 % higher than the needed materials in order to account for on-site processes, broken elements and superfluous purchased quantities. The materials are transported by truck over 100 km. The building elements lifespans are 10 years for finishes, 20 years for equipment, 30 years for windows and doors, and 50 years for the building itself. The materials and equipment are replaced at their end of life in the renovation stage. The

⁵ ecoinvent is a global reference database specializing in life cycle inventory (LCI) data, used to assess the environmental impacts of products and services through life cycle assessment (LCA).



distance from the material factories to the construction site is assumed as 100 km. These assumptions could be done in the software interface as shown below.

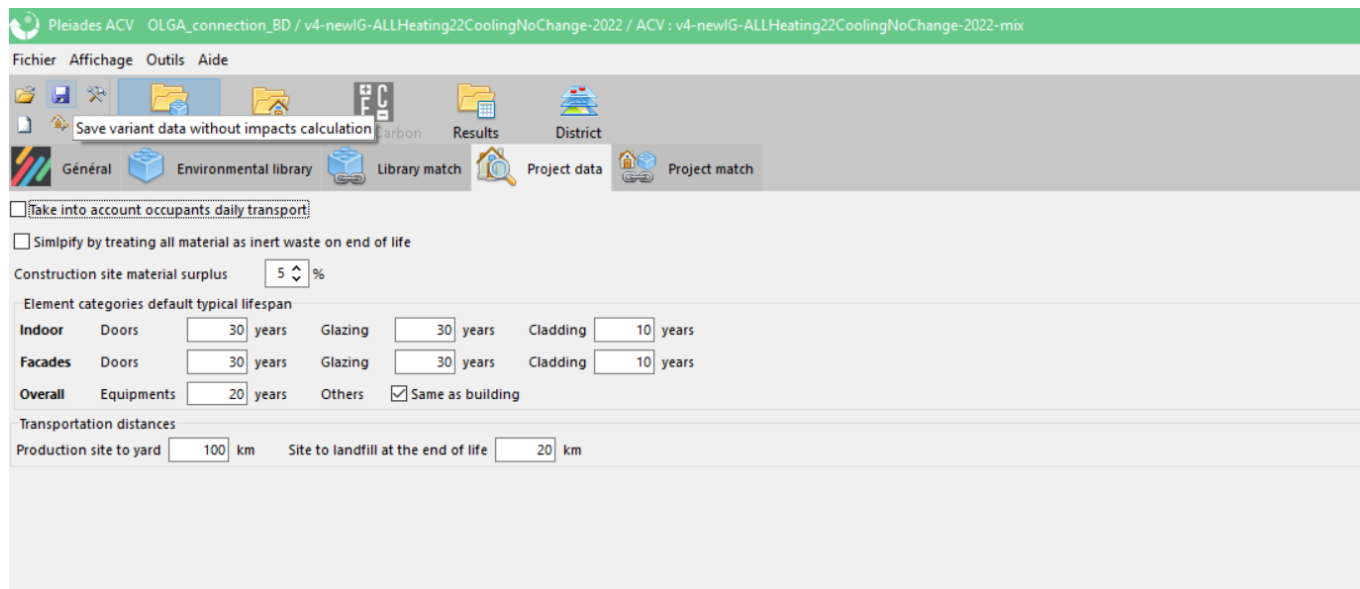


Figure: Interface of assumption settings in Pleiades LCA

The treatments of the materials at end of life are landfilling, incineration or recycling. The concrete and the steel are supposed to be recycled at a recycling rate of 100%, 50% for aluminium double glazing windows. Polystyrene and polyurethane are assumed to be incinerated and the other materials are supposed to be landfilled. The distance from the site to landfill plant in the deconstruction stage is 20 km.

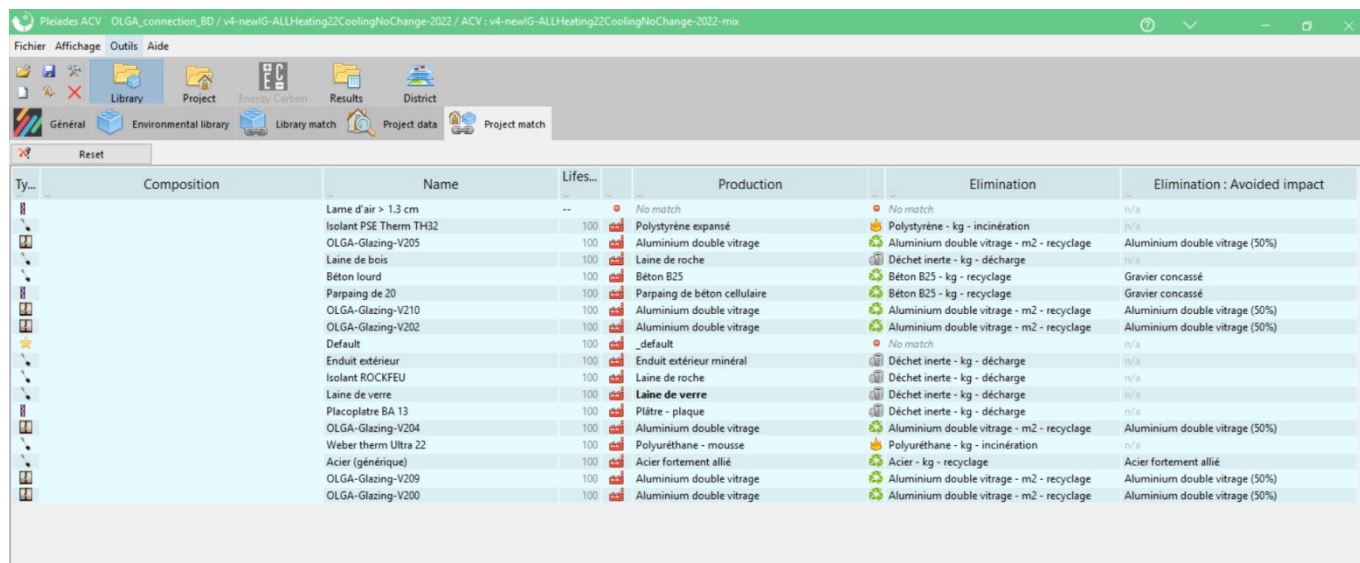


Figure: Interface of life end settings of materials in Pleiades LCA



The total number of occupants, resulting from ratios of m^2 per person for different uses, is 3138 and the useful (net) area (SURT) is assumed to be $22,833 \text{ m}^2$ for link BD. These could be set in the interface below. The corresponding values for terminal 2B are 5579 occupants for $44,200 \text{ m}^2$.

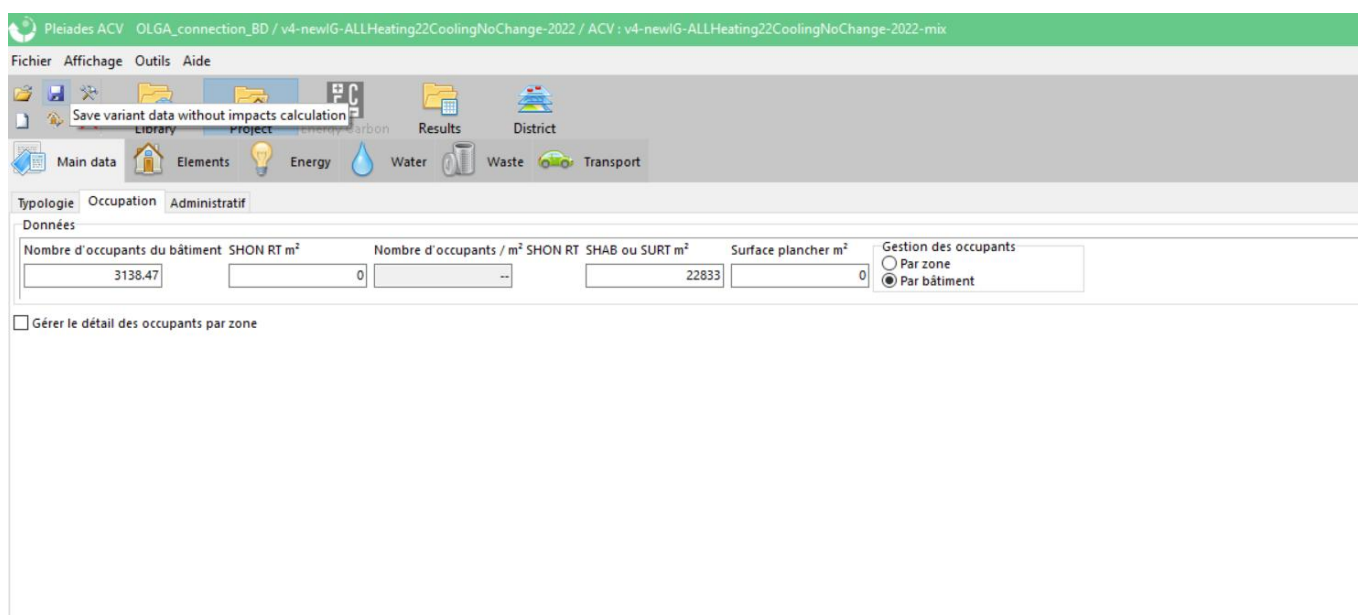


Figure: Interface of occupant number and useful (net) area settings in Pleiades LCA

Regarding the energy consumption, there are four main uses to be considered: heating, cooling, DHW and specific electricity (including lighting and ventilation). Heating and DHW are provided by district heating based upon 75% natural gas and 25% wood. The cooling is supplied by a heat pump driven by electricity with an Energy Efficiency Ratio (EER) of 4. The specific electricity is supplied by the electricity grid. The electricity network loss is 9%. An hourly dynamic electricity mix in France is considered, corresponding to an average over 50 years according to a scenario provided by the French Environment Agency (ADEME). These could be set in the interface below.

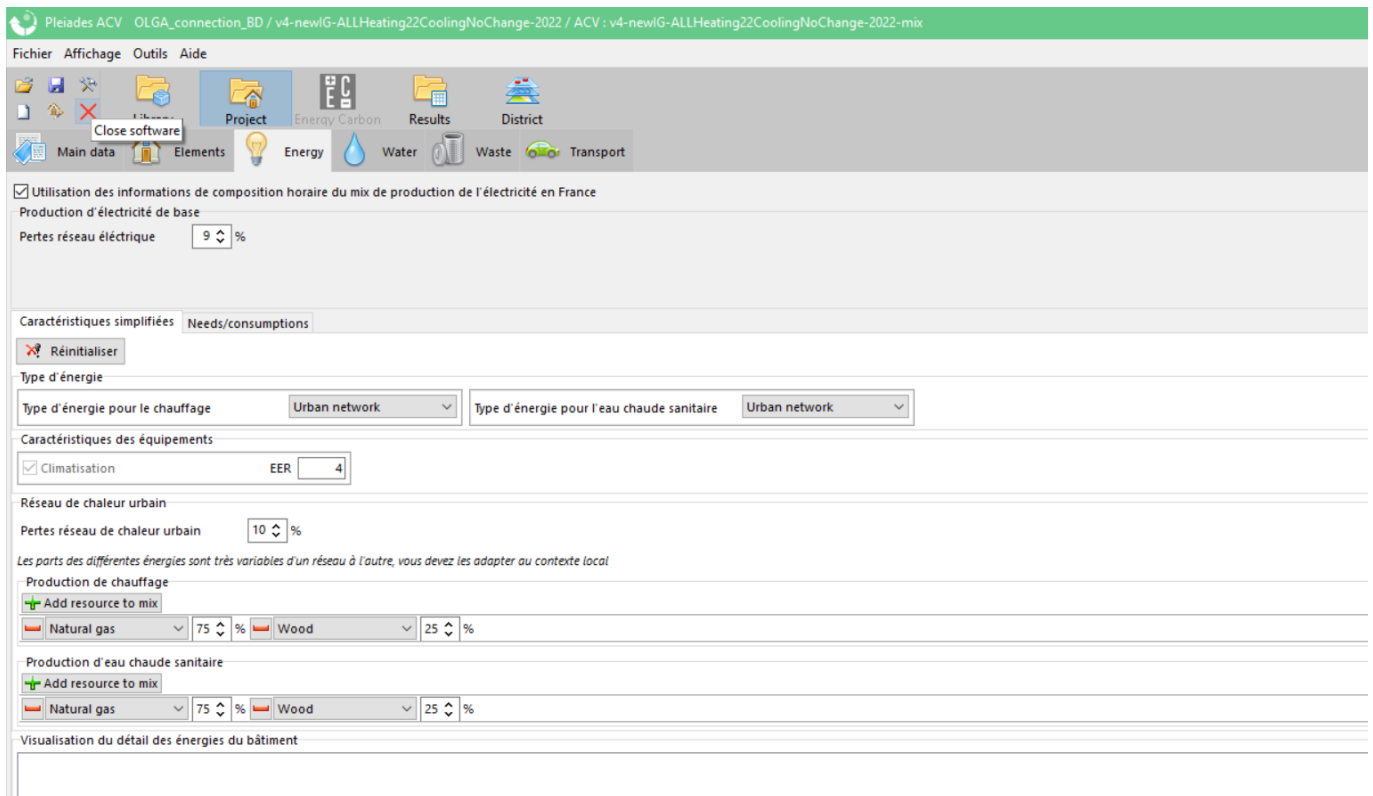
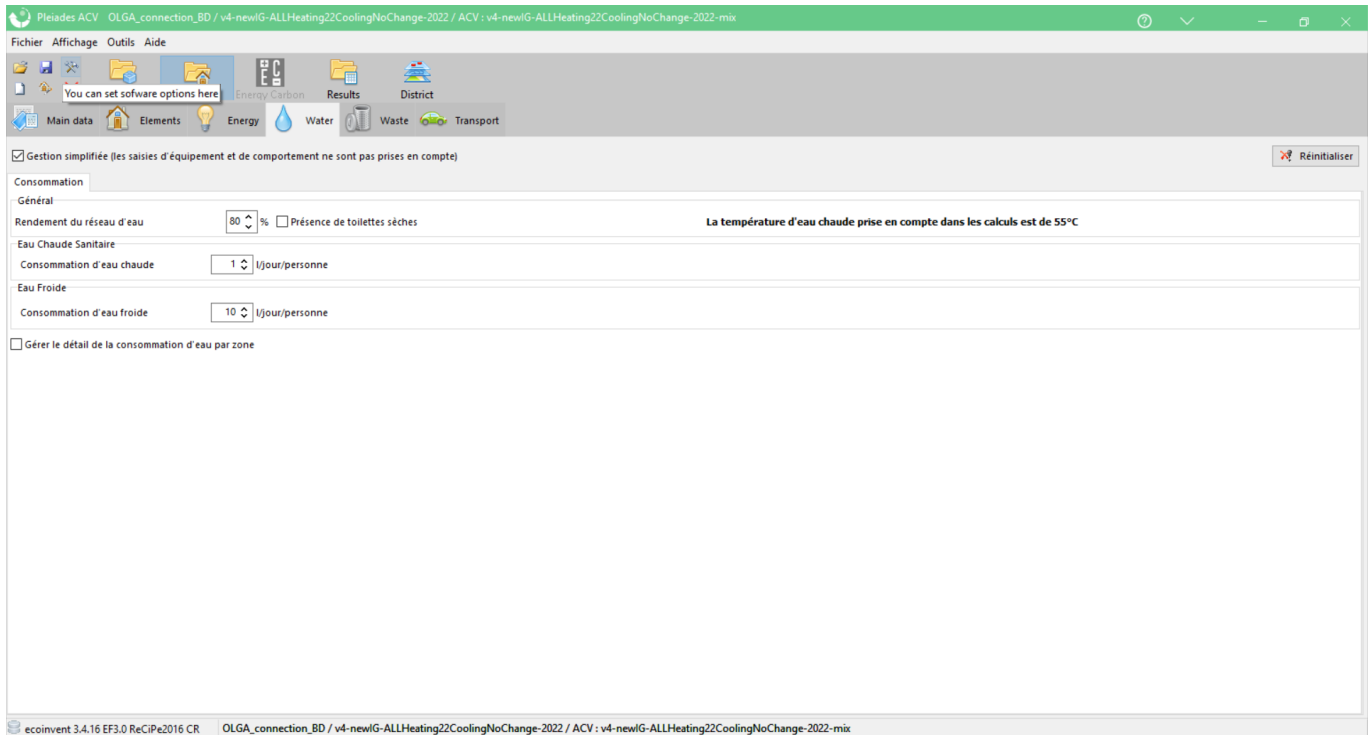


Figure: Interface of energy settings in Pleiades LCA

The water network leakage is set at 20 % (average in French cities), and the hot and cold-water consumptions are set at 1 liter/day/person and 10 liters/day/person. The daily transportation of the persons and waste generation are 0. These could be set in the interface below.



3.5.3 Impact assessment

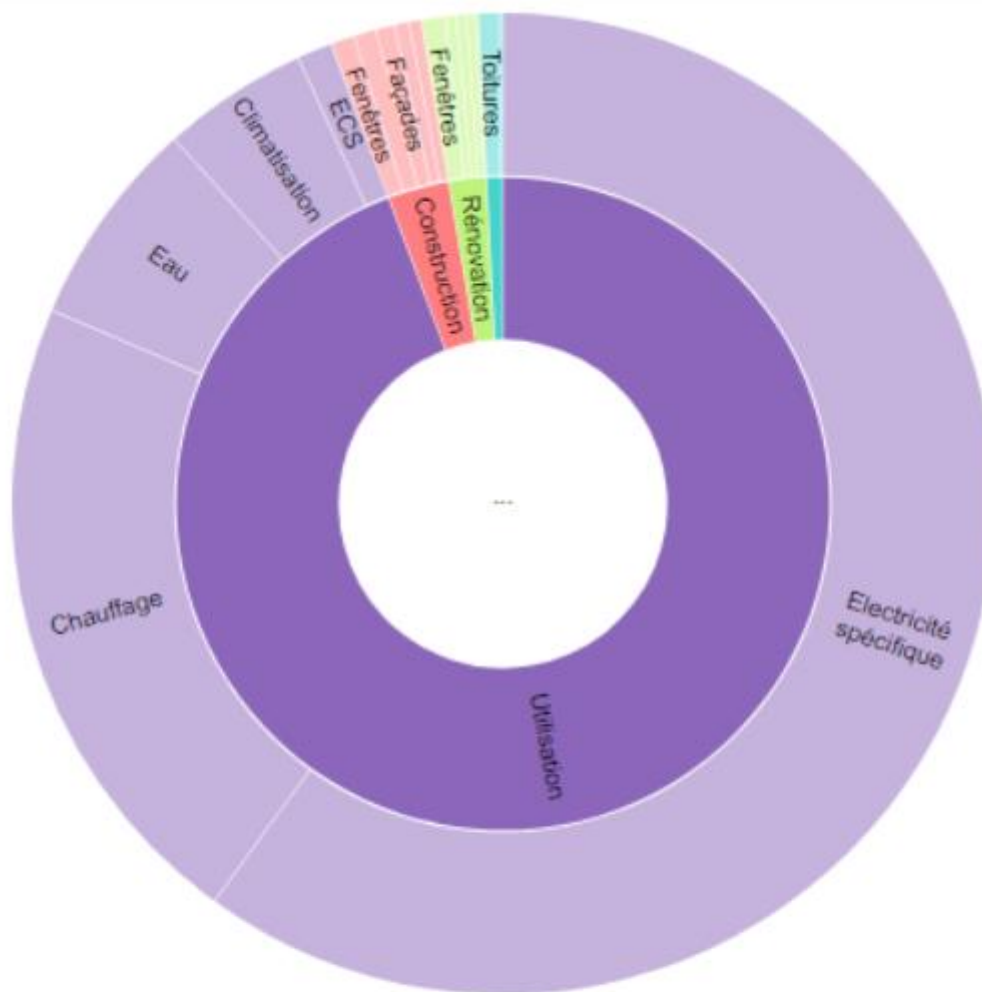
3.5.3.1 Terminal 2B

The number of elements being very large, the maximum size of the model had to be increased.

LCA results are indicated in the table below.

Table: The environmental impact (per m² and per year) of Terminal 2B in the four stages of its life span

Impact/m2/year	<i>Construction</i>	<i>Use</i>	<i>Renovation</i>	<i>Deconstruction</i>	<i>Total</i>
Climate change (kg CO₂ eq.)	1,17E+00	3,64E+01	7,17E-01	3,11E-01	3,86E+01
Abiotic depletion potential, minerals and metals (kg Sb eq.)	1,15E-05	2,24E-05	4,11E-06	-1,61E-07	3,78E-05
Total primary energy use, without raw material (MJ)	1,60E+01	1,69E+03	1,15E+01	-6,28E+00	1,71E+03
Net water consumption (m³)	5,37E-02	4,90E+00	4,55E-02	-2,08E-02	4,97E+00
Eliminated wastes, total (kg)	4,62E-01	9,12E+00	3,95E-01	5,66E-01	1,05E+01
Eliminated radioactive wastes (kg)	5,19E-05	8,74E-03	2,68E-05	-5,17E-05	8,77E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	6,38E-09	9,28E-08	4,93E-09	8,36E-10	1,05E-07
Total damage, human health, ReCiPe2016 - H (DALY)	2,47E-06	4,70E-05	1,87E-06	2,61E-07	5,16E-05



OLGA CDG T2B / Longv4 / Longv4

Etapes

Changement climatique (kg CO2 eq.)

Figure: CO₂ equivalent emission of different stages and different processes/elements for Terminal 2B

The use stage, and particularly electricity consumption, is the largest contributor in greenhouse gases emissions.

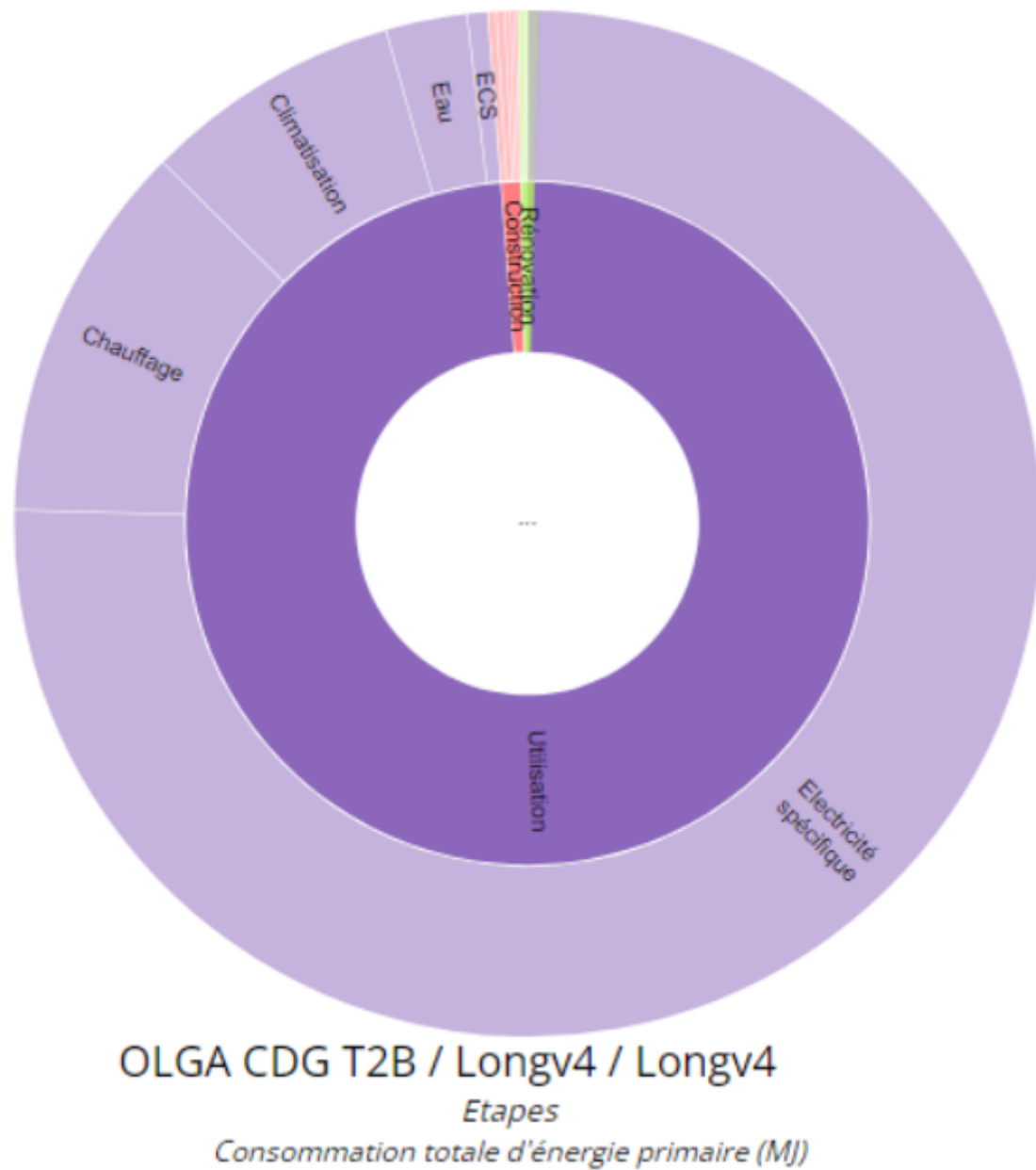


Figure: Total primary energy use of different stages and different processes/elements for Terminal 2B

Again, electricity consumption is the largest contributor.

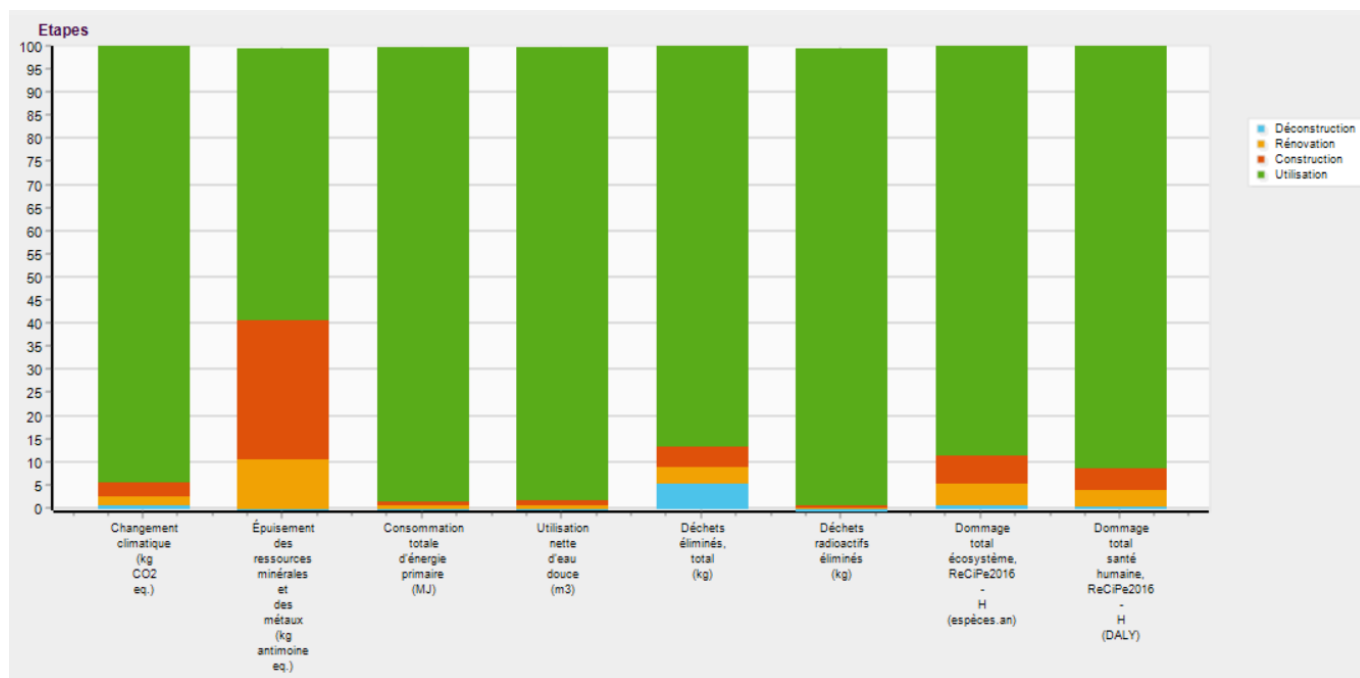


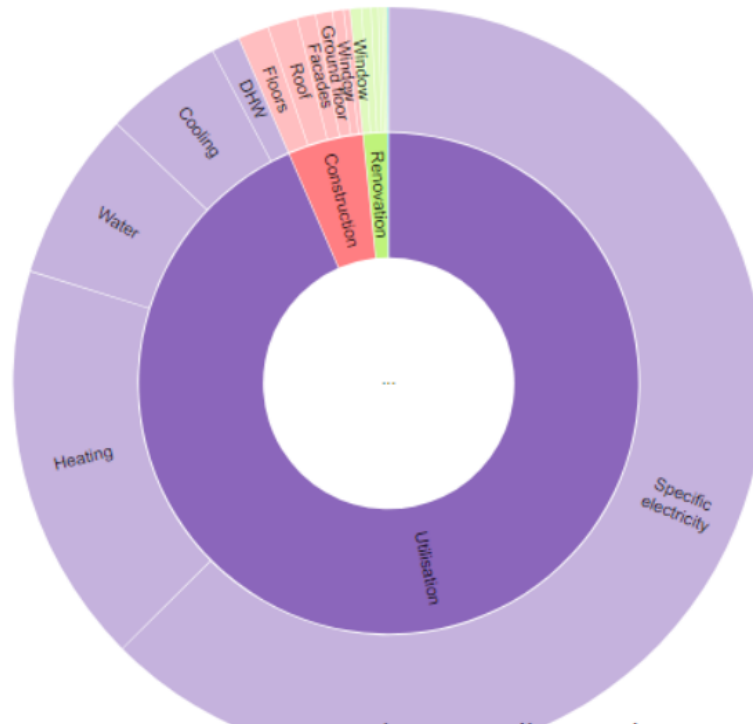
Figure: Contribution of life cycle stages to eight different environmental impact indicators for Terminal 2B

3.5.3.2 Link BD

The environmental impacts of link BD are listed in the table below. The use stage is the main contributor among the four stages for all impact indicators. CO₂eq emission is 40 kg/m².year over the whole lifespan. The total primary energy is 1795 MJ/m².year. The specific electricity consumption generates most CO₂eq emission and primary energy. For the abiotic depletion potential, the reconstruction stage contributes by 31 %. Cooling is only the 4th contributor for CO₂eq emission, and 3rd for the primary energy.

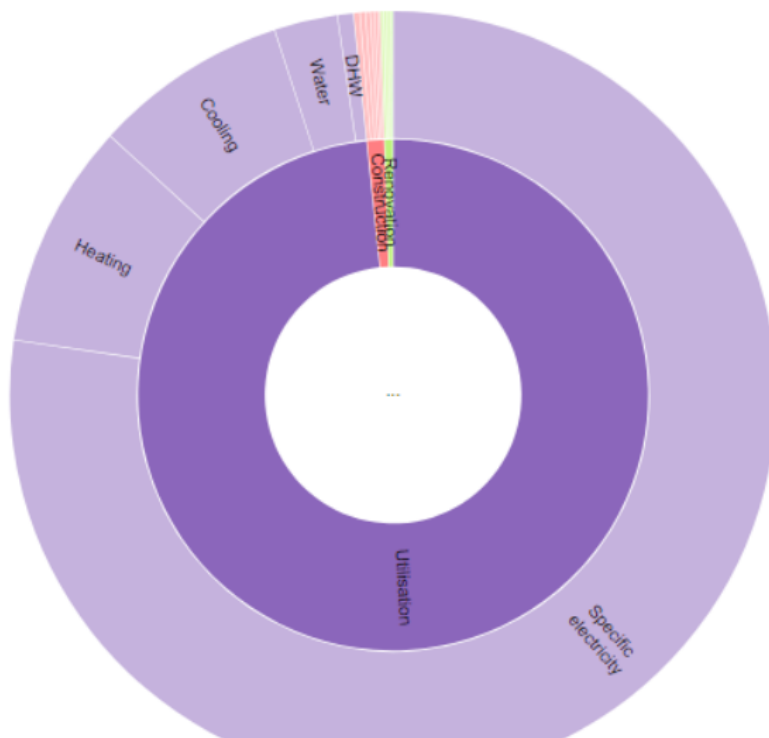
Table: The environmental impact (per m² and per year) of the link BD in the four stages of its life span

Impact/m ² /year	Construction	Use	Renovation	Deconstruction	Total
Climate change (kg CO₂ eq.)	1.95	37.23	0.62	0.03	39.83
Abiotic depletion potential, minerals and metals (kg Sb eq.)	1.28E-05	2.42E-05	3.79E-06	4.59E-09	4.08E-05
Total primary energy use, without raw material (MJ)	19.78	1 765.75	9.79	0.13	1 795.45
Net water consumption (m³)	0.07	5.26	0.04	0.00	5.36
Eliminated wastes, total (kg)	0.92	9.81	0.35	0.82	11.90
Eliminated radioactive wastes (kg)	5.85E-05	9.36E-03	2.11E-05	8.07E-07	9.44E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	8.56E-09	8.80E-08	4.85E-09	1.15E-10	1.01E-07
Total damage, human health, ReCiPe2016 - H (DALY)	3.96E-06	4.77E-05	1.64E-06	3.91E-08	5.33E-05



OLGA_connection_BD / v4-newIG-ALLHeating22CoolingNoChange-2022 / v4-newIG-ALLHeating22CoolingNoChange-2022-mix
Etapes
Climate change (kg CO2 eq.)

Figure: CO₂ equivalent emission of different stages and different processes/elements for link BD



OLGA_connection_BD / v4-newIG-ALLHeating22CoolingNoChange-2022 / v4-newIG-ALLHeating22CoolingNoChange-2022-mix

Etapas

Total primary energy use, without raw material (MJ)

Figure: Total primary energy use of different stages and different processes/elements for link BD

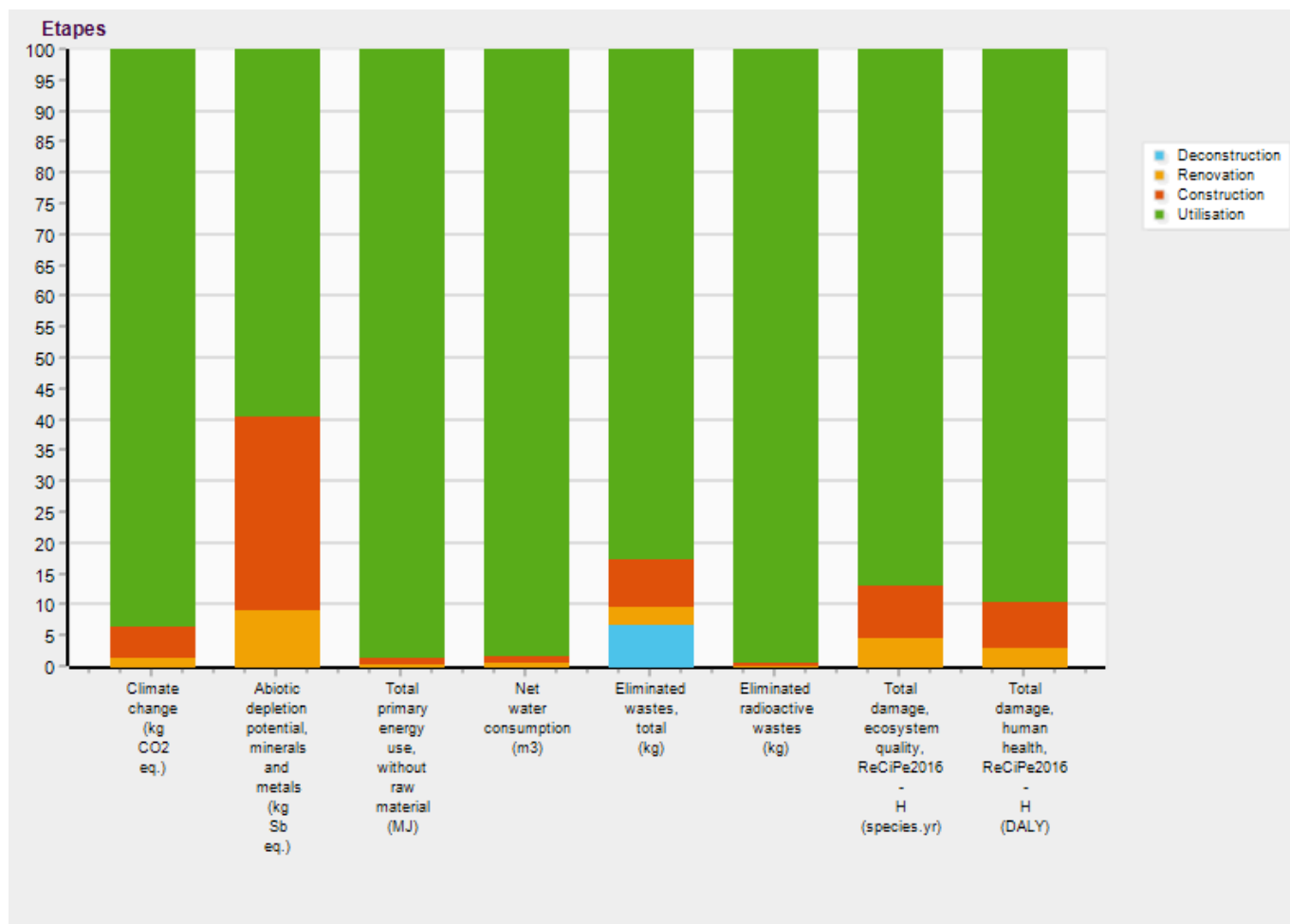


Figure: Contribution of life cycle stages to eight different environmental impact indicators for link BD

3.5.4 Interpretation

It is possible to compare the impact indicators of the studied building to reference values, but such a benchmark is available only for residential buildings, offices, or schools. As an order of magnitude, greenhouse gases emissions range from 5 (best practice) to 160 (highest impact) kg CO₂ eq./m²/year for apartment buildings and offices.

Results obtained for Terminal 2B could constitute a first contribution in a benchmark related to airport spaces. The following table provides impacts per m² for 4 types of spaces: check-in, boarding, security and border check, and shops. The system includes materials corresponding to the building envelope, excluding foundations and devices used inside the building like computers, servers etc.

Impact indicators per m²/year, check-in zone



Impact/m ² /year	Construction	Use	Renovation	Deconstruction	Total
Climate change (kg CO₂ eq.)	1,09E+00	3,65E+01	5,40E-01	4,82E-01	3,86E+01
Abiotic depletion potential, minerals and metals (kg Sb eq.)	1,41E-05	3,11E-05	3,04E-06	-2,31E-07	4,80E-05
Total primary energy use (MJ)	1,76E+01	1,68E+03	8,57E+00	-9,04E+00	1,69E+03
Net water consumption (m³)	5,80E-02	4,98E+00	3,37E-02	-2,97E-02	5,04E+00
Eliminated waste, total (kg)	4,43E-01	1,06E+01	2,94E-01	4,26E-01	1,18E+01
Radioactive waste (kg)	5,15E-05	8,85E-03	2,04E-05	-7,44E-05	8,85E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	6,37E-09	4,94E-08	3,64E-09	1,30E-09	6,07E-08
Total damage, human health, ReCiPe2016 - H (DALY)	2,39E-06	4,20E-05	1,40E-06	4,08E-07	4,62E-05

Impact indicators per m²/year, boarding zone

Impact/ m ² /year	Construction	Use	Renovation	Deconstruction	Total
Climate change (kg CO₂ eq.)	7,58E-01	3,91E+01	7,59E-01	4,60E-01	4,11E+01
Abiotic depletion potential, minerals and metals (kg Sb eq.)	5,60E-06	2,74E-05	3,91E-06	-2,68E-07	3,66E-05
Total primary energy use (MJ)	1,59E+01	1,74E+03	1,17E+01	-1,03E+01	1,76E+03
Net water consumption (m³)	5,03E-02	4,89E+00	4,35E-02	-3,39E-02	4,95E+00
Eliminated waste, total (kg)	4,25E-01	9,93E+00	3,83E-01	1,46E-01	1,09E+01
Radioactive waste (kg)	4,96E-05	8,74E-03	3,01E-05	-8,46E-05	8,73E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	5,51E-09	8,33E-08	4,55E-09	1,20E-09	9,46E-08
Total damage, human health, ReCiPe2016 - H (DALY)	2,11E-06	4,77E-05	1,93E-06	3,71E-07	5,21E-05

Impact indicators per m²/year, security and border check

Impact/ m ² /year	Construction	Use	Renovation	Deconstruction	Total
Climate change (kg CO₂ eq.)	1,28E+00	3,52E+01	6,79E-01	1,12E-02	3,72E+01
Abiotic depletion potential, minerals and metals (kg Sb eq.)	4,99E-06	3,70E-05	3,80E-06	-1,93E-09	4,58E-05
Total primary energy use (MJ)	1,20E+01	1,67E+03	1,08E+01	-8,95E-02	1,69E+03
Net water consumption (m³)	4,19E-02	5,20E+00	4,21E-02	-3,45E-04	5,28E+00
Eliminated waste, total (kg)	3,51E-01	1,18E+01	3,67E-01	1,97E-01	1,27E+01
Radioactive waste (kg)	4,26E-05	9,20E-03	2,57E-05	-8,04E-07	9,27E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	5,60E-09	1,25E-08	4,54E-09	3,57E-11	2,27E-08
Total damage, human health, ReCiPe2016 - H (DALY)	2,34E-06	3,72E-05	1,76E-06	1,17E-08	4,13E-05

Impact indicators per m²/year, shops



Impact/ m ² /year	Construction	Use	Renovation	Deconstruction	Total
Climate change (kg CO₂ eq.)	5,39E-01	3,04E+01	3,49E-01	1,85E-03	3,13E+01
Abiotic depletion potential, minerals and metals (kg Sb eq.)	1,84E-06	2,70E-05	2,17E-06	1,94E-09	3,10E-05
Total primary energy use (MJ)	4,79E+00	1,58E+03	5,74E+00	6,37E-02	1,59E+03
Net water consumption (m³)	1,76E-02	5,19E+00	2,40E-02	8,85E-05	5,23E+00
Eliminated waste, total (kg)	1,61E-01	1,01E+01	2,06E-01	4,14E-01	1,09E+01
Radioactive waste (kg)	1,77E-05	9,19E-03	1,24E-05	4,04E-07	9,22E-03
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)	2,40E-09	3,56E-08	2,67E-09	1,35E-11	4,07E-08
Total damage, human health, ReCiPe2016 - H (DALY)	9,55E-07	3,65E-05	9,32E-07	4,83E-09	3,84E-05

Because the goal of the study is to compare the optimized cases, the interpretation is described in more detail in section 3.6.

3.6 Optimisation results

The optimisation process was performed using the tool Amapola developed by Kocliko, which was integrated in Pleiades by Izuba. The optimisation is based on a genetic algorithm and it is possible to determine the best design choices to achieve performance objectives according to energy, comfort and overall cost criteria.

The optimisation process requires numerous simulations regarding different design parameters such as thermal insulation layer thicknesses and window types, so this needs a large amount of calculation time. **It is only used for the model link BD**, because one simulation for this model is around 3 minutes, which is acceptable for Amapola. On the contrary, one simulation for the model terminal 2B is around 2 hours, since the number of total simulations could reach thousands, the optimisation for this model will not be done in Amapola.

We did an optimisation analysis for link BD based on the targets of investment and heating load, by considering 14 varying parameters, including the thicknesses of insulation layers of different external walls, intermediate floor and roof (seven in total) which vary from 1 to 30 cm, and the window types of seven windows categories which vary from double or triple glazings. This corresponds to a total number of combinations of 700 billion. The numbers of individuals and generations are set at 40 and 10. The price curves of insulation layers with different thicknesses is shown in the figure below. The prices of double and triple glazings windows are 450 €/m² and 615 €/m². The interfaces of Amapola settings are shown in the figures below.

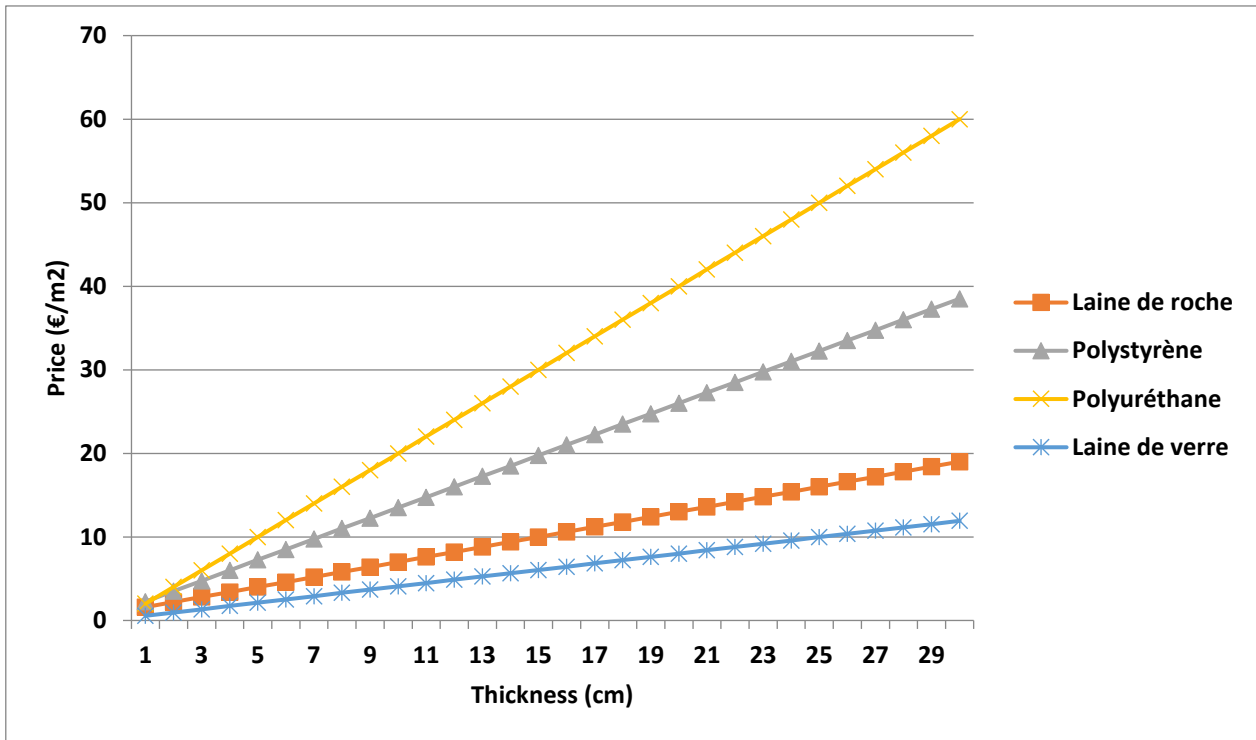


Figure: Prices of insulation layers with different thicknesses

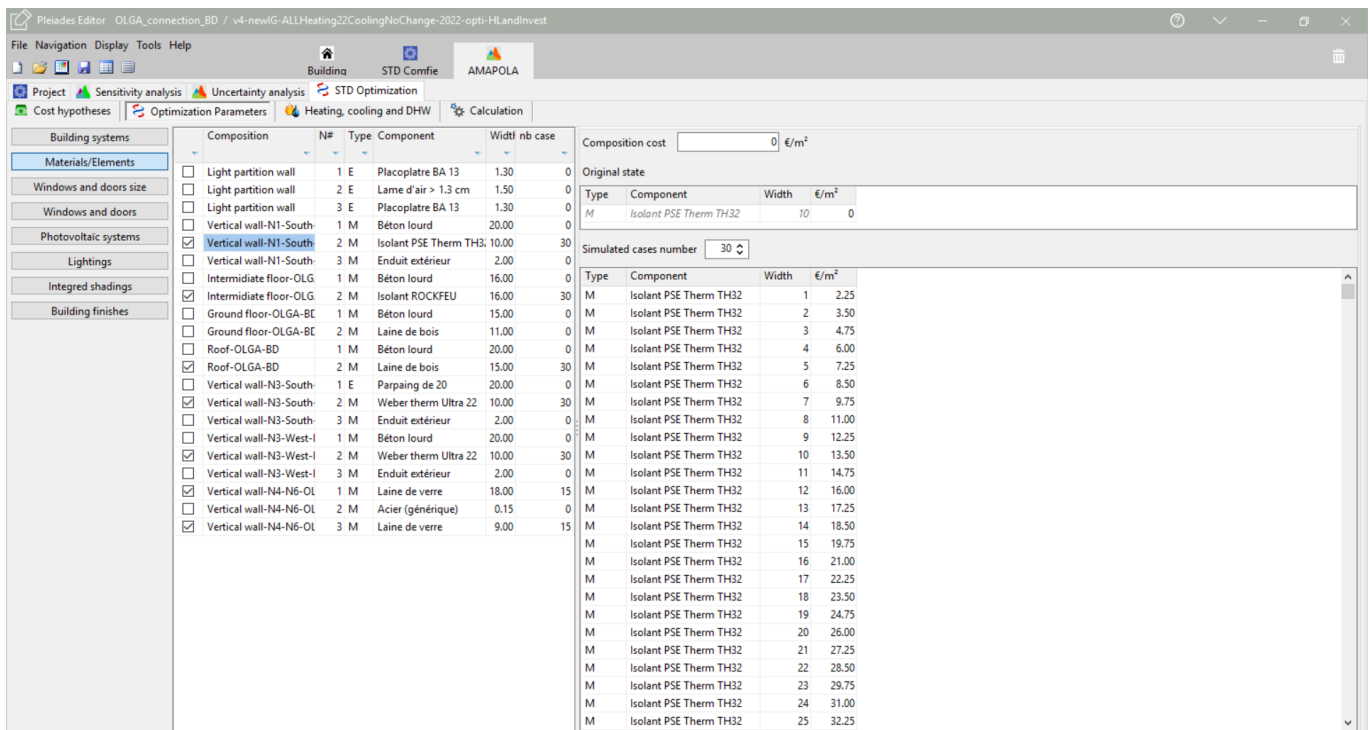


Figure: Interface of Amapola for setting insulation thickness of different walls

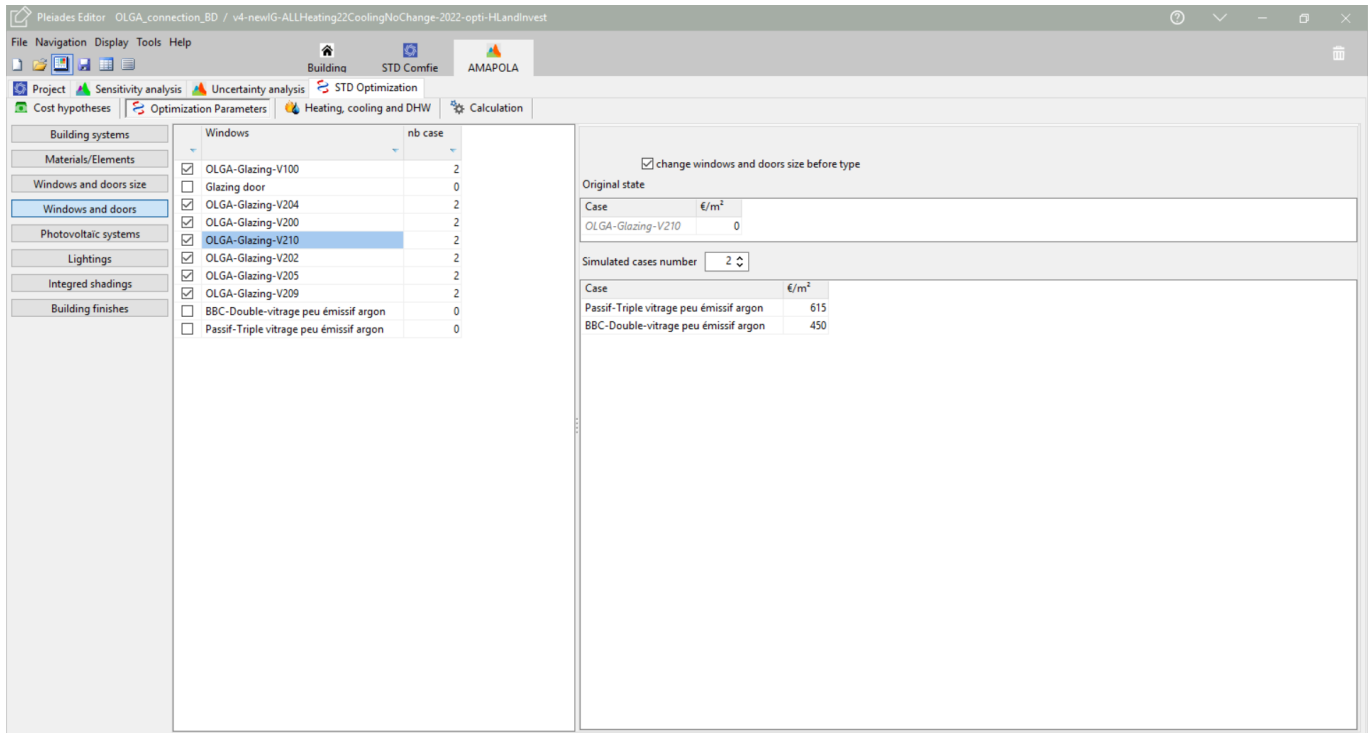


Figure: Interface of Amapola for setting glazing types of different window categories

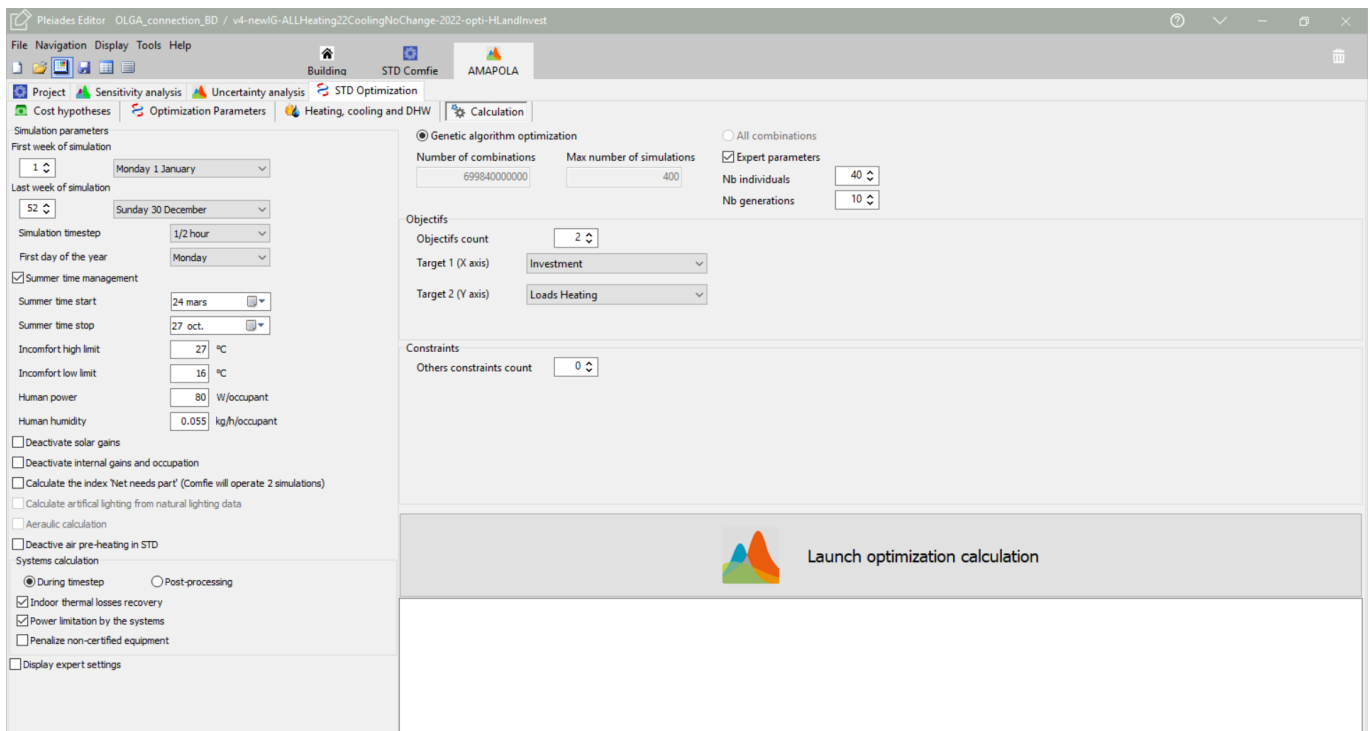


Figure: Interface of Amapola for setting numbers of individuals and generations

The optimisation results by Amapola are shown in the figure below. There are 36 points number from case 1 to 36 indicating the optimised designs which provide the lowest heating load at a



certain investment. We propose to consider the three points (case 9, 10 and 11) in the red rectangle, because they provide the best rate of performance to investment. On the left of the rectangle, the performance is low and on the right the performance does not increase much with the investment. Case 1 indicates the worst heating load performance but lowest investment and case 36 indicates the best heating load performance but highest investment.

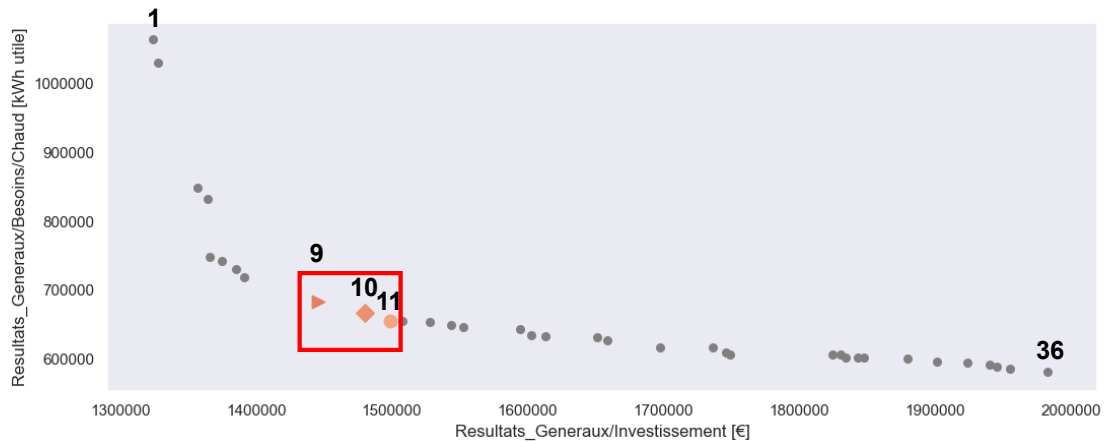


Figure: Optimisation results based on criteria heating load and investment

All cases 9, 10 and 11 have low insulated intermediate floors but well insulated roofs (25 cm, compared to 18 cm in the reference case) and low emissivity double glazing. They differ in the insulation thickness in the different vertical walls (according to the level and orientation), from 2 to 16 cm (10 cm in the reference case). The investment and heating load of each optimised case are shown in the table below, as well as the reference case (the existing building in section 3.4, considered as a reference).

Table: Investments and heating loads of the optimised cases and the reference case

Nb.Case	Investment	Heating load	Cooling load
	€	kWh	kWh
9	1 445 562	682 740	1 991 980
10	1 480 107	667 417	2 008 165
11	1 499 147	655 566	2 018 104
Reference	1 569 006	696 909	1 793 614

According to these results, around 100,000 € could be saved while reducing the heating load by 2%, but the cooling load is increased. This adverse effect could be avoided by a free cooling strategy, which will be studied in a second step (see below).

LCA was performed for the four cases, as shown in the figures below. It can be inferred that the reference case during the construction stage has smaller impacts compared to other three cases.



Considering the whole life span, the four cases have similar impacts, especially the CO₂ equivalent emission and the total primary energy use.

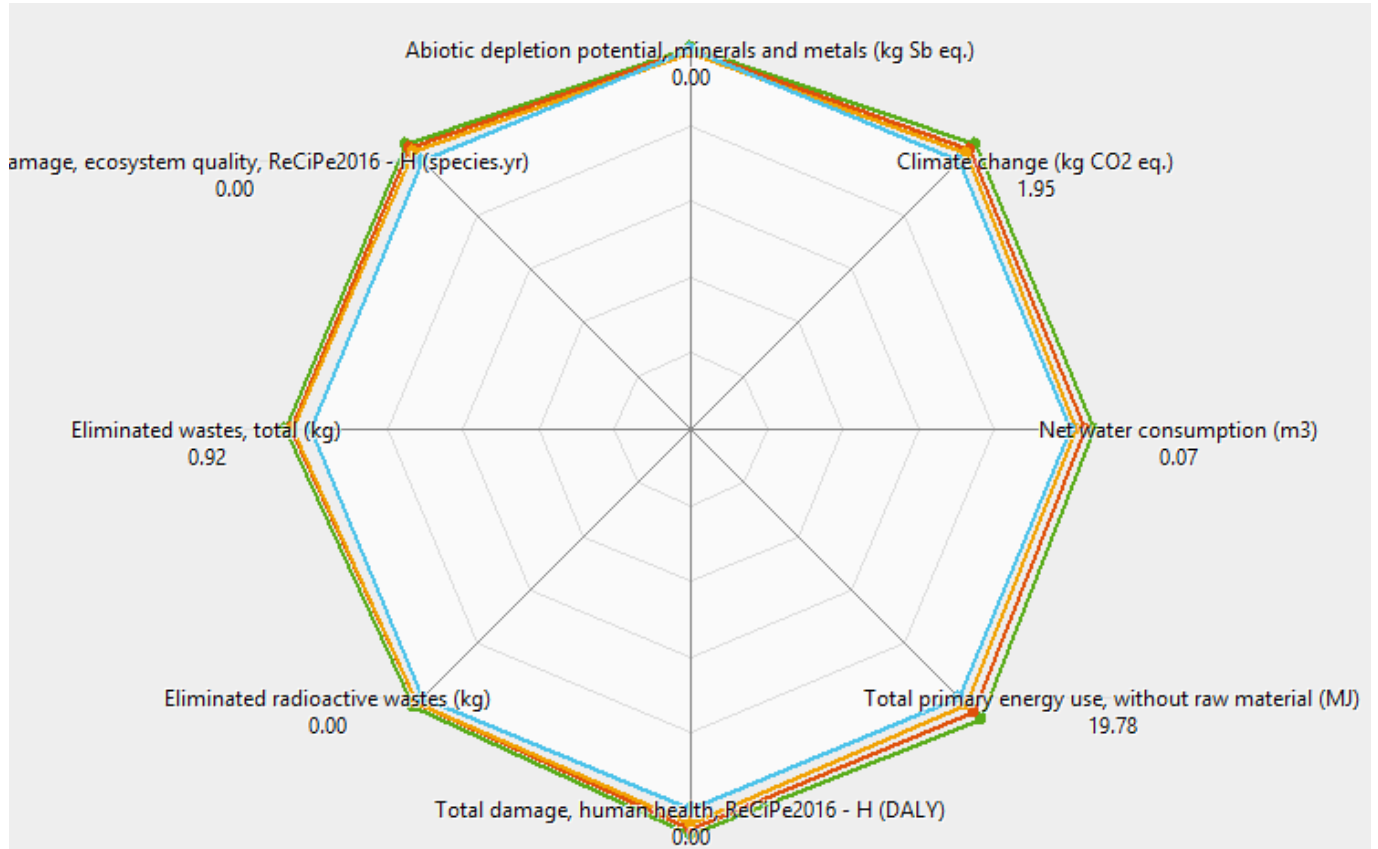


Figure: Environmental impacts comparison (per m² per year) during the construction stage between case 9 (in yellow), case 10 with (in red), case 11 (in green) and the reference case (in blue)

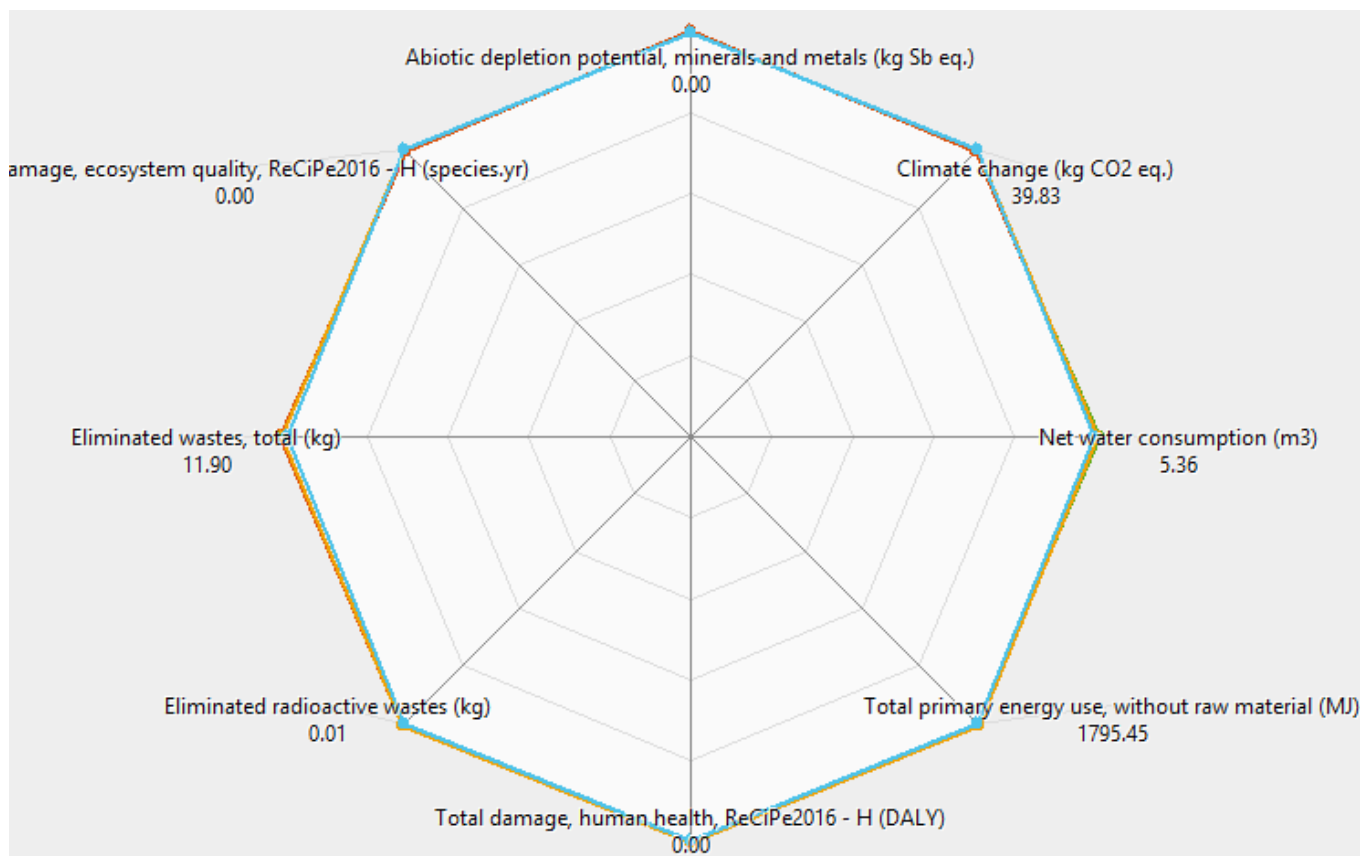


Figure: Environmental impacts (per m² per year) comparison during the whole life span between case 9 (in yellow), case 10 with (in red), case 11 (in green) and the reference case (in blue)

It could be interesting to compare case 10 with the least investment (case 1), and the case with highest performance (case 36). The environmental impacts comparison during the construction stage is shown in the figure below. It could be inferred that case 1 has the least impacts and case 36 has the highest impacts.

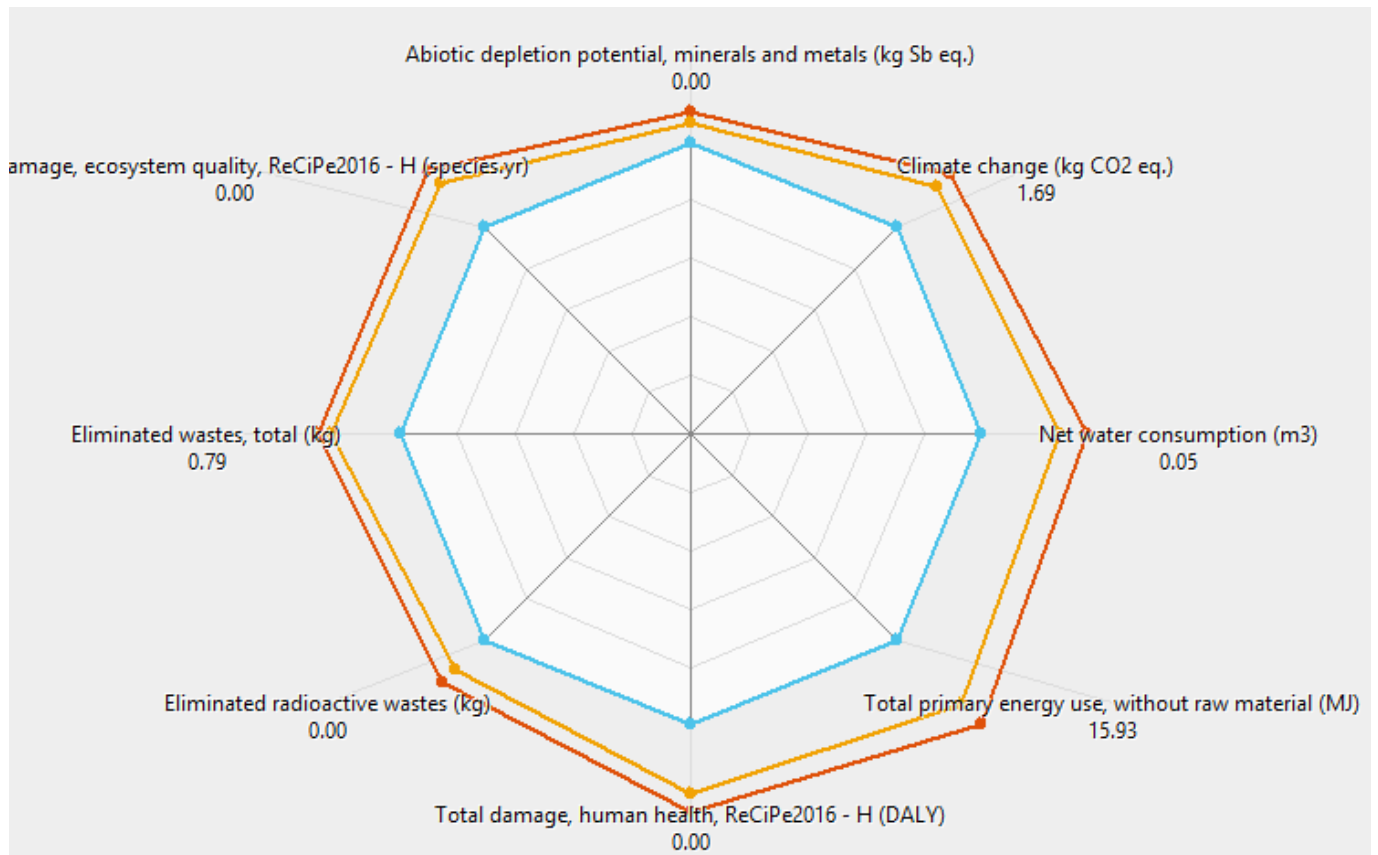


Figure: Environmental impacts (per m² per year) comparison during the construction stage between case 1 (in blue), 10 (in yellow) and 36 (in red)

The environmental impacts comparison between case 1, 10 and 36 for the total life cycle is shown in the figure below. It is indicated that case 1 has the largest impacts though it has the least during the construction stage. Case 10 and case 36 has similar impacts, showing that the optimisation process could help to reduce the investment cost but maintaining a good level of environmental performance.

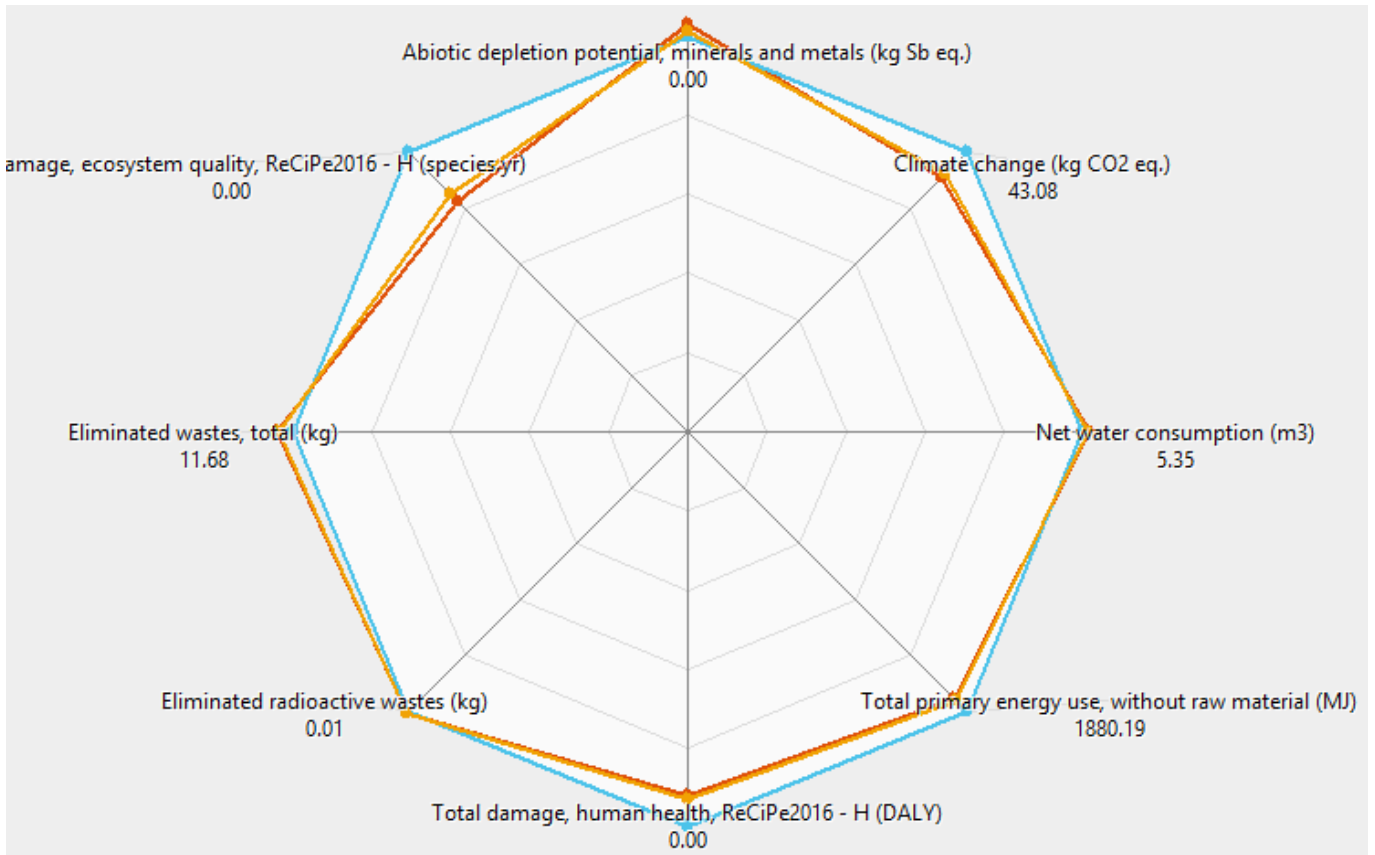


Figure: Environmental impacts (per m² per year) comparison during the whole life span between case 1 (in blue), 10 (in yellow) and 36 (in red)

Application of a free cooling strategy

Thermal insulation may in some cases increase the cooling load of a building if solar and internal gains cannot be evacuated. One way is a free cooling strategy, e.g. creating an air flow by natural ventilation if it is too warm inside and cooler outside.

Here we propose an opening control to reduce the cooling load. When the outdoor temperature is 1 °C lower than the current zone temperature, we assume that some opening will be opened and this brings a natural ventilation of 10 vol/hour. This control stops once the outdoor temperature is higher than the current zone temperature or the current zone temperature is smaller than 26 °C. The setting interface is shown in the figure below. This control was applied to case 10. The yearly heating and cooling loads are 29 kWh/m² and 48 kWh/m², respectively, which are 2 % higher and 44 % lower than case 10 without free cooling.

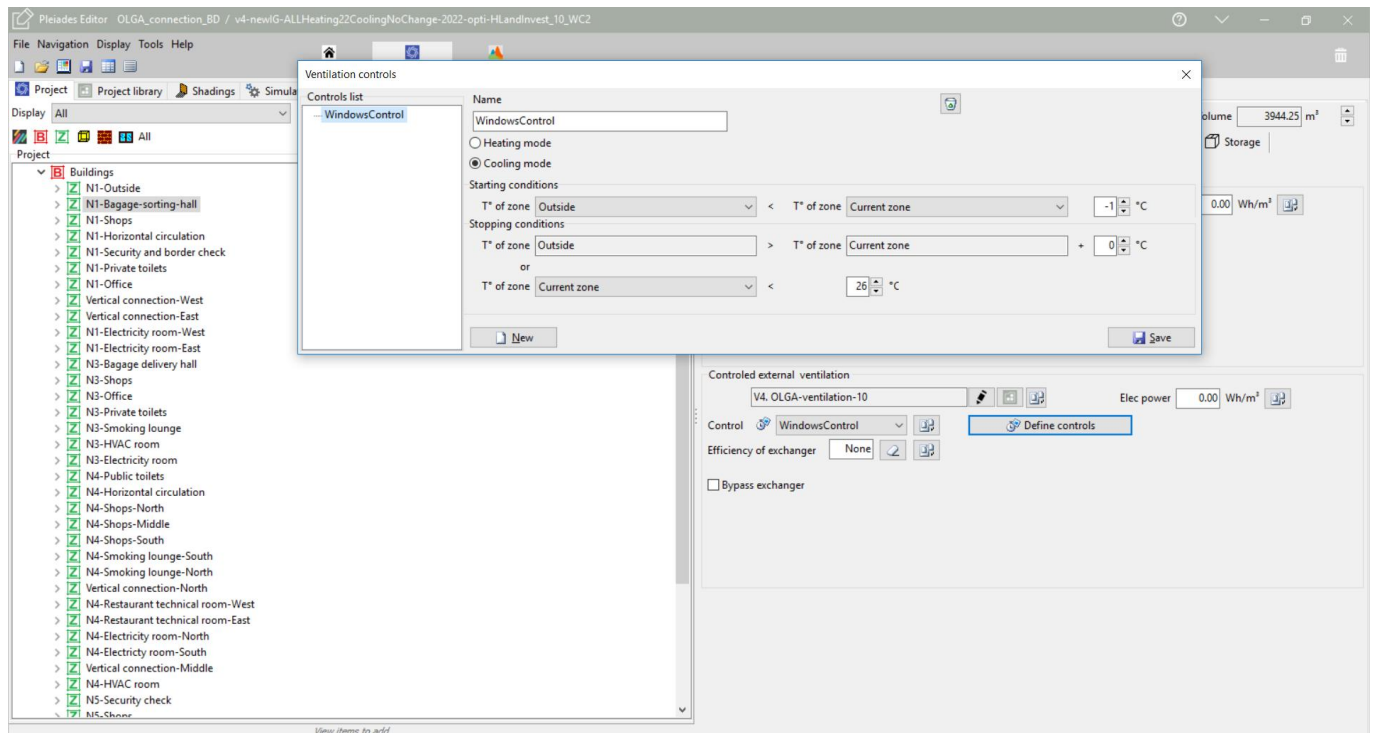


Figure: Interface setting for the controlled ventilation in case 10

The LCA comparison is shown below for case 10 with and without free cooling. It can be inferred that with opening control, the nuclear waste decreases since the cooling is supplied by a higher efficiency heat pump with an EER of 4, and the electricity mix is with a high nuclear percentage. CO₂ equivalent emission slightly increases because the heating load increases and it is supplied 75% by natural gas.

If solar protection is added from April to September (60% reduction of solar factor on all windows), the cooling load is reduced by another 14% (and even 22% in the shops of level 5 where façades are largely glazed), reaching 41 kWh/m² per year.

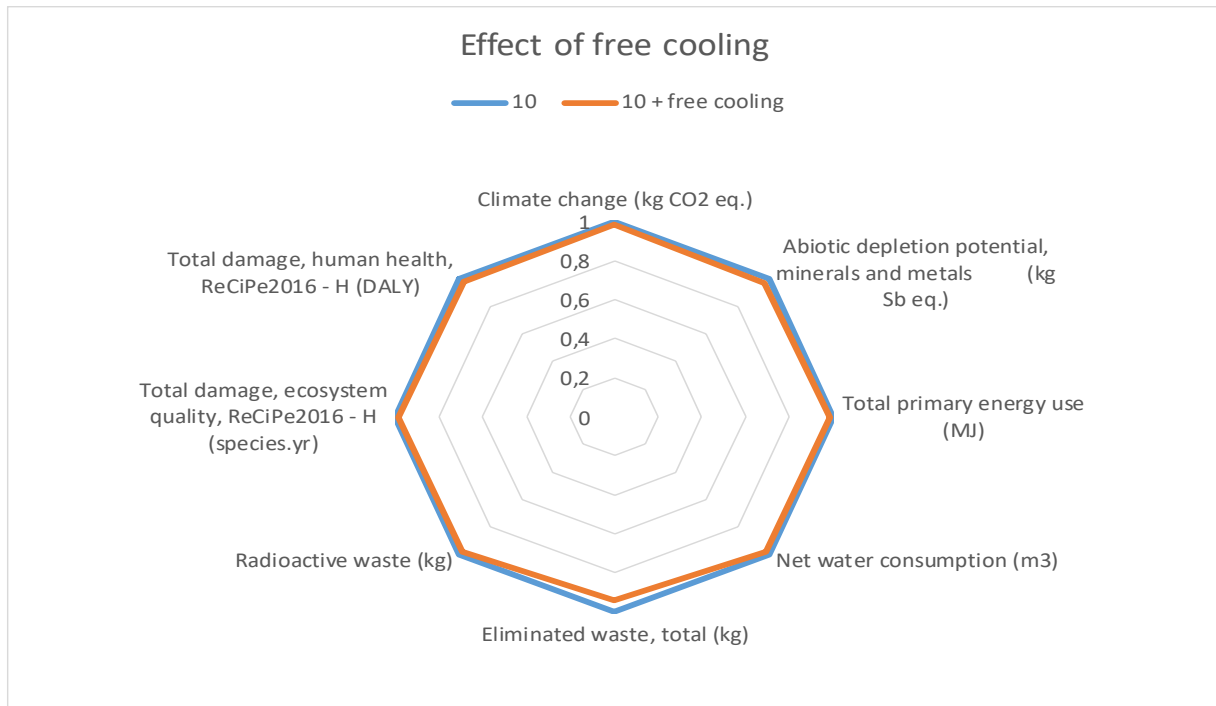


Figure: Environmental impacts (per m2 per year) comparison during the whole life span between case 10 with (in yellow) and without free cooling (in blue)

The reason of this small difference is the importance of contributors which are not influenced by free cooling; impacts related to materials, electricity, and water.

4 Results for a future project

4.1 Presentation of the project

The building studied in this project is Terminal 2A of Charles de Gaulle Airport, as shown in the photograph below. The project corresponds to the renovation of this building.



Figure 4-1: The photo of Terminal 2A.



The present building has no insulation (walls, floors, roof). Façades include partly single glazing, and partly low performance double glazing. It is heated by a district heating system, heat being generated by 75% gas and 25% wood. In this project, the renovation of the envelope is studied, and compared with an action on the district heating: lowering the % of gas generation, by integrating a geothermal heat source and heat pumps.

4.2 Elaboration of the building model

Based on the studies and comparisons conducted in the previous chapter, it was concluded that generating a Pleiades model from AutoCAD files in the Modeler is the most robust and efficient method for creating a building model that can be used for thermal simulation. Therefore, in this chapter, this approach is applied to the future refurbishment project in order to interactively evaluate the energy and environmental impacts of various design and construction choices.

4.2.1 Import DWG file for each building level

The plan view of each floor can be drawn using the DWG file for each level, which can be imported as a background image in Pleiades Modeler, as shown in the figure below. By activating the 'Snap to CAD' function at the top toolbar, you can magnetically align wall points while drawing.

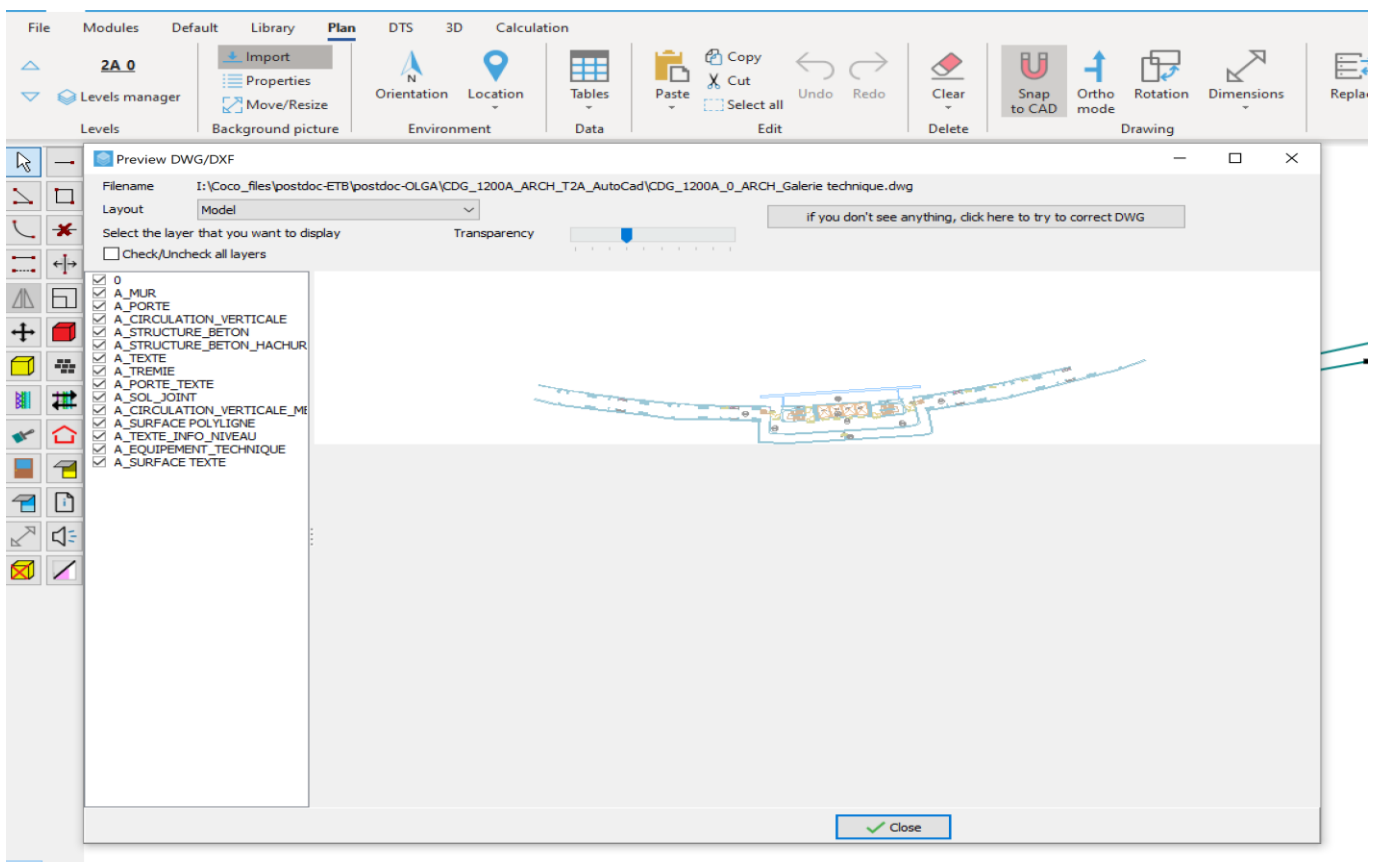


Figure 4-2: The interface of importing the DWG file as a background.



4.2.1.1 Plan view of all levels

For the initial version of the building model, we aimed to create a detailed and dedicated representation that considered all design elements to ensure high accuracy. The plan views of each level in the dedicated model are shown in Figure 4-3 to Figure 4-10.

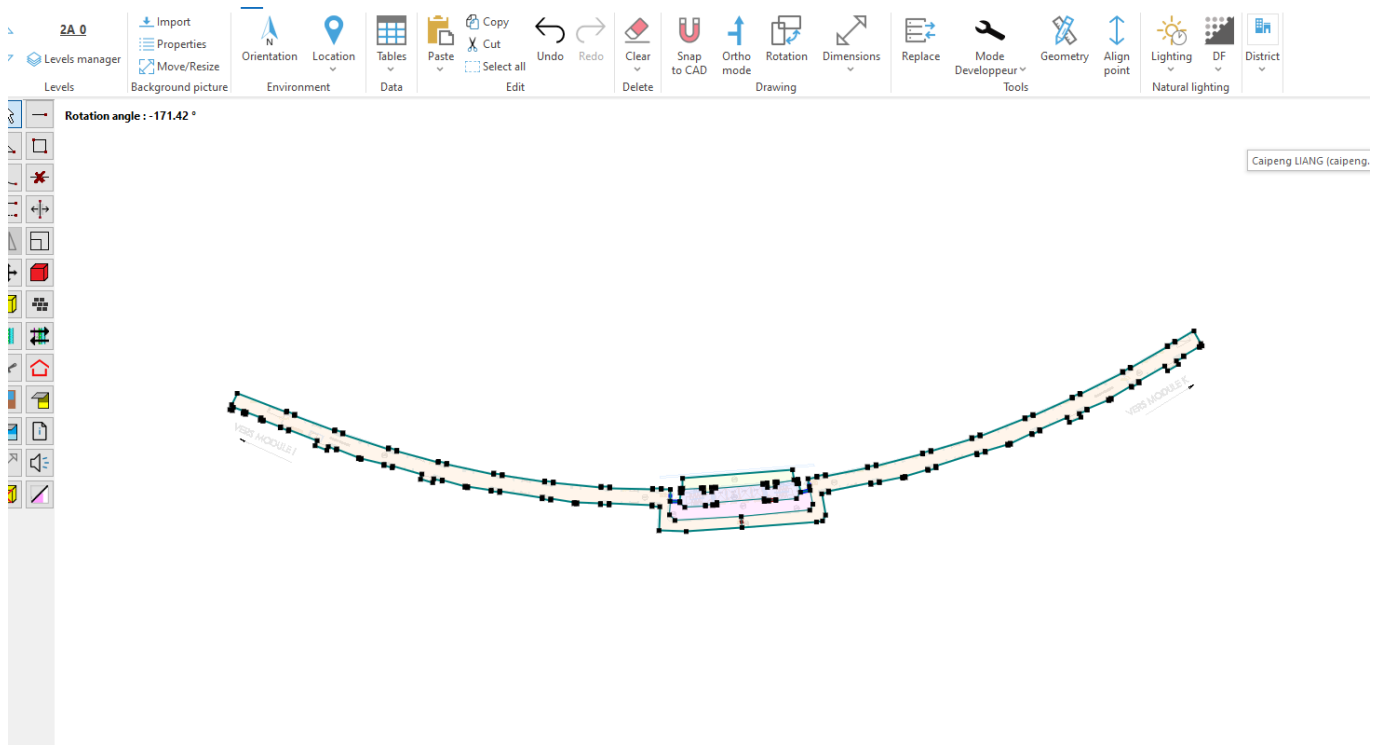


Figure 4-3: The plan view of level 0.

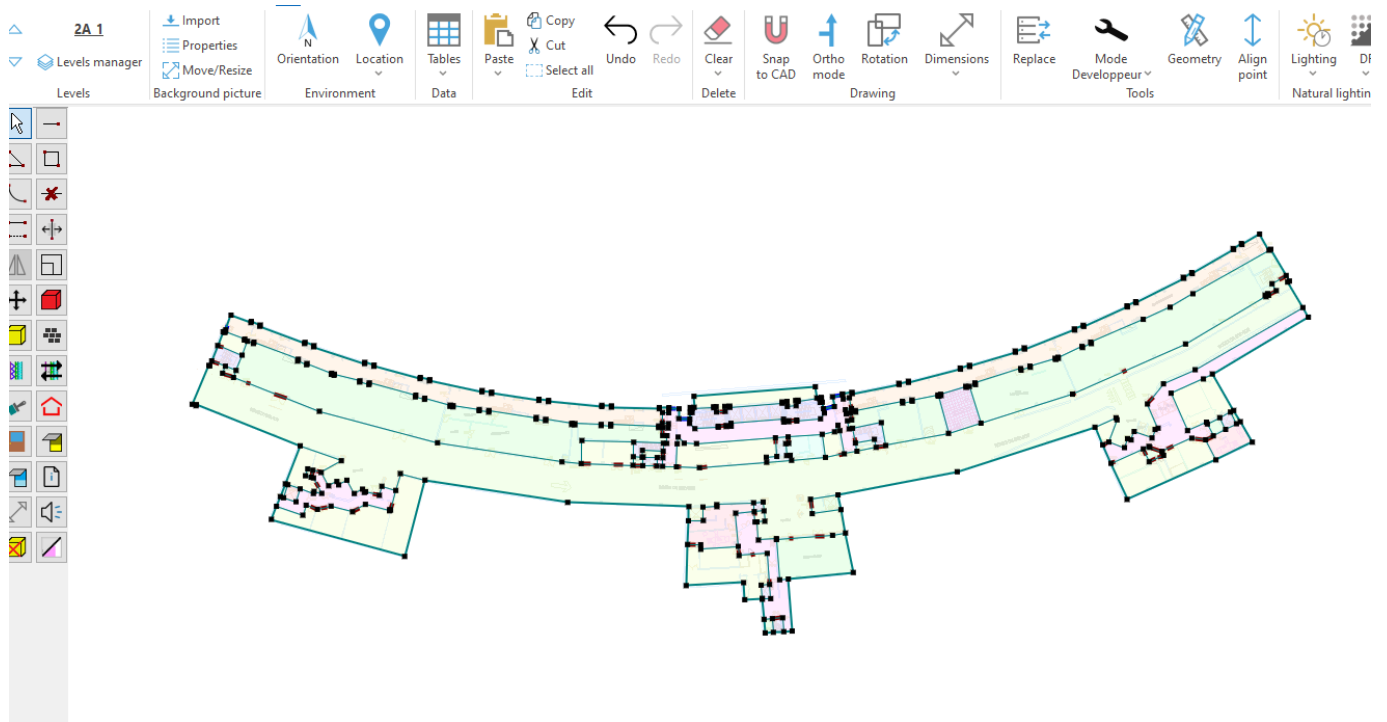


Figure 4-4: The plan view of level 1.

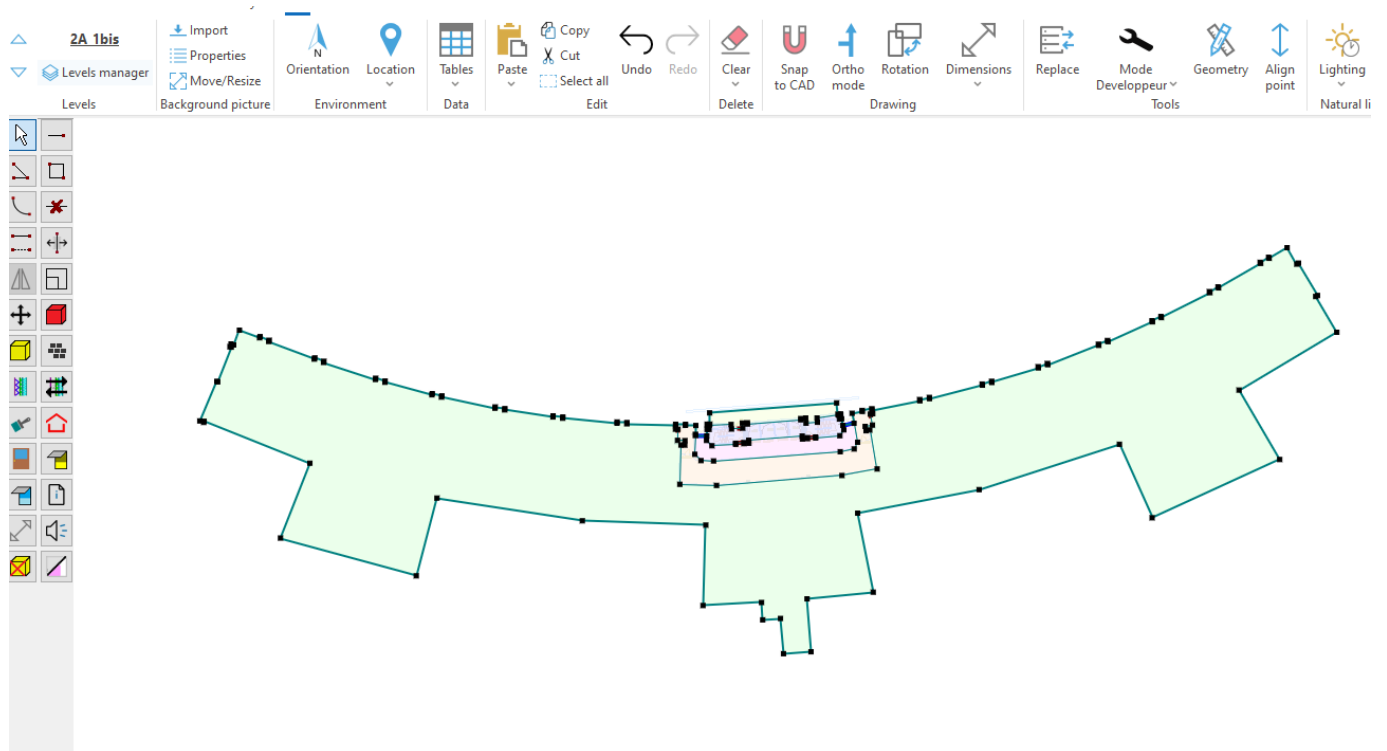


Figure 4-5: The plan view of level 1bis.

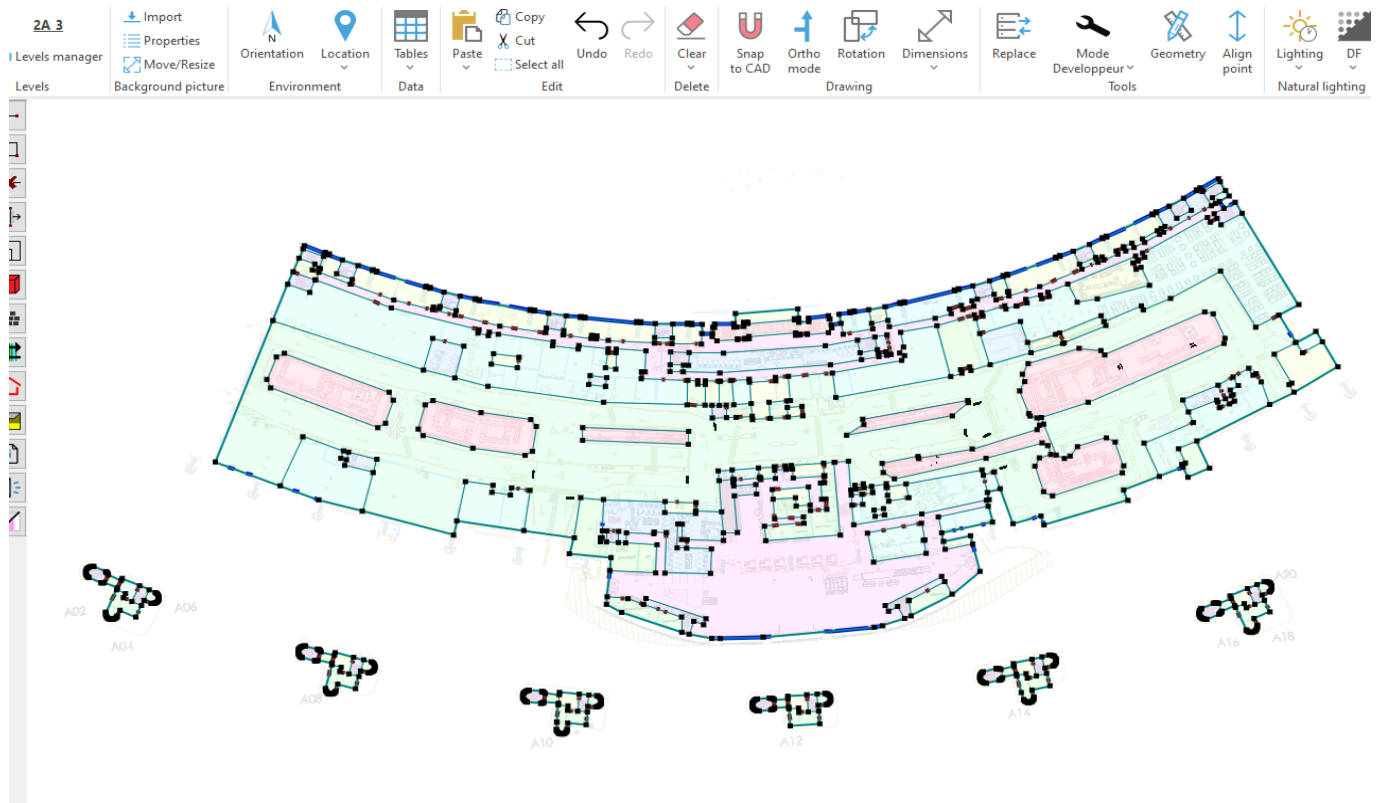


Figure 4-6: The plan view of level 3.

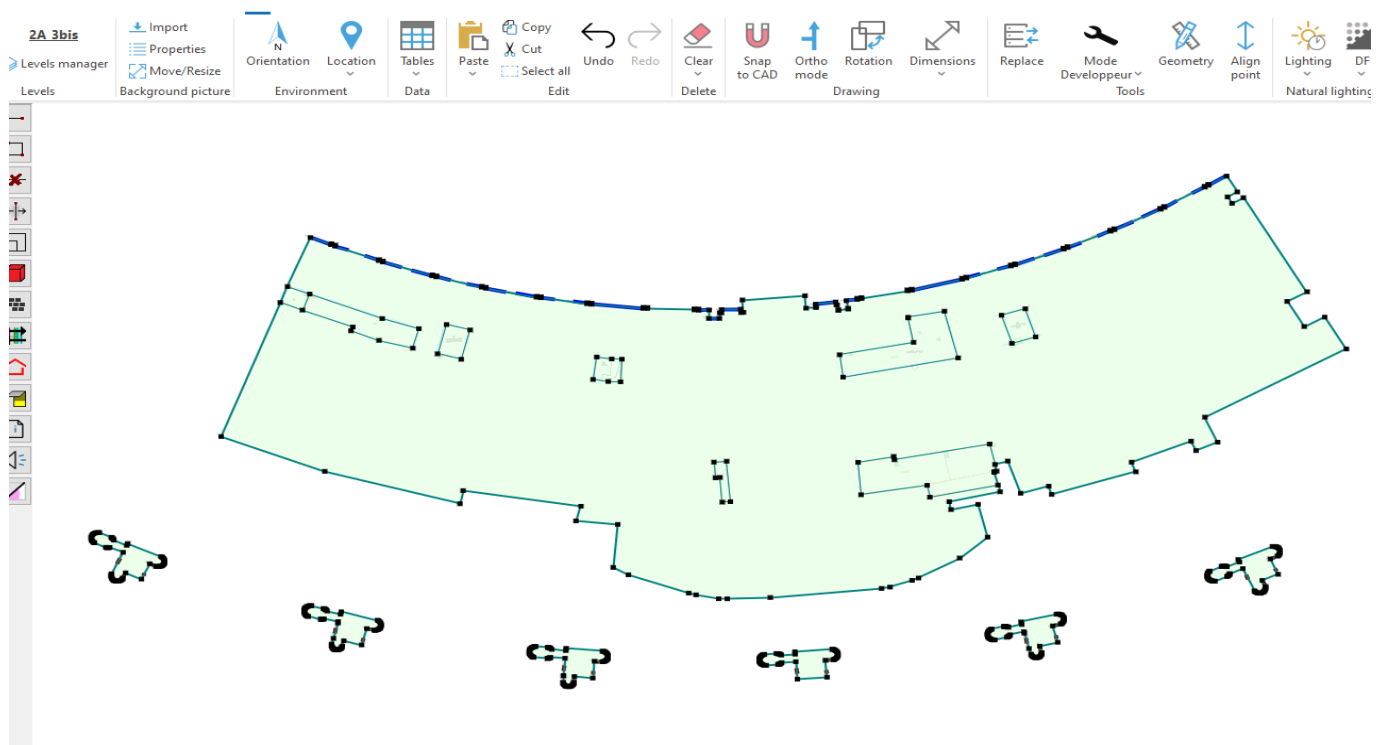


Figure 4-7: The plan view of level 3bis.

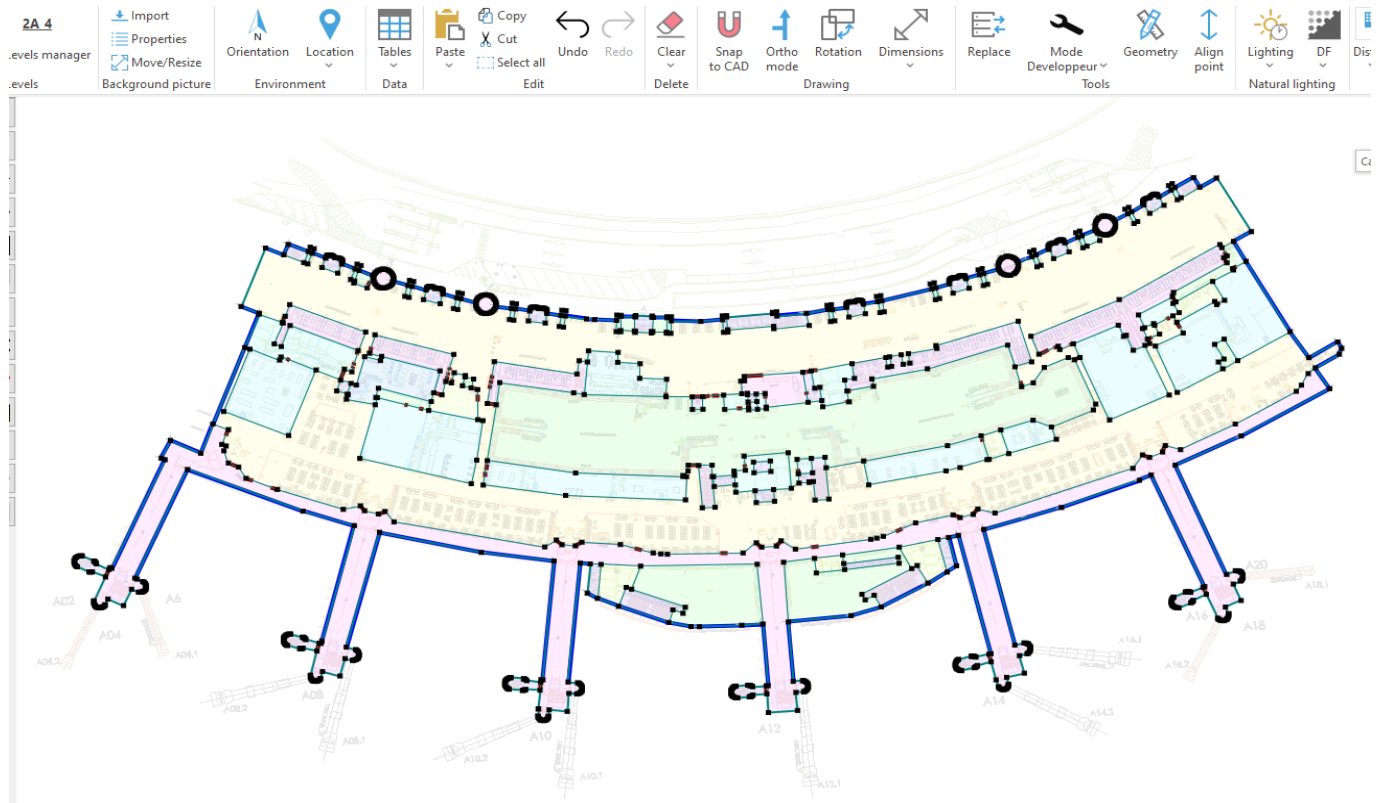


Figure 4-8: The plan view of level 4.

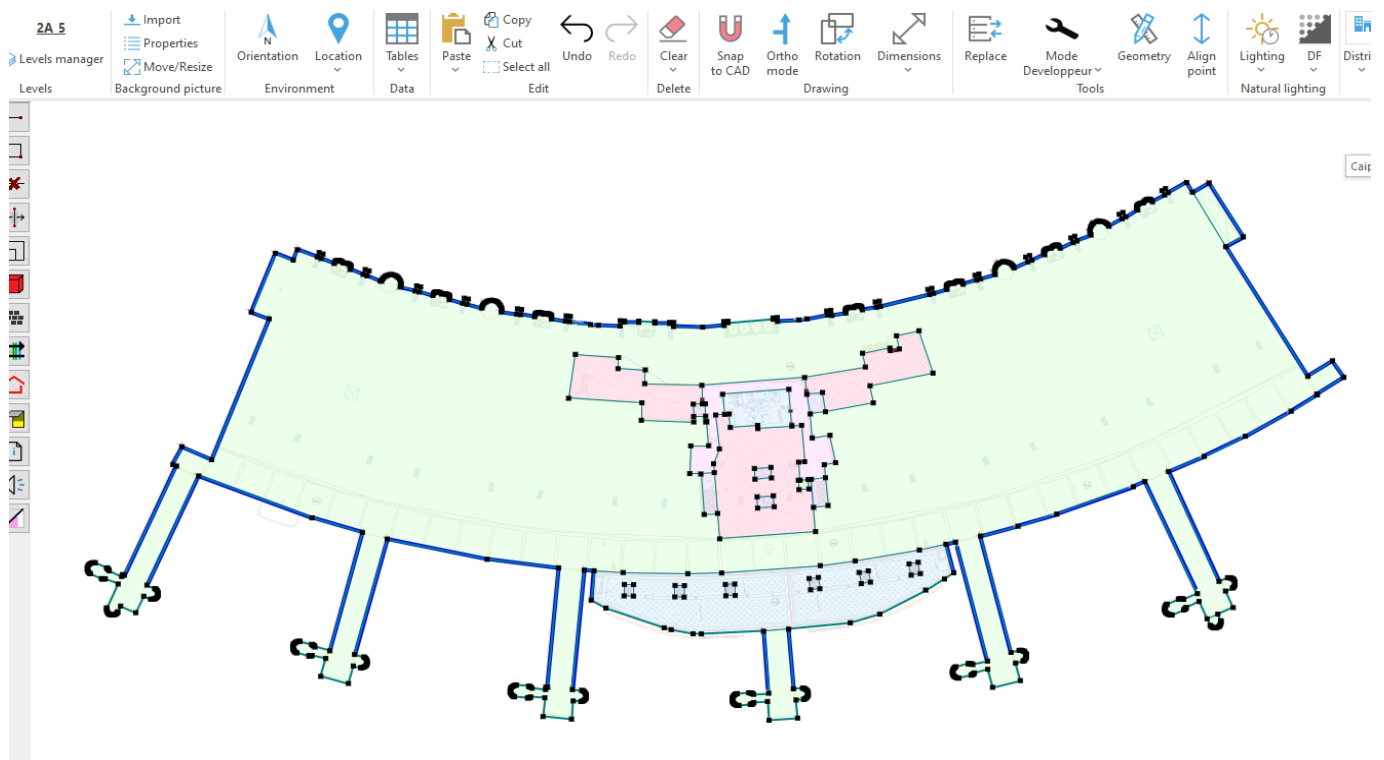


Figure 4-9: The plan view of level 5.

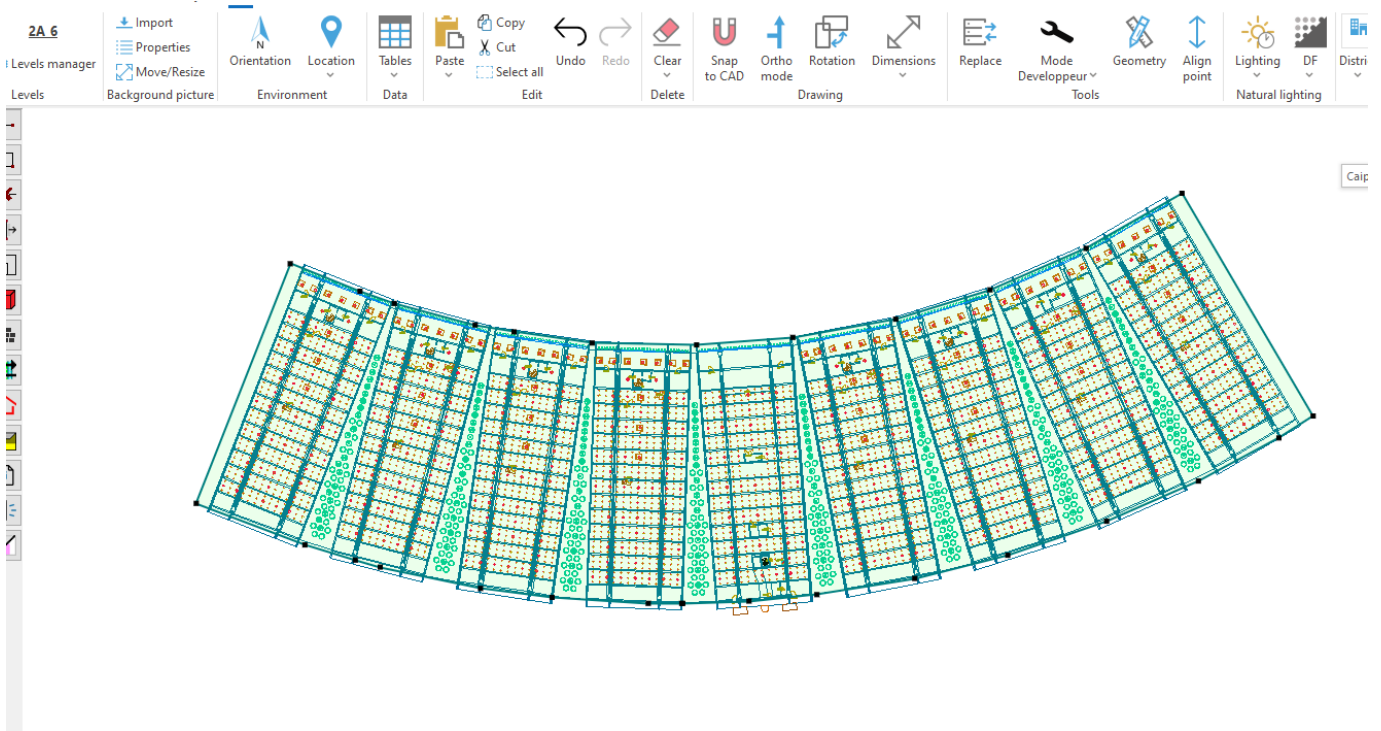


Figure 4-10: The plan view of level 6.

4.2.1.2 Alignment of different levels

It should be noted that once all levels are imported, the background images may not align perfectly—for example, the default position of Level 1 might be significantly offset from Level 0. As such, some manual adjustments are required. One effective method is to first complete Level 0, then copy all elements to Level 1. Using the 'Move/Resize' option under the 'Background picture' tab, the background image can then be adjusted until it aligns precisely with the overlapping areas between Level 0 and Level 1 (see Figure 4-11). The same procedure applies to the upper levels.

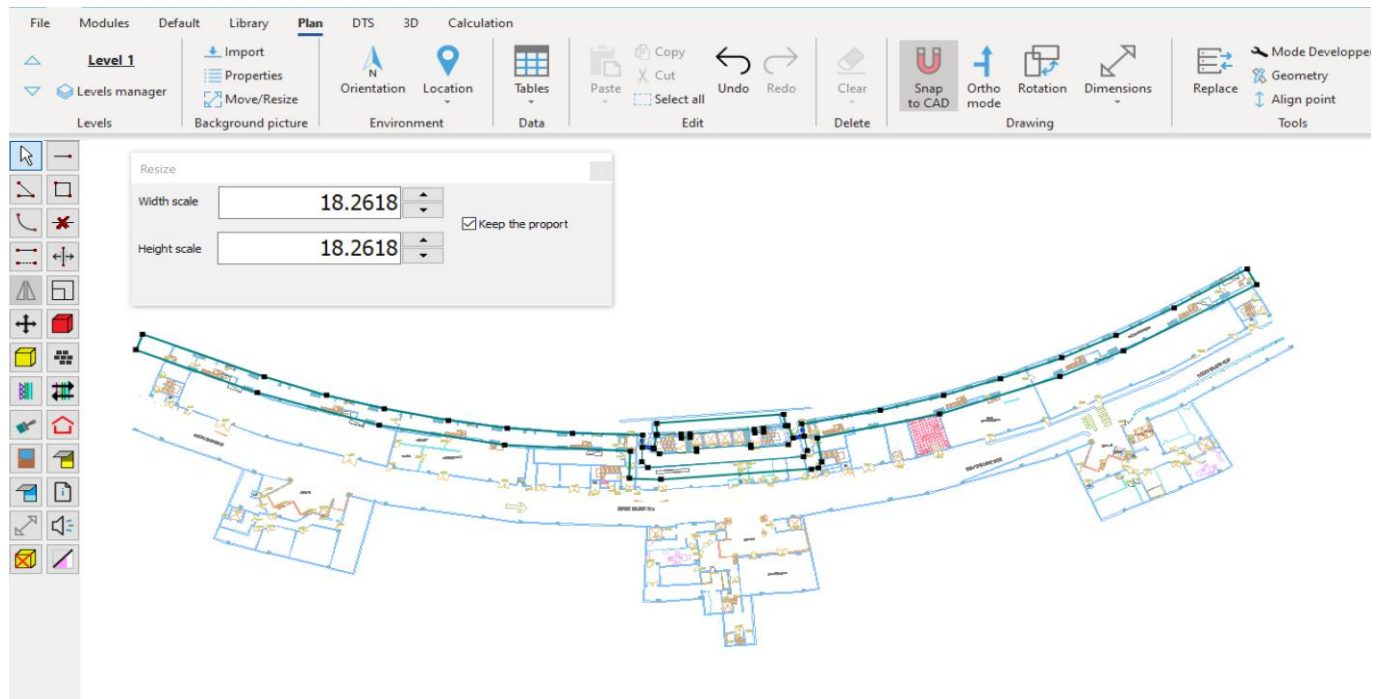


Figure 4-11: Interface for moving and resizing background images to align levels.

4.2.1.3 Height of each level

The side section of the building is shown in Figure 4-12, from which the height of each floor can be determined. For the curved roof, its average height was taken as a representative value.

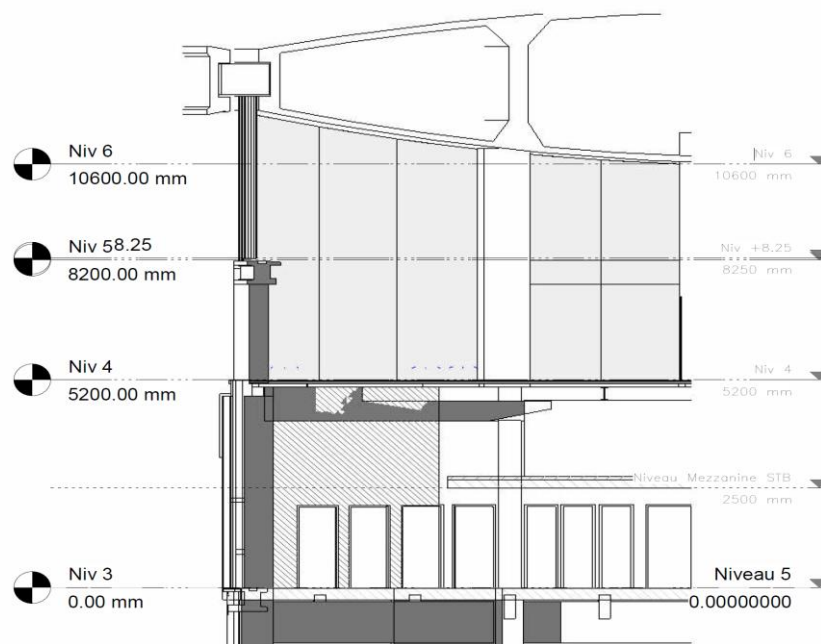


Figure 4-12: Side section of the building.



4.2.1.4 Open floor of Mezzanine levels

Levels 1bis, 3bis, and 5 in Terminal 2A are mezzanine levels, meaning that most of the floor area in these levels is open. In the DWG file, only the mezzanine structures are visible in some levels (e.g., Level 1bis). However, this does not reflect the actual layout, so the outer boundaries should be added manually to ensure consistency with the real building configuration, as seen in the figure below.

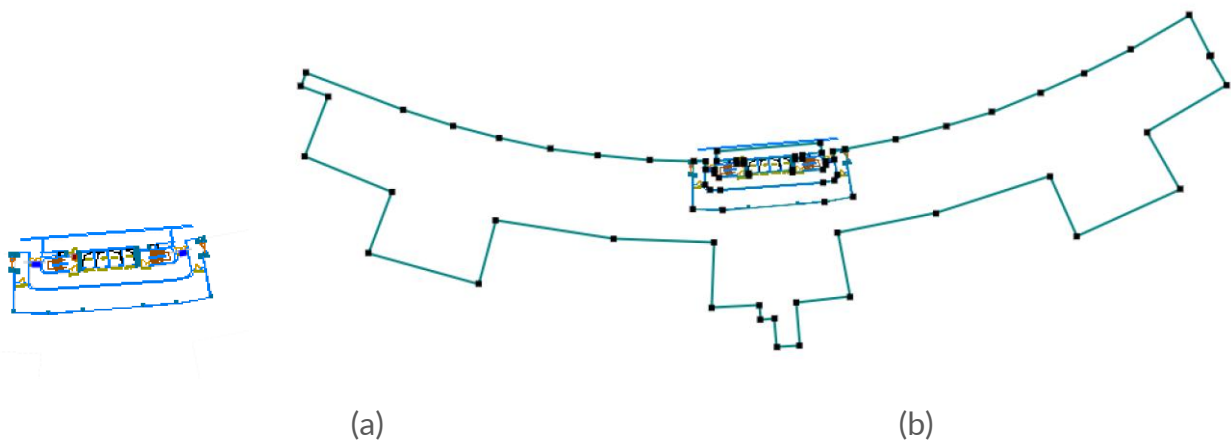


Figure 4-13: The level 1bis in the (a) DWG file and (b) Modeler.

By default, when a level is created in Pleiades Modeler, its floor covers the entire area. Therefore, it is necessary to identify the parts of the floor that do not exist and set them as open in the software, as illustrated in the figure below.

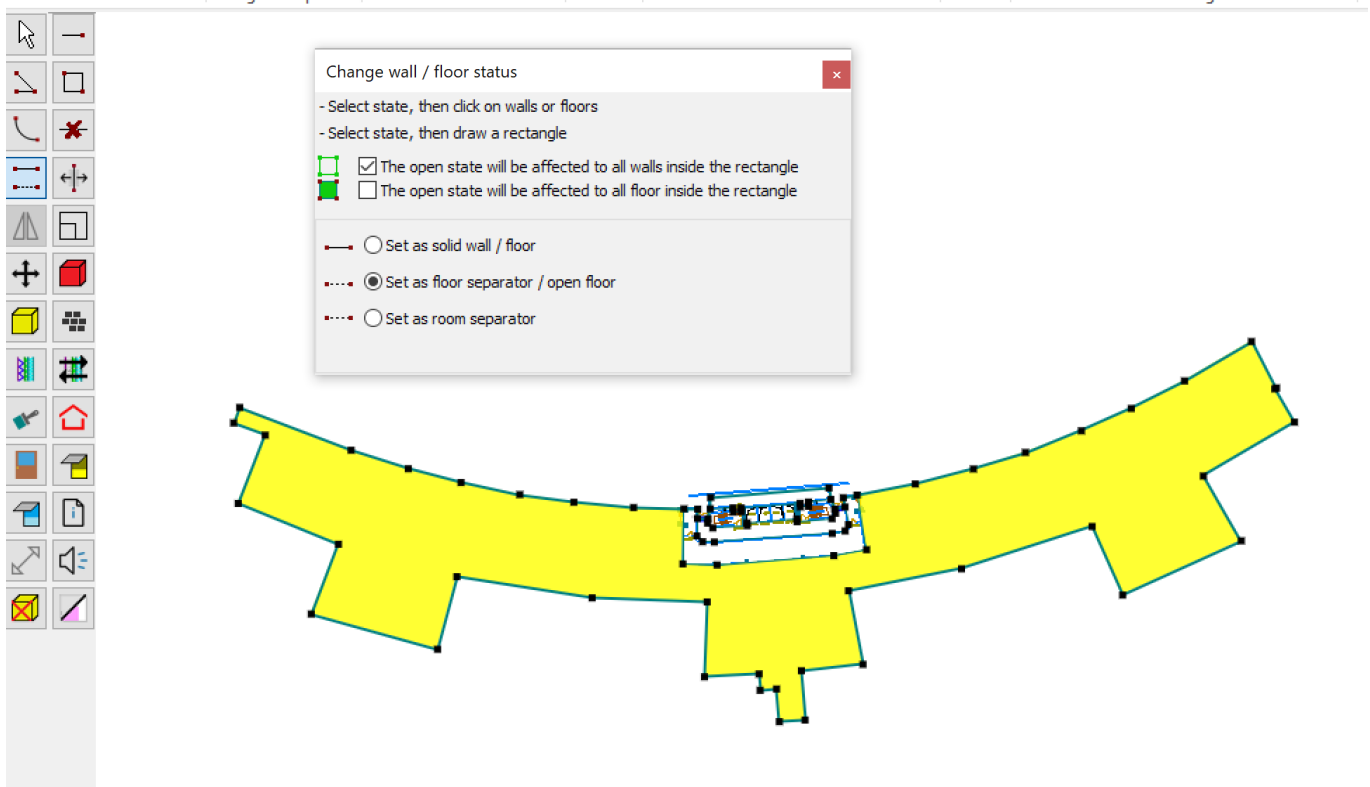


Figure 4-14: The interface for changing the status of wall/floor in Modeler.

4.2.1.5 External wall attachment and evaluation of thermal bridges

After importing the DWG file of a given level into Modeler, all walls can be drawn along the existing lines in the plan. However, since the walls in the DWG file have a certain thickness, it raises the question of which side of the wall line should be followed when drawing. In this model, the inner line of the wall was selected as the reference, as shown in Figure 4-15(a). Accordingly, the “inside” setting was applied for the attachment of external walls, as illustrated in Figure 4-15(b). To compensate for the underestimated heat losses resulting from this choice, thermal bridges were added at the corners under the “default” tab, as shown in Figure 4-16. The values correspond to the French regulation, based upon finite elements calculations.

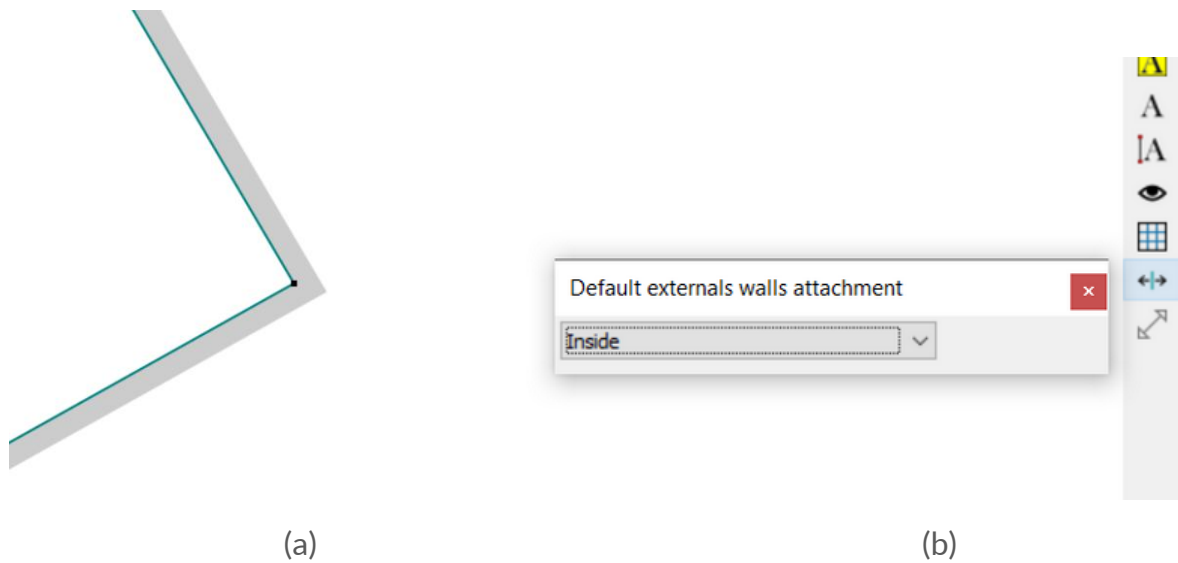


Figure 4-15: (a) Selection of wall side and (b) Default externals walls attachment.

Default thermal bridges			
High Floor	Roof-External wall	ψ 0.31	Outgoing angle
Intermediate floor	Intermediate floor-External wall	ψ 0.99	d.1 - Angle sortant
Low Floor	Floor-Underground	ψ 0.49	0° < Outgoing angle < 135 °
Shear wall (T)		ψ 0	Incoming angle
			225 ° < Incoming angle < 360°

Figure 4-16: Default thermal bridges.

4.2.1.6 Doors and windows

In this project, “glazing doors” was used for all doors. As for windows, two different types (double glazing windows and single glazing windows) were created in the library based on the information provided by ADP.

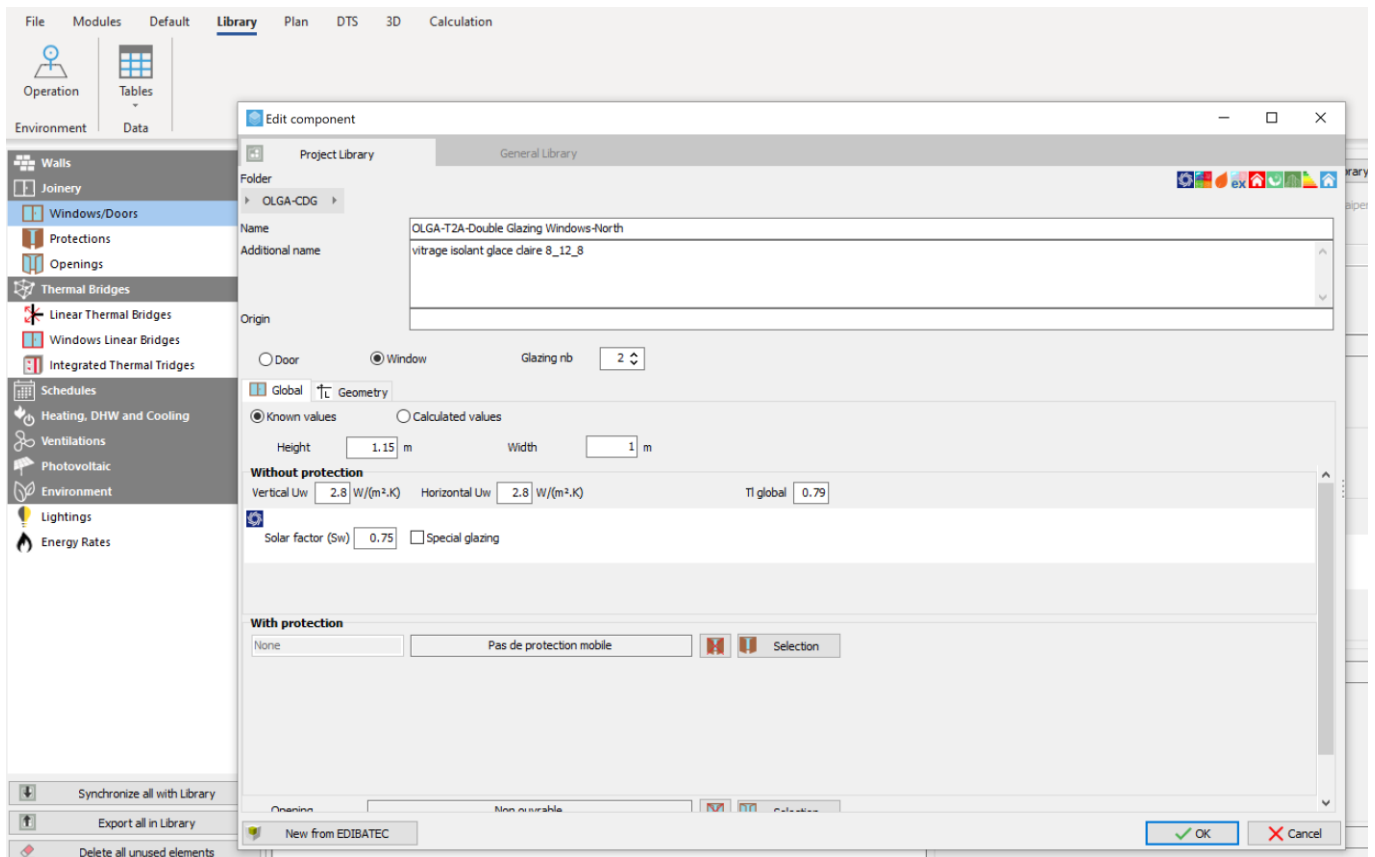


Figure 4-17: The interface of creating double glazing windows.

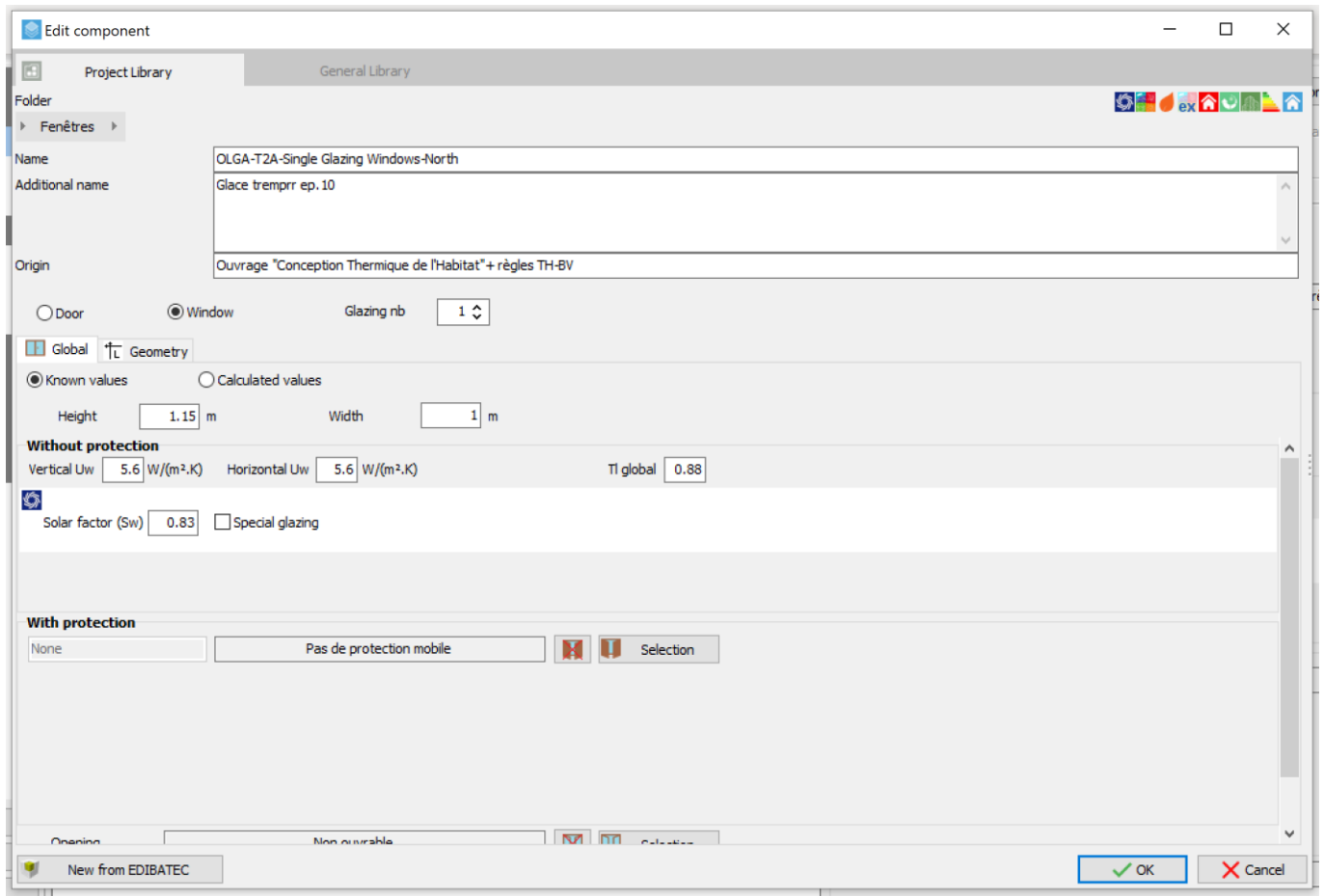


Figure 4-18: The interface of creating single glazing windows.

It is convenient to draw the doors and windows based on the DWG file and the architectural drawings, as shown in the figure below.

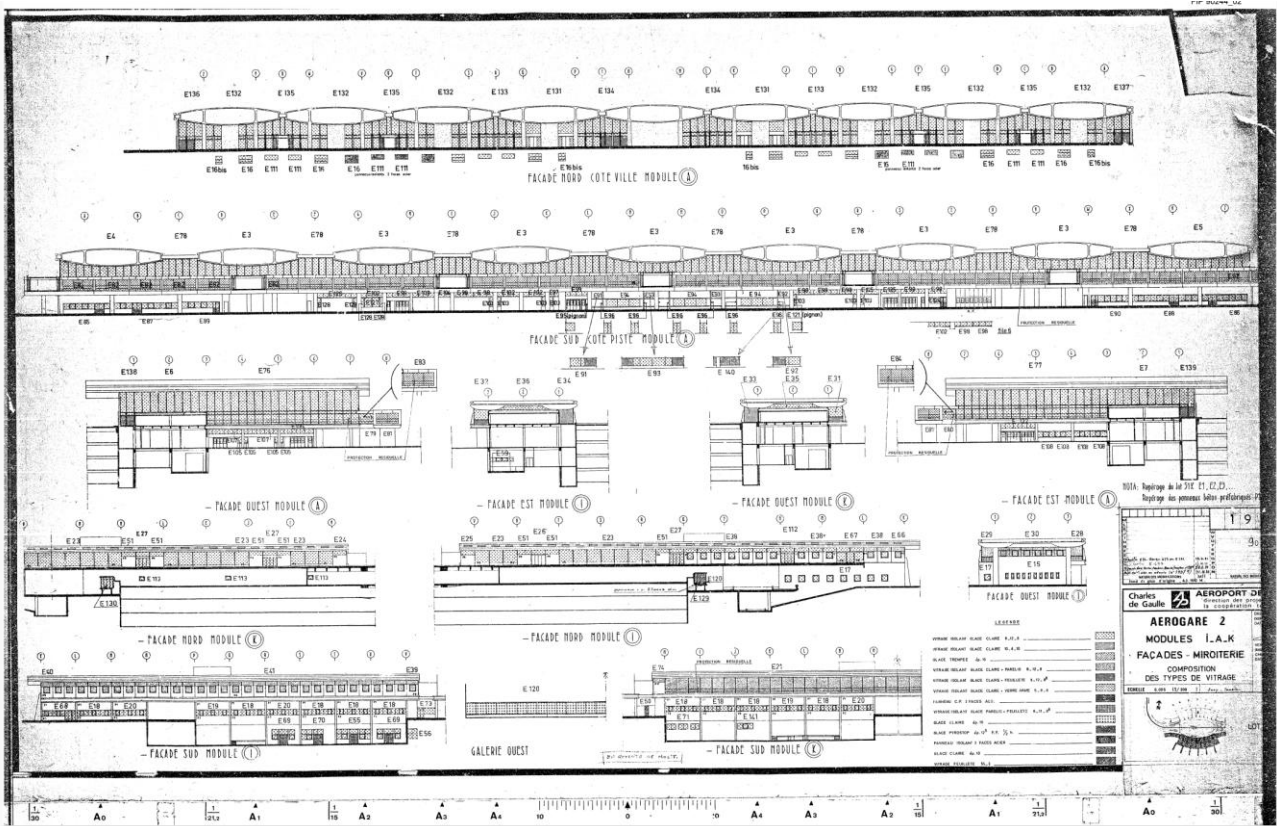


Figure 4-19: The architectural drawings of the Terminal 2A.

Furthermore, doors and windows are classified according to their position in the plan view – those located on external walls are defined as windows, while those on internal walls are considered doors. Once all lines have been drawn, the length of each can be displayed by clicking the “Display length of walls on sketch” button in the top right corner of the interface, as shown in the figure below. This feature makes it easier to estimate the dimensions of doors and windows accurately. When drawing the façades on the external walls, the width of each façade should be determined based on the length of the corresponding wall. As you move the mouse, the distance from one side of the window to the edge of the wall will appear, which helps accurately position the window without exceeding the wall boundary. Additionally, users should pay attention to the height differences between levels.

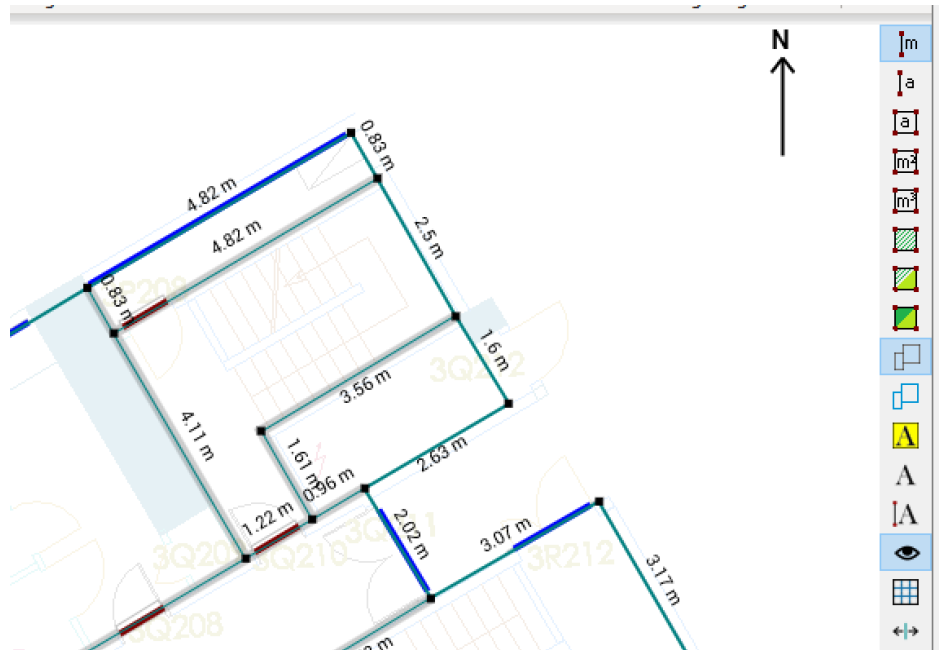


Figure 4-20: The interface of displaying length of walls on the sketch.

4.2.2 Default settings of wall compositions

4.2.2.1 Creation of new compositions

Based on the information provided by ADP (see Table 4-1), the compositions for the floors, walls, roof, windows, and other elements can be defined in Modeler under the 'Default' tab, as shown in Figure 4-21. “Default” means that these compositions are allocated to all walls, except if a specific composition is indicated for some walls.

Table 4-1: Compositions information provided by ADP.

	T2A
Façades	The curtain walls are made of aluminum without thermal break.
Floors	Technical areas: 10 cm concrete + 5 cm screed Passenger areas: 10 cm concrete + 5 cm screed + 2 cm covering
Roofs	15 cm concrete
Internal walls	15 cm breeze block 2 cm plaster + paint.
Glazed elements	The characteristics of glazing is specified in Table 4-7.

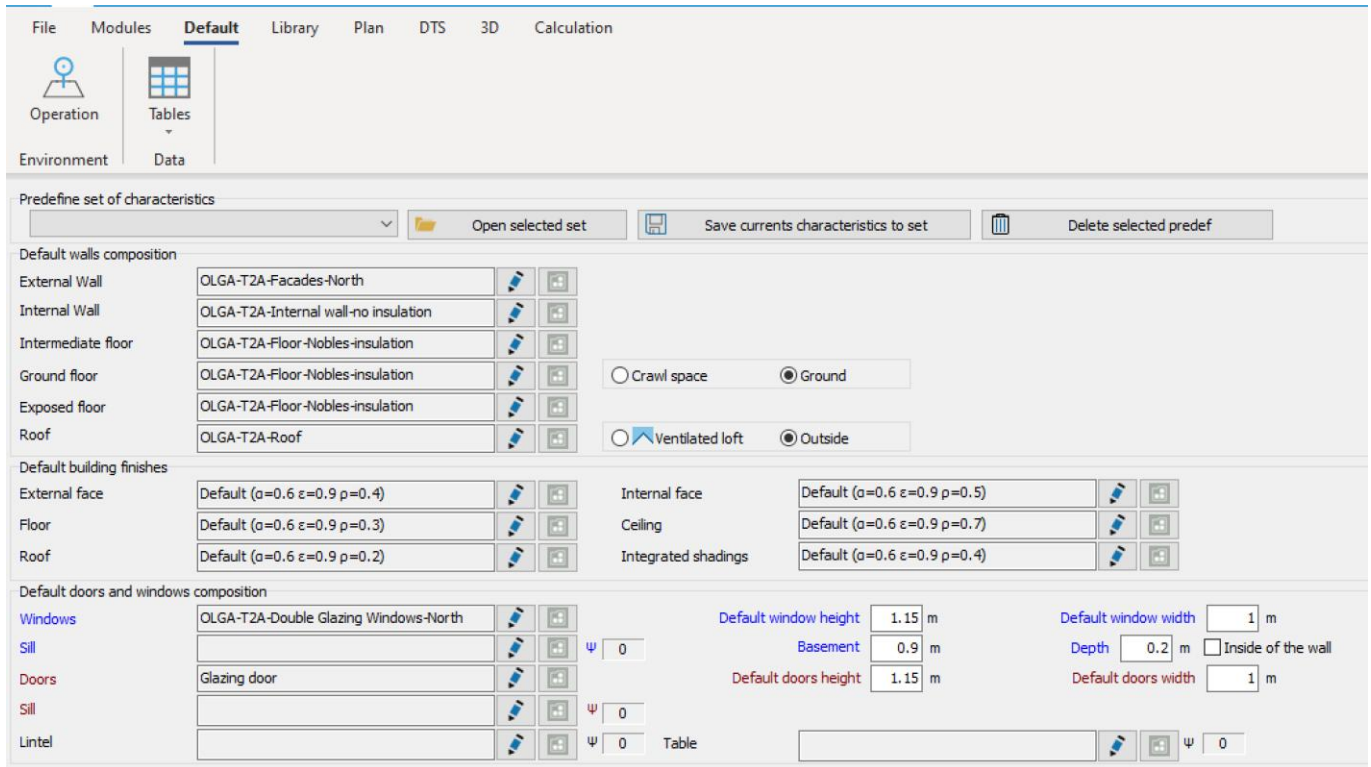


Figure 4-21: Interface of setting default compositions.

The detailed compositions can be found in Figure 4-22 to Figure 4-25. Insulation thickness of 0.001 m (i.e. nearly zero in the existing building before renovation) is considered in order to vary this parameter in a further optimisation study.

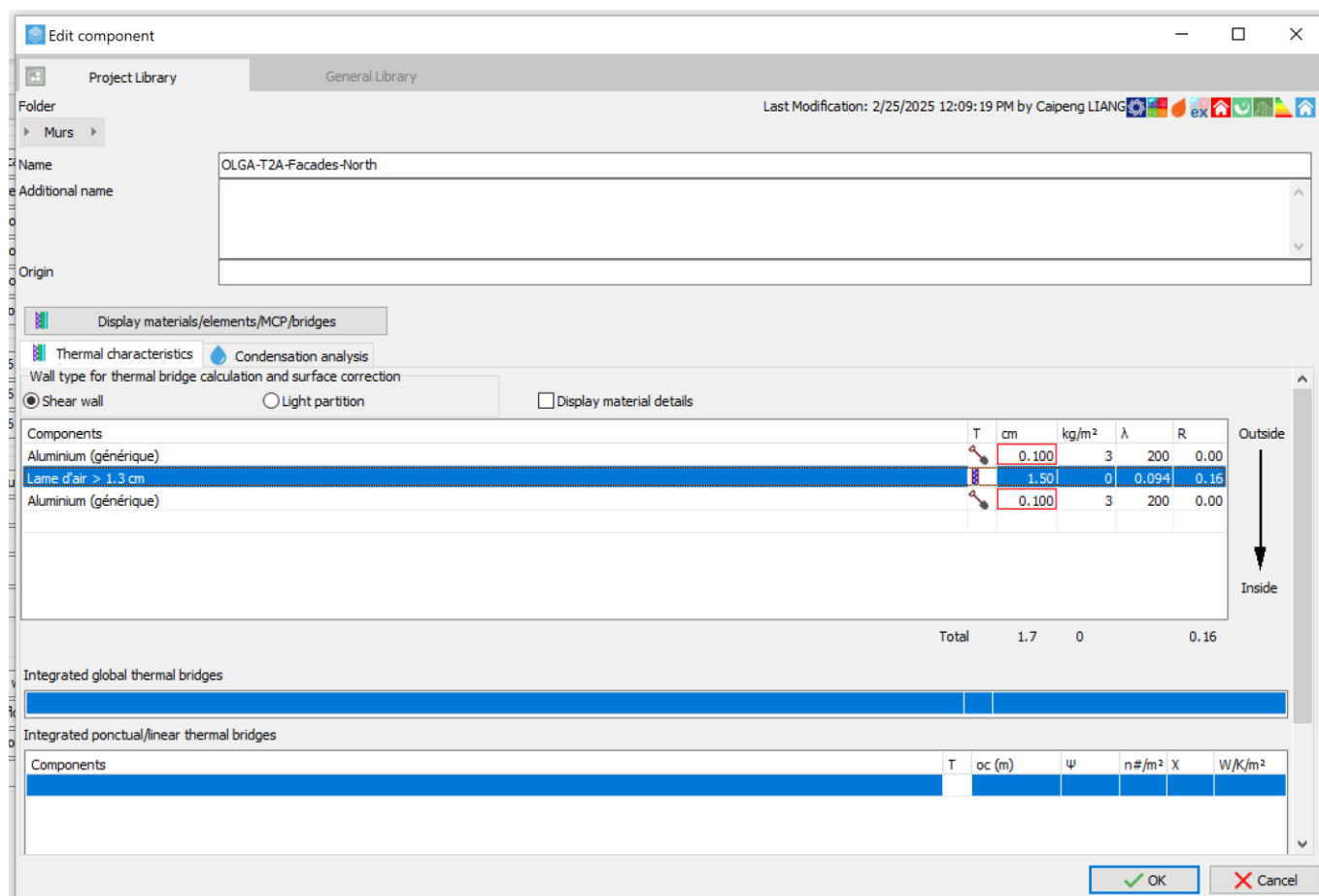


Figure 4-22: Detailed compositions of façades.

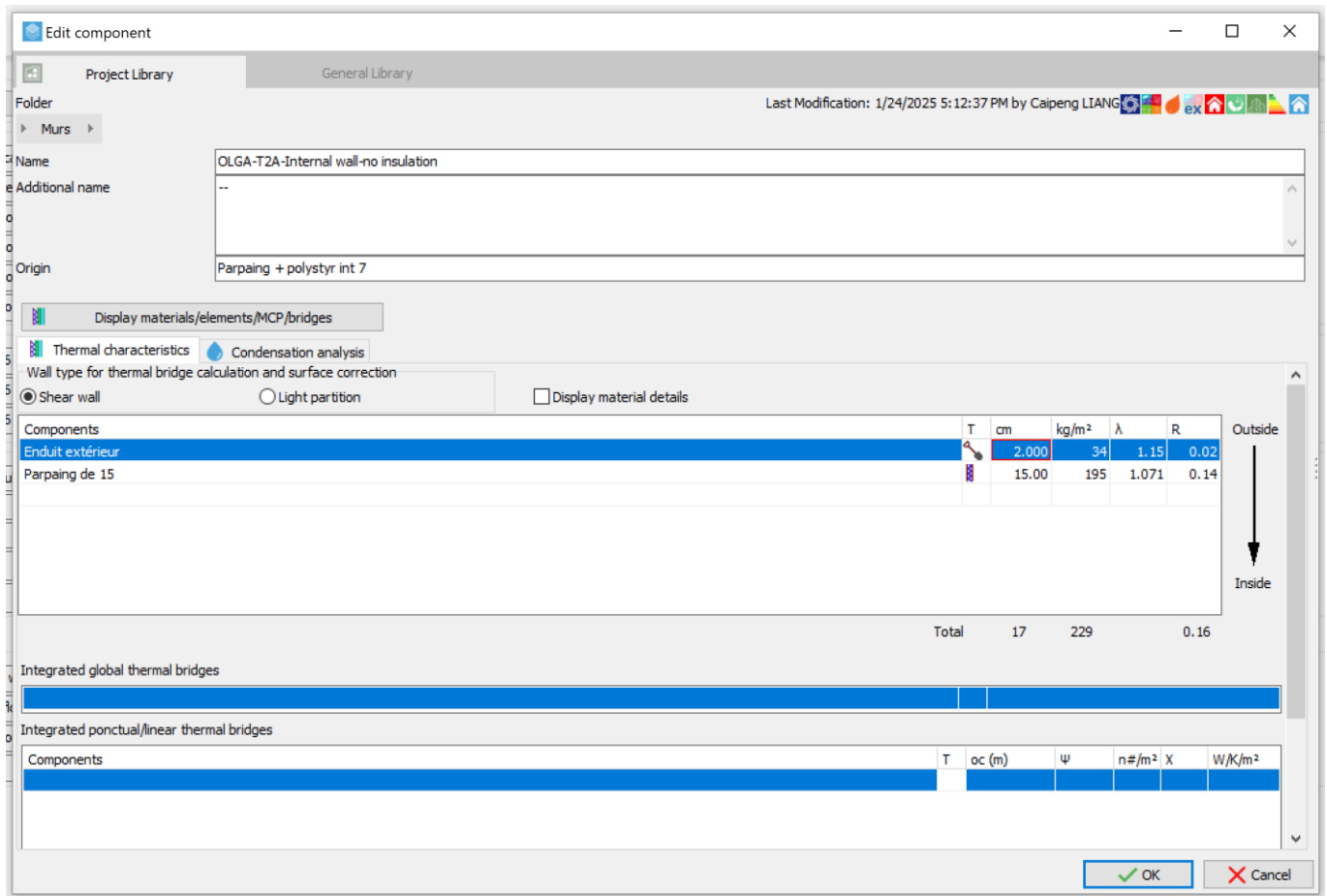


Figure 4-23: Detailed compositions of internal wall.



Edit component

Project Library | General Library

Folder: Planchers

Name: OLGA-T2A-Floor-Nobles-insulation

Additional name:

Origin: Plancher Béton brut

Display materials/elements/MCP/bridges

Thermal characteristics | Condensation analysis

Wall type for thermal bridge calculation and surface correction: Shear wall Light partition Display material details

Components	T	cm	kg/m ³	λ	R
Béton lourd	↕	10.000	230	1.75	0.06
Laine de verre	↕	0.001	0	0.041	0.00
OLGA-T2A-Chape	↕	5.000	115	1.75	0.03
Marbres	↕	2.000	54	3.5	0.01
Total					0.1

Integrated global thermal bridges

Integrated ponctual/linear thermal bridges

Components	T	oc (m)	ψ	n#/m ²	X	W/K/m ²

Outside ↓ Inside

OK Cancel

Figure 4-24: Detailed compositions of floor.

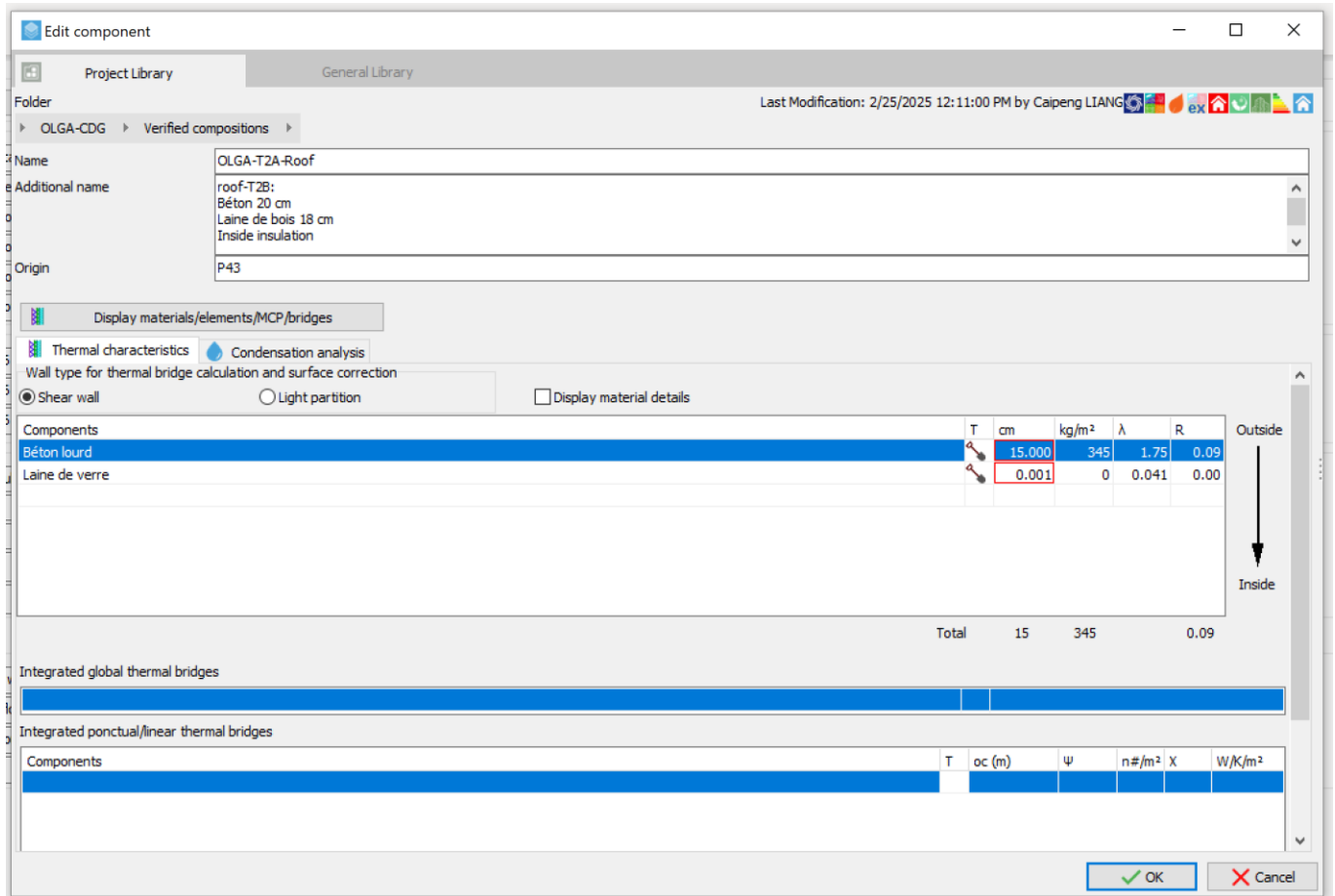


Figure 4-25: Detailed compositions of roof.

4.2.2.2 Insulation for exposed floor

Due to the varying structures across different levels, some higher levels may have a larger or smaller surface area compared to the lower levels. As a result, parts of the floor or roof may be exposed to the outside environment and require an insulation layer. The software can automatically detect and modify the composition for smaller exposed areas, changing them to a roof with insulation. However, for larger exposed areas, manual adjustments are necessary. To do this, the exposed area must first be distinguished from the unexposed area by drawing an open wall in the corresponding level. Figure 4-26 illustrates the open floors drawn in Level 4, with the red lines indicating the floor separator between the exposed floor and the unexposed floor.

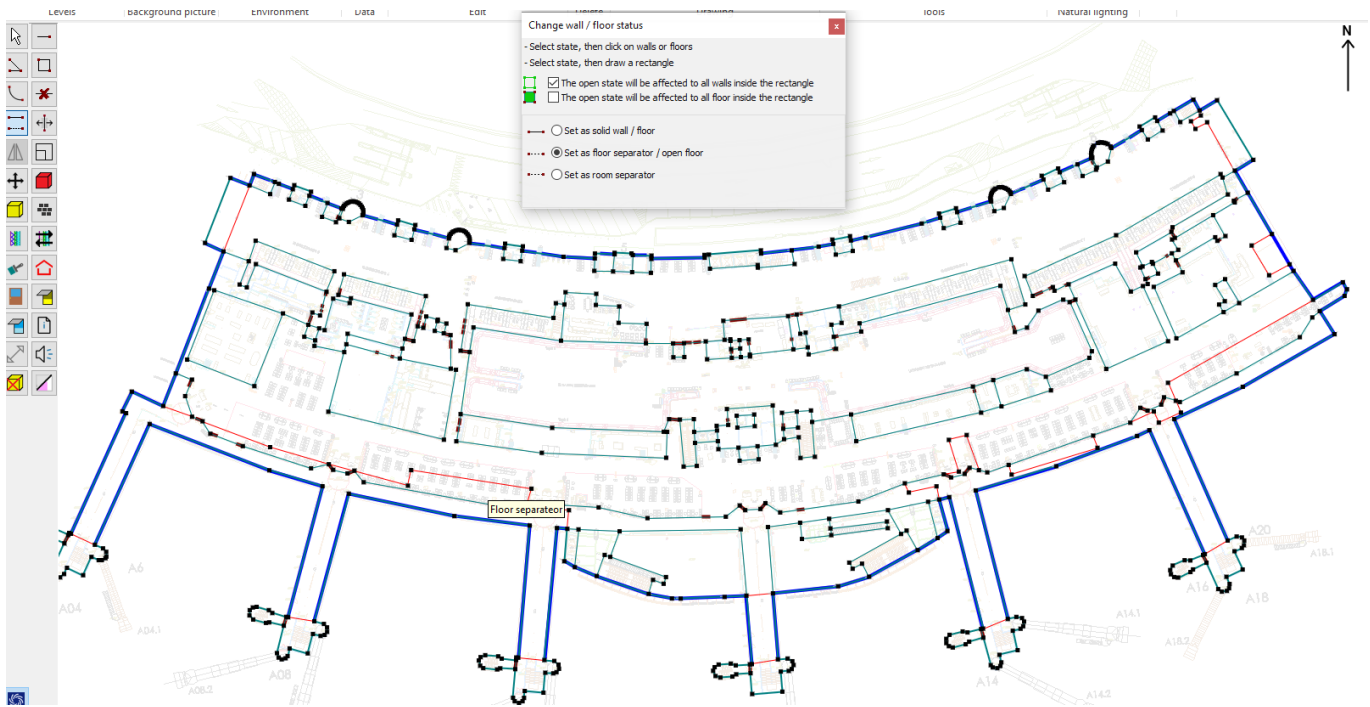


Figure 4-26: The floor separator and the function of changing wall/floor status.

The figure 4-27 shows the corresponding floor composition at Level 4. As seen in the figure, the composition of the exposed floor area has been changed to an insulated floor with nobles, represented by the highlighted yellow area.

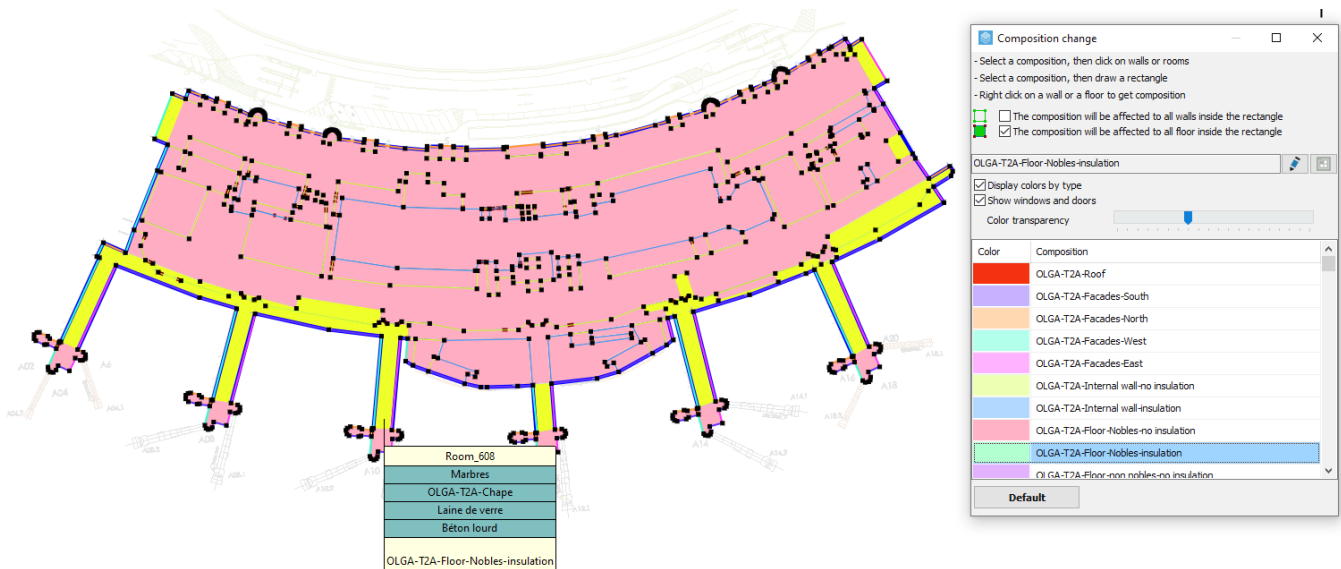


Figure 4-27: The exposed floor after correcting the composition.



4.2.2.3 Creation of new materials

It should be noted that 15 cm breeze block (named “parpaing de 15”) is not included in the general library, so we should create a new element in the library. The characteristics of 15 cm breeze block were based on interpolation of the 10 cm breeze block (parpaing de 10) and 20 cm breeze block (parpaing de 20), as shown in the figure below.

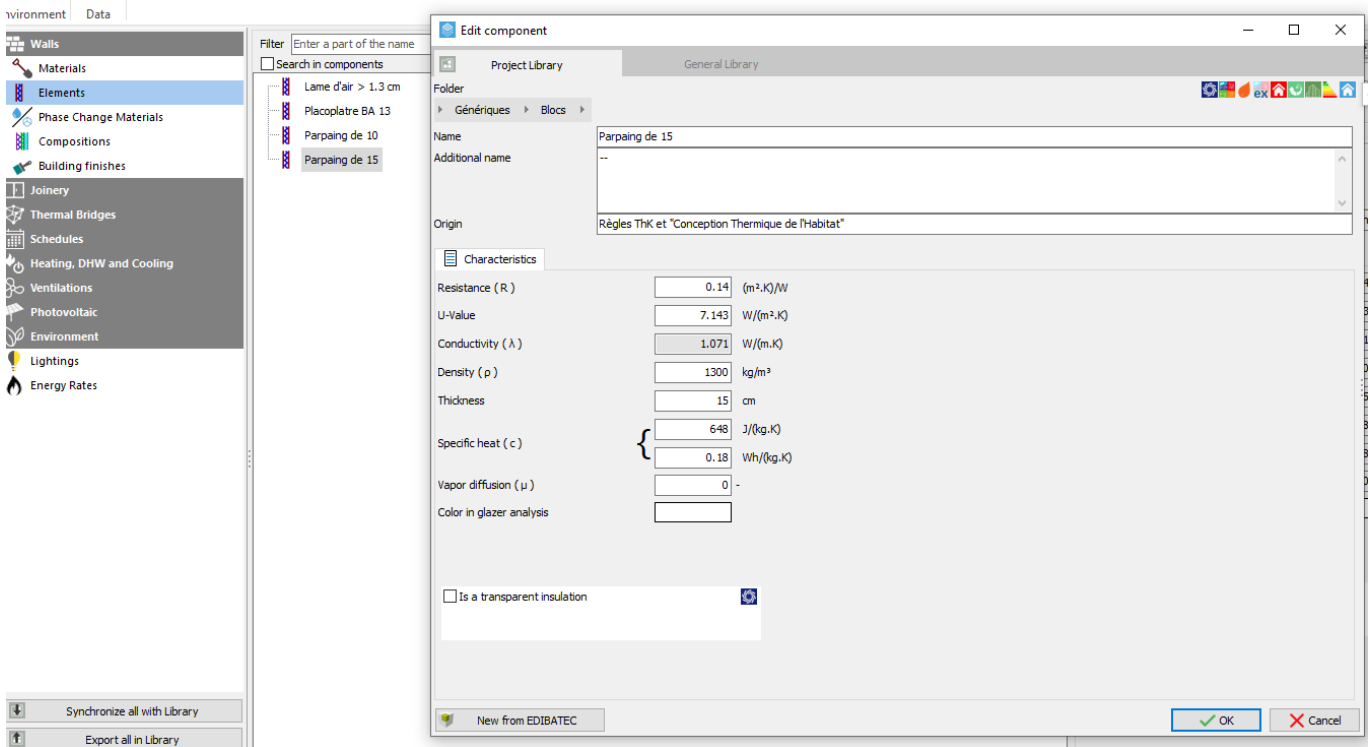


Figure 4-28: Creation of new elements ‘Parpaing de 15’ in the library.

4.2.3 Thermal zones distribution and scenarios definition

4.2.3.1 Thermal zones distribution

In this project, thermal zones on different levels are defined based on the functions of various areas, according to the information provided by ADP, as shown in Figure 4-29 to Figure 4-36. This step is essential because defining thermal zones allows for a more accurate representation of energy use, occupancy patterns, internal loads, and heating/cooling needs, which is critical for precise simulation and optimisation in building performance analysis.

The considered zones are the following: Check-in desks, boarding and departure hall, commercial shells, company lounges and restaurants, security control, luggage sorting, offices, retail areas, toilets, vertical and horizontal corridors, technical spaces (technical gallery, unheated spaces, service road, underground zones), roof (which is made of large cells between concrete shells).

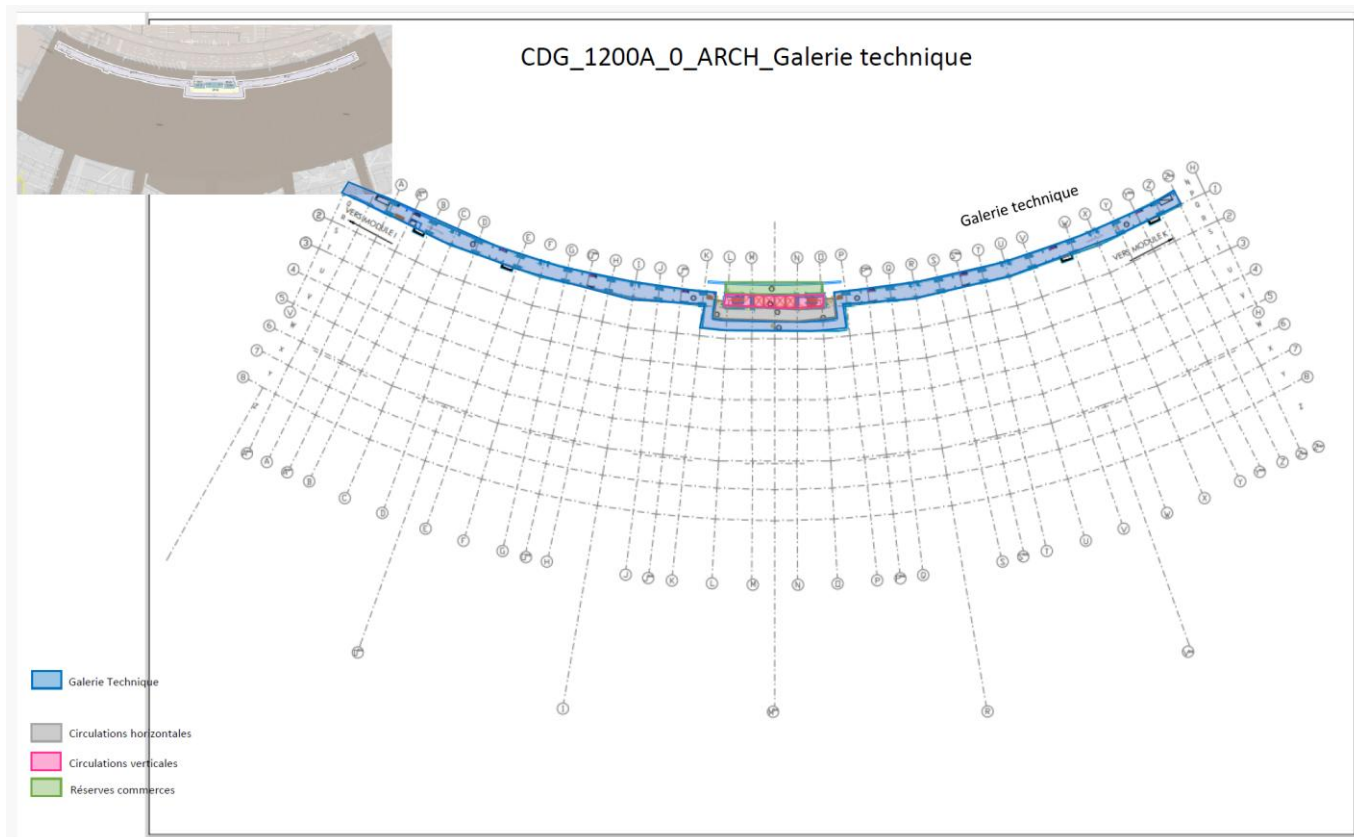


Figure 4-29: The functional zoning of Level 0.

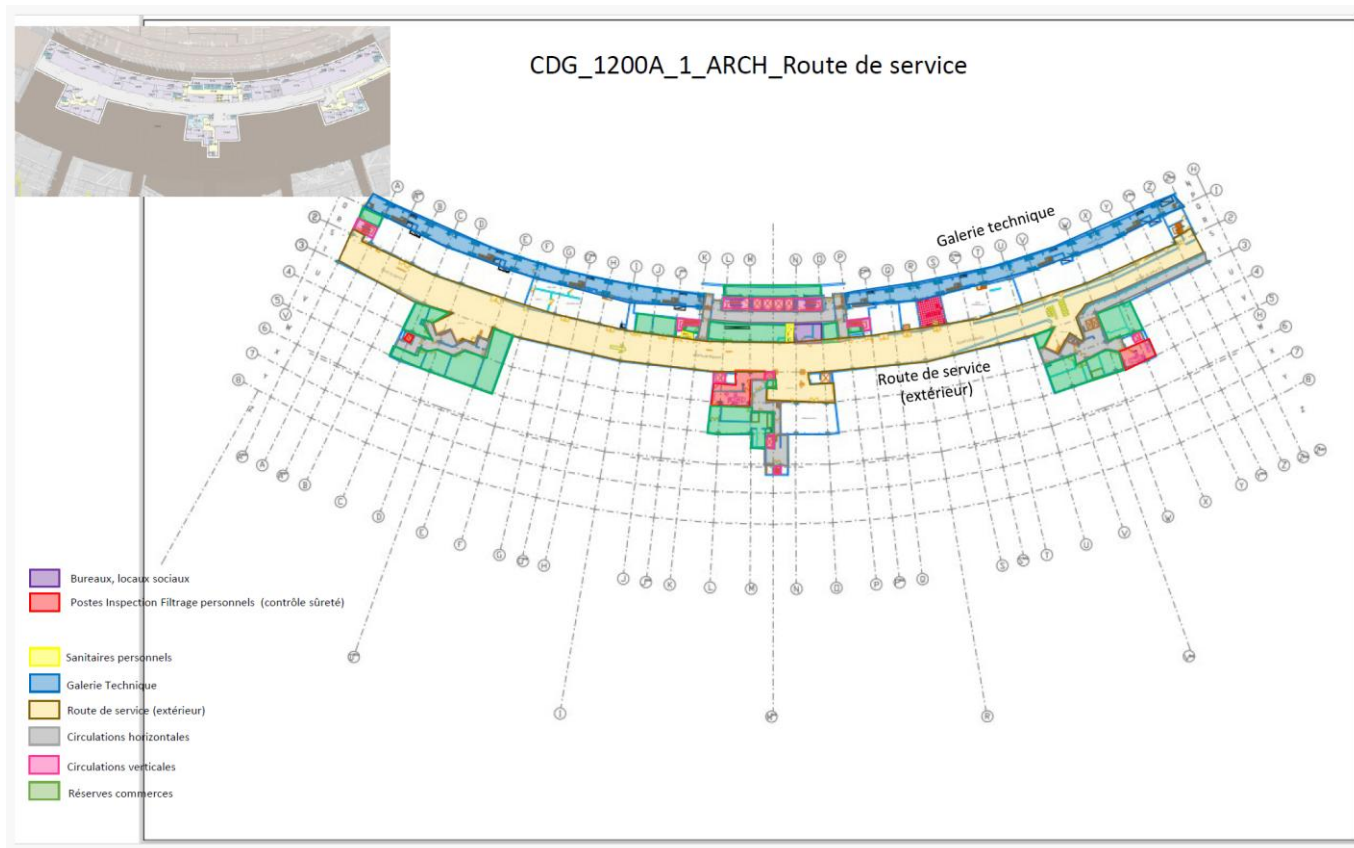


Figure 4-30: The functional zoning of Level 1.

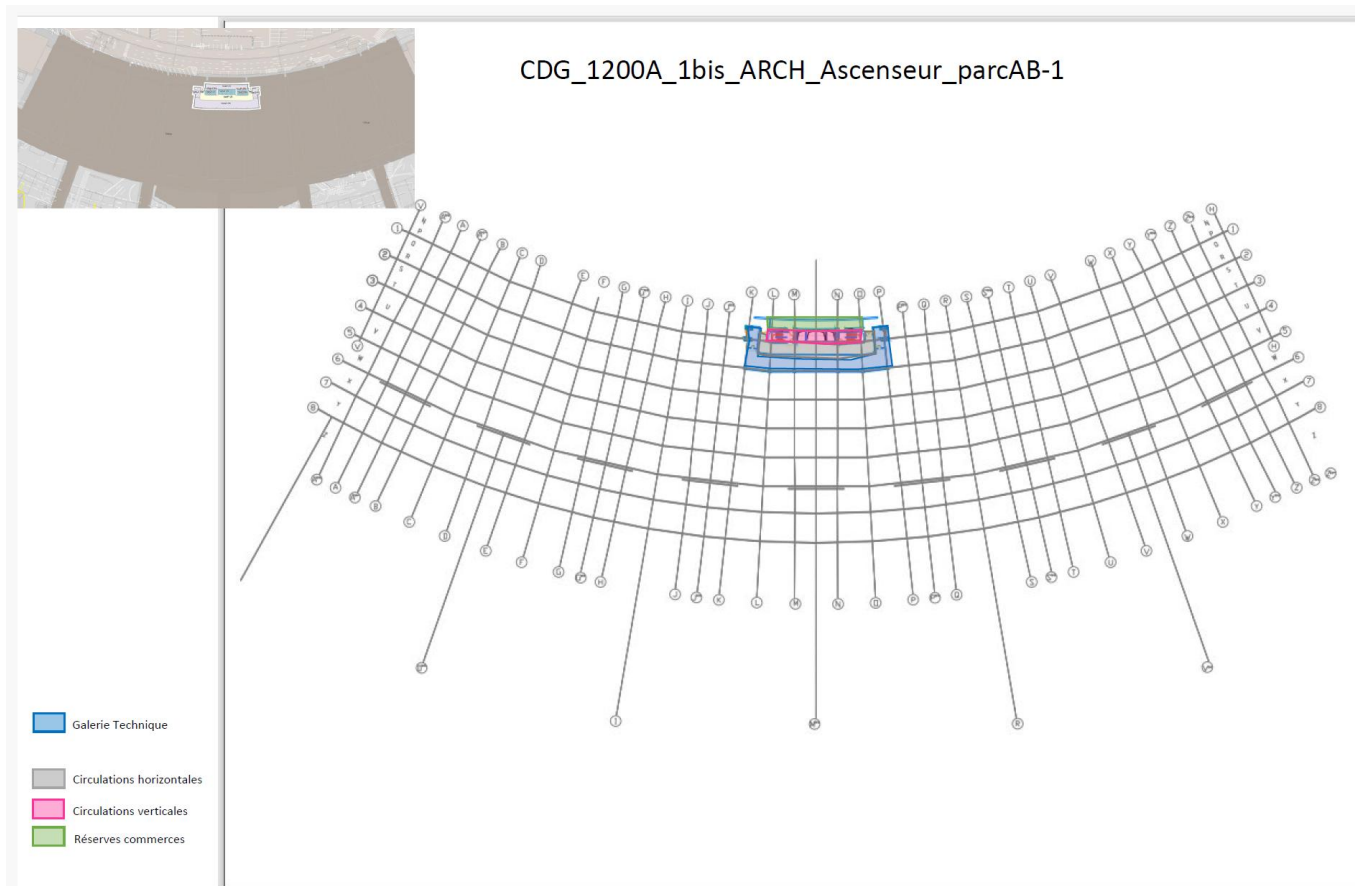


Figure 4-31: The functional zoning of Level 1bis.

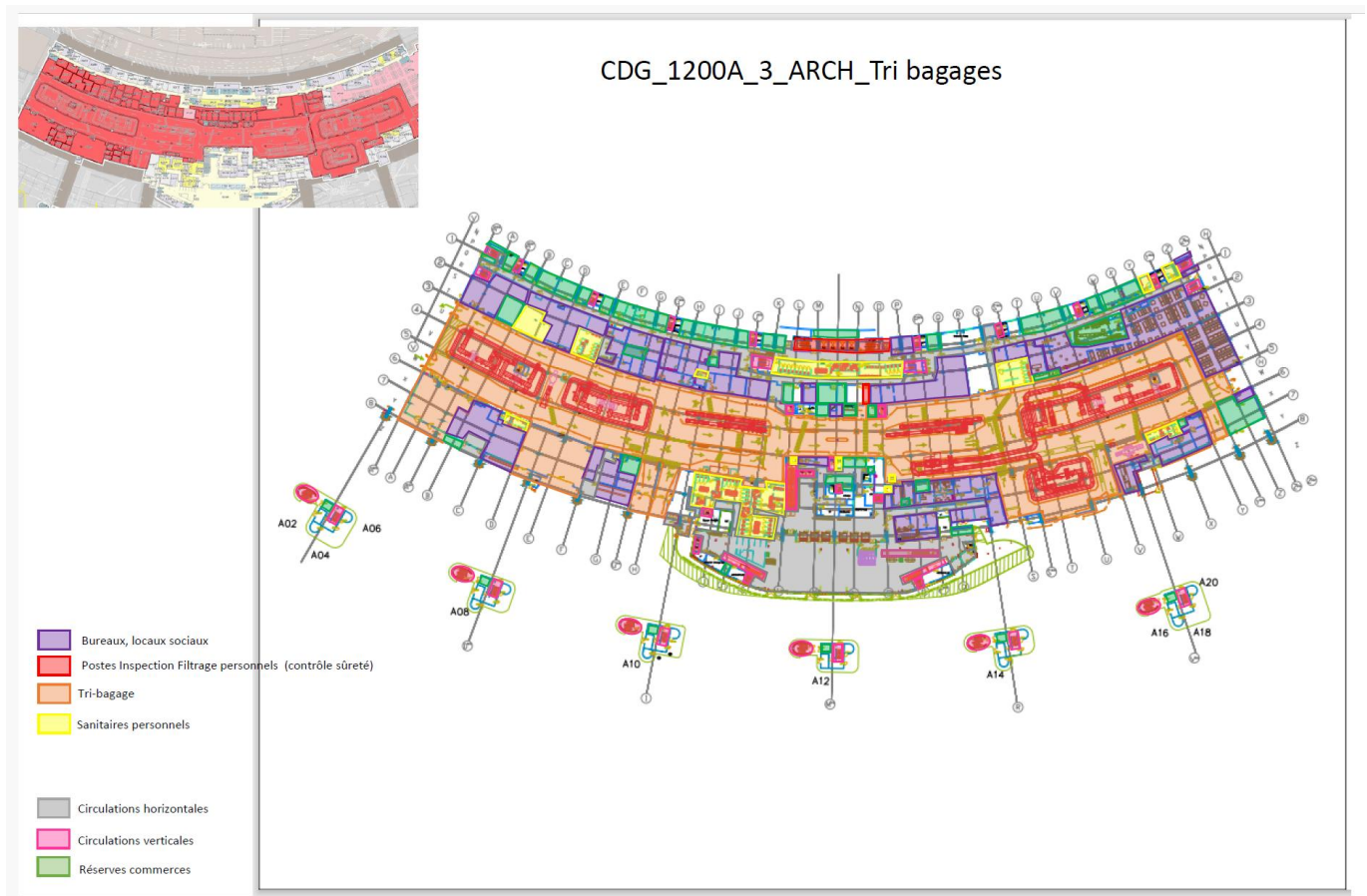


Figure 4-32: The functional zoning of Level 3.

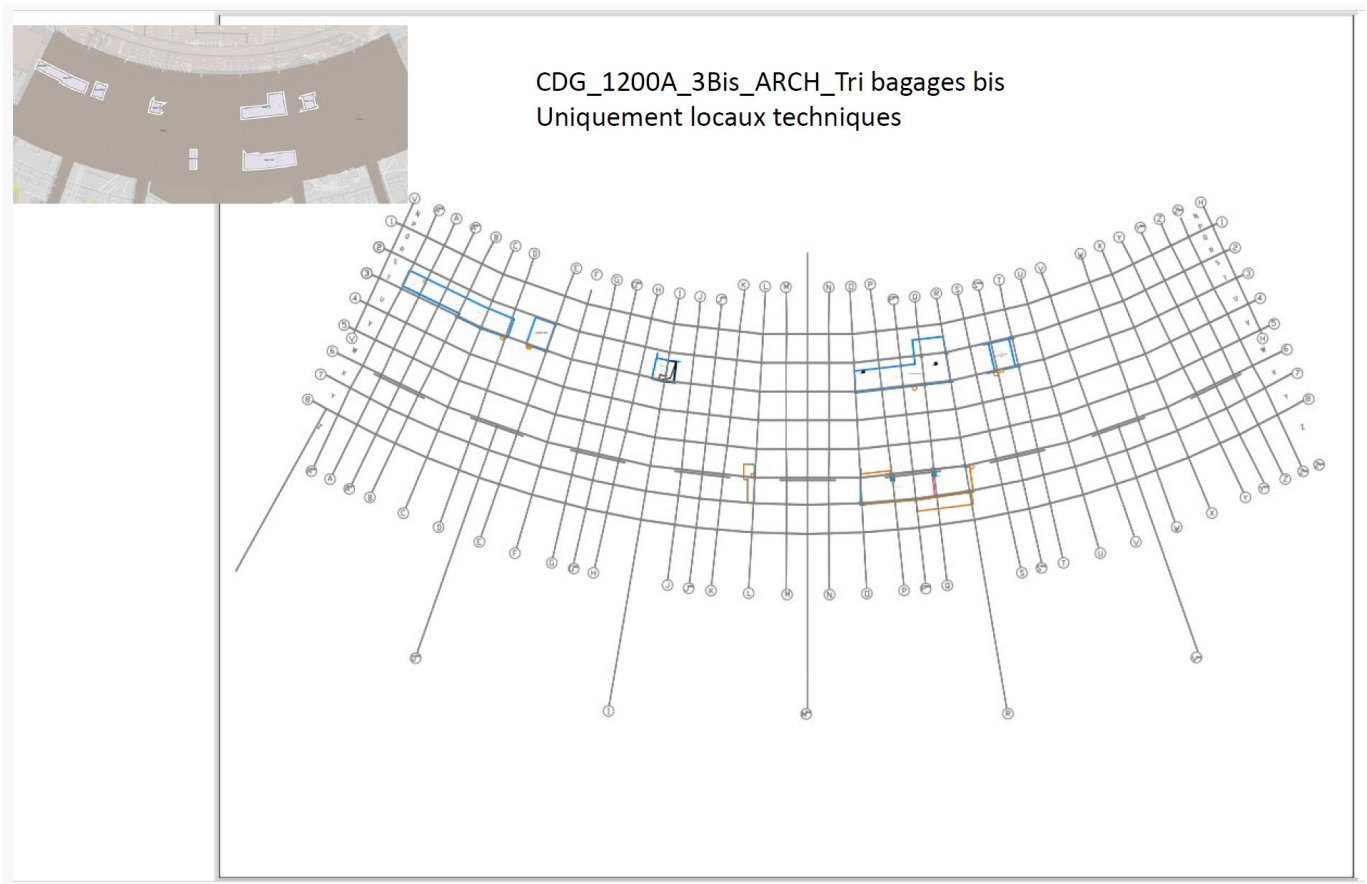


Figure 4-33: The functional zoning of Level 3bis.

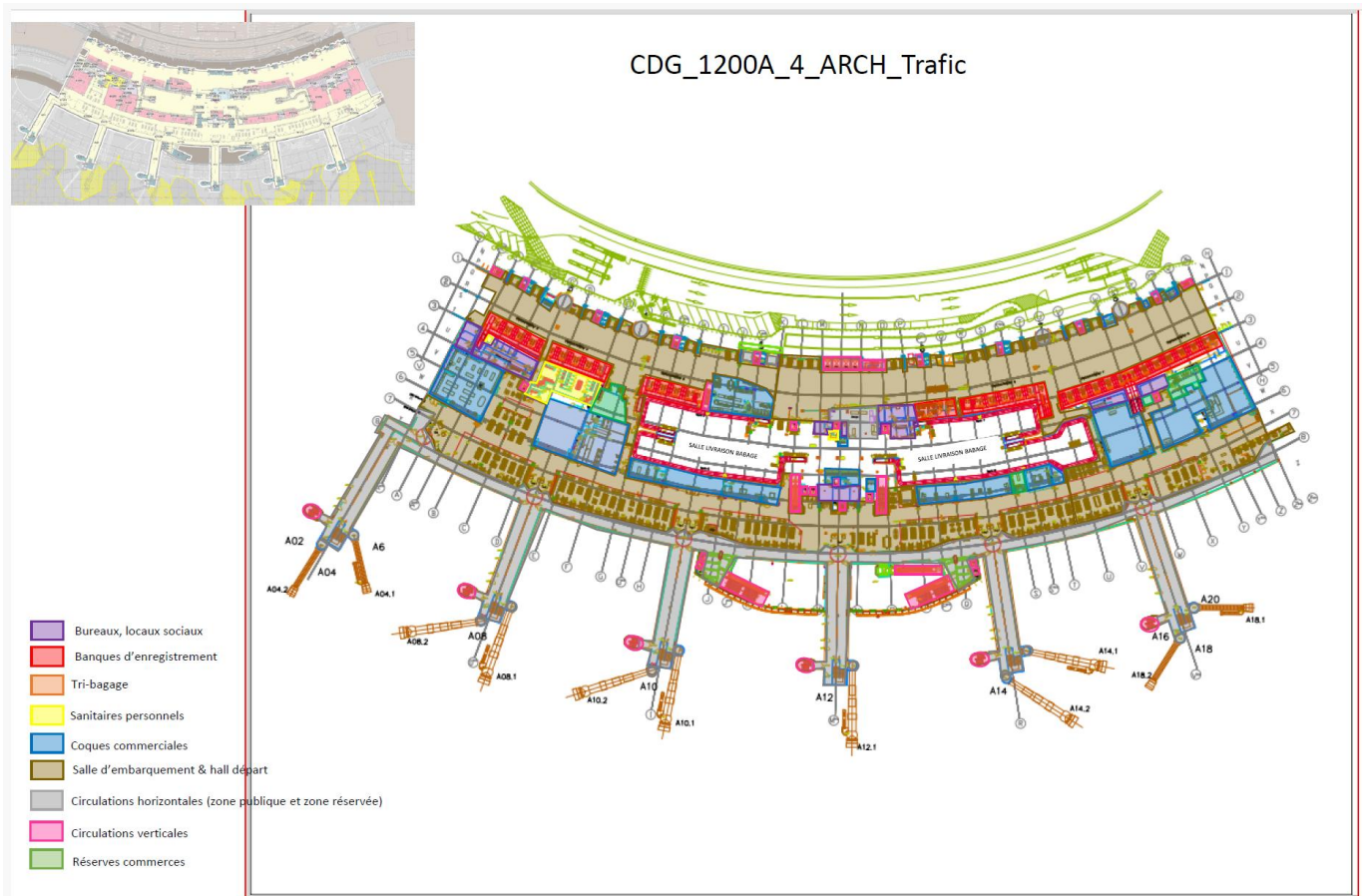


Figure 4-34: The functional zoning of Level 4.

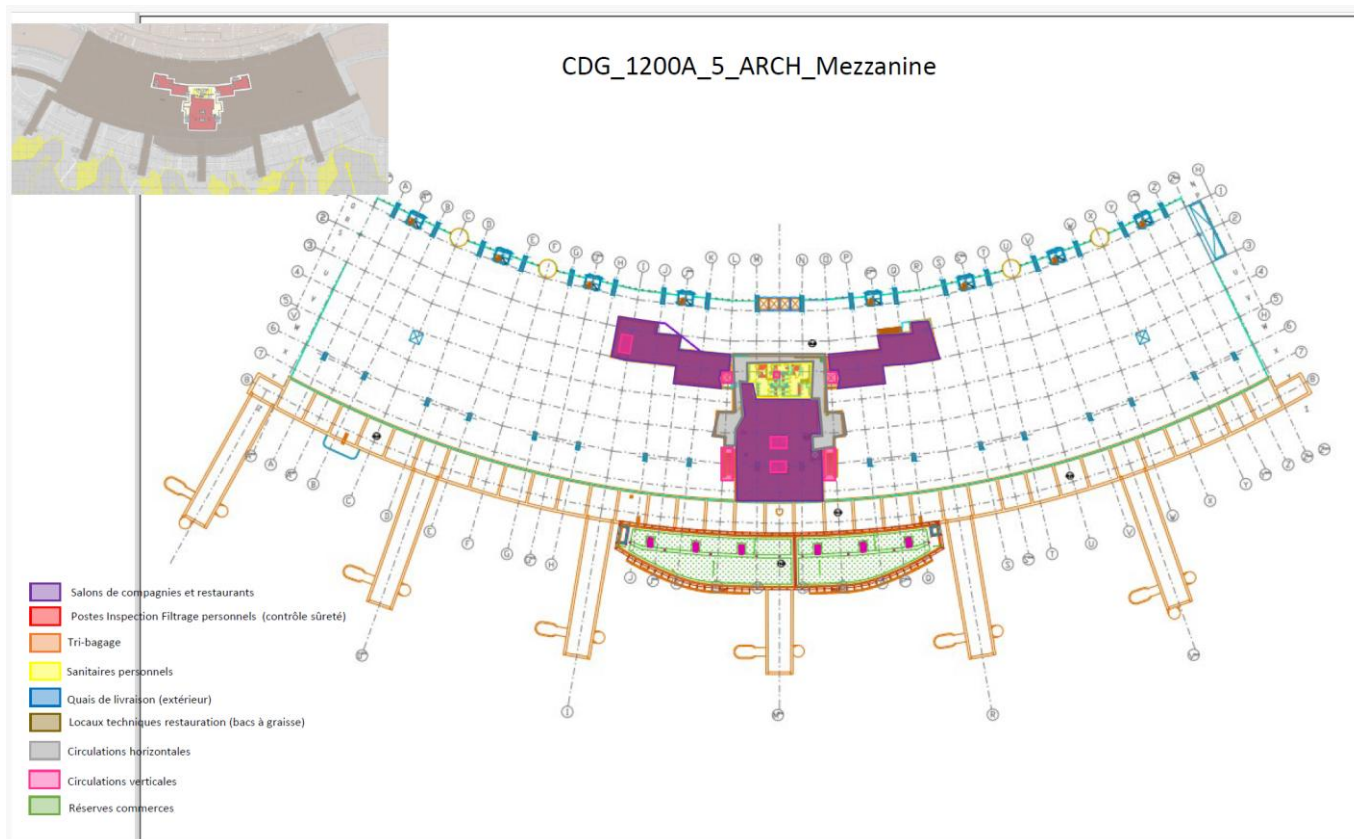


Figure 4-35: The functional zoning of Level 5.

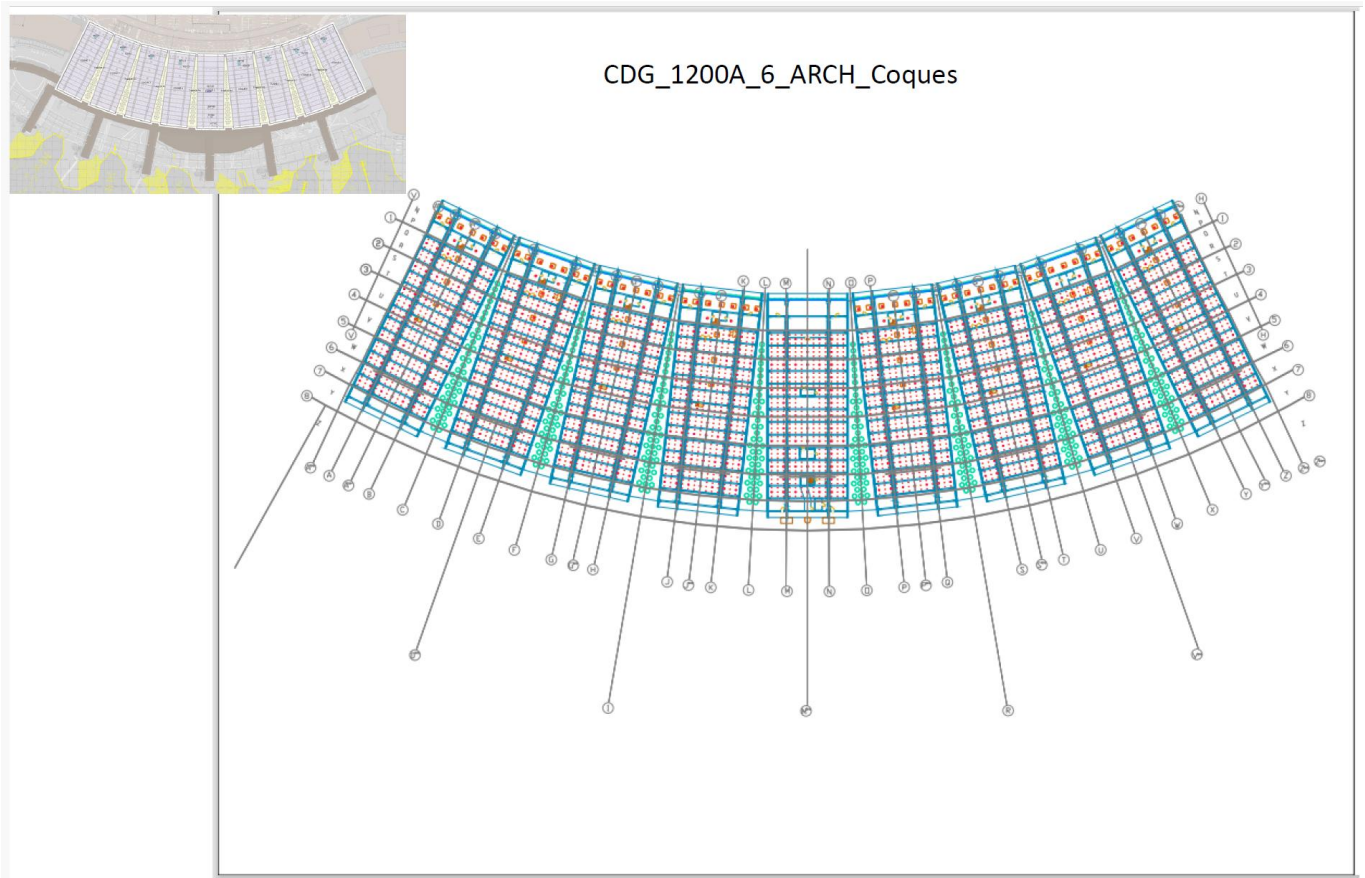


Figure 4-36: The functional zoning of Level 6.

4.2.3.2 Scenarios definition for different thermal zones

The scenarios for Terminal 2A are summarised in the table below.

Table 4-2: Zone definition and their scenarios for Terminal 2A.

Zone number	Zone name	Heating scenario	Cooling scenario	Internal gain	Occupancy	Ventilation
1	Unheated space	-	-	IG2	O8	V0.5
2	Vertical corridors	22°C all year	C4	IG1	O6	V0.5
3	Technical gallery	22°C all year	C5	IG3	O7	V0.5
4	Offices	22°C all year	C2	IG3	O5	V0.5
5	Horizontal corridors	22°C all year	-	IG1	O6	V0.5
6	Retail areas	22°C all year	C4	IG3	O4	V0.5
7	Personal toilets	22°C all year	C4	IG1	O4	V0.5
8	Security control	22°C all year	C3	IG3	O2	V0.5
9	Luggage sorting	22°C all year	-	IG3	O4	V0.8



10	Check-in desks	22°C all year	C4	IG3	O3	V0.5
11	Boarding & departure hall	22°C all year	C4	IG3	O6	V0.5
12	Commercial shells	22°C all year	C4	IG3	O4	V0.5
13	Company lounges and restaurants	22°C all year	C4	IG3	O4	V0.5
14	Service road (outside)	-	-	-	-	V1.4
15	Retail areas-underground	-	-	IG3	O4	V0.5
16	Horizontal corridors-underground	-	-	IG1	O6	V0.5
17	Vertical corridors-underground	-	-	IG1	O6	V0.5
18	Roof	-	-	-	-	-
19	Technical gallery-underground	-	-	IG3	O7	V0.5

Hour Scenario		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Cooling set point (°C)	C2					26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	
	C3			26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26			
	C4			26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	
	C5	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Internal gain scenario (W/m2)	IG 1	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	7.0 8	
	IG 2	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
	IG 3	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	21. 25	
Occupancy scenario (person /m²)	O2	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	0.2 5	
	O3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
	O4	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7	0.1 7
	O5	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4	0.1 4
	O6	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0	0.1 0
	O7	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3	0.0 3
	O8	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2	0.0 2
Ventilation scenario (ach*)	V0 .5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
	V0 .8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	



	V1 .4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
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* air change per hour



4.2.4 Correction of the model

After completing the first version of the original Terminal 2A model with all scenarios configured, a dynamic thermal simulation was conducted to validate the model. However, several errors were encountered at this stage, primarily related to the structure and sizing of the façades.

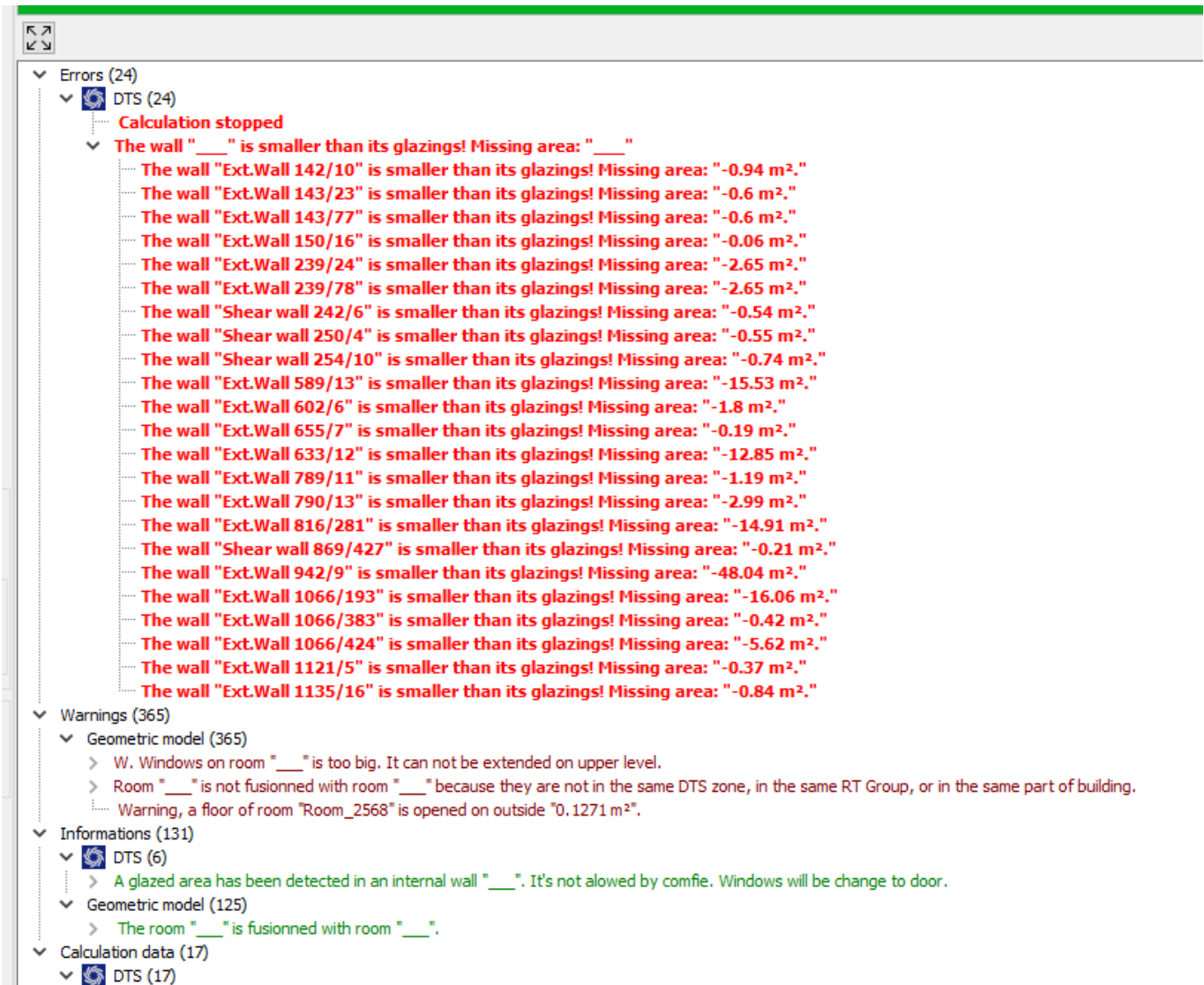


Figure 4-37: Errors during the first simulation test.

These issues were mainly caused by placing windows with areas larger than the corresponding wall sections during the façade drawing step. Since the windows are added manually, their dimensions may exceed the wall size if not carefully adjusted—especially without zooming in during placement. To resolve these errors, users can click on each error message to locate the problematic element in



the plan view. Then, it is needed to review the parameters of the window or door and redraw it to ensure it fits properly within the corresponding wall segment. Additionally, these issues can be visually identified in the 3D view, where errors are highlighted in red, as shown in Figure 4-38.

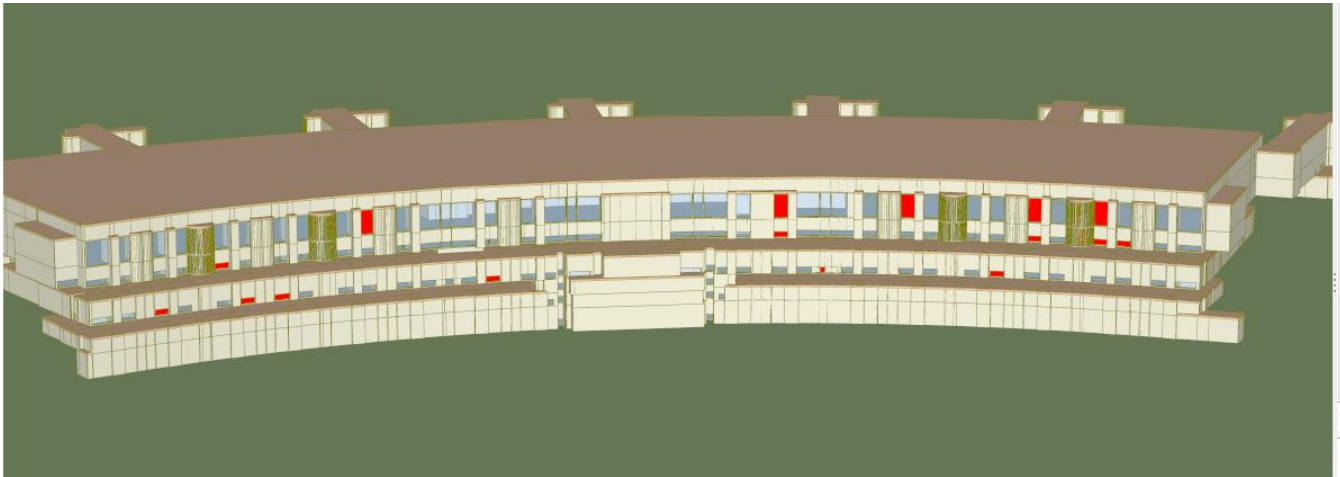


Figure 4-38: The errors shown in the 3D view.

4.3 Simplification of the model

4.3.1 Simplification strategies

After fixing all the geometry issues, thermal simulation can finally be conducted successfully. However, the simulation time was as long as 3 hour and 41 minutes, which is too long for one simulation because optimisation will require to perform several hundred calculations. Therefore the next step is to simplify the model while maintaining its accuracy.

4.3.1.1 Merge small rooms into one thermal zone

The first proposal was to merge or regroup the small rooms having the same function (e.g. offices) into a single thermal zone, since all rooms shared the same set of scenarios (particularly the same heating/cooling thermostat set points). However, even after removing all possible small rooms within each thermal zone, the simulation time remained lengthy—3 hours and 33 minutes, which is only 8 minutes shorter than that of the previous model.

4.3.1.2 Clean aligned and nearby points

After analysing the model, we found that the original complex model had generated many small wall segments instead of larger continuous walls. Even after removing small rooms, these fragmented wall elements remained, resulting in numerous unnecessary connection points and a more complex model structure.



To address this, a second approach was proposed—replacing the small walls with larger, continuous wall segments. This process can be initiated automatically in Pleiades Modeler using the “Clean aligned points” and “Delete nearby points” functions, as displayed in the figure below.

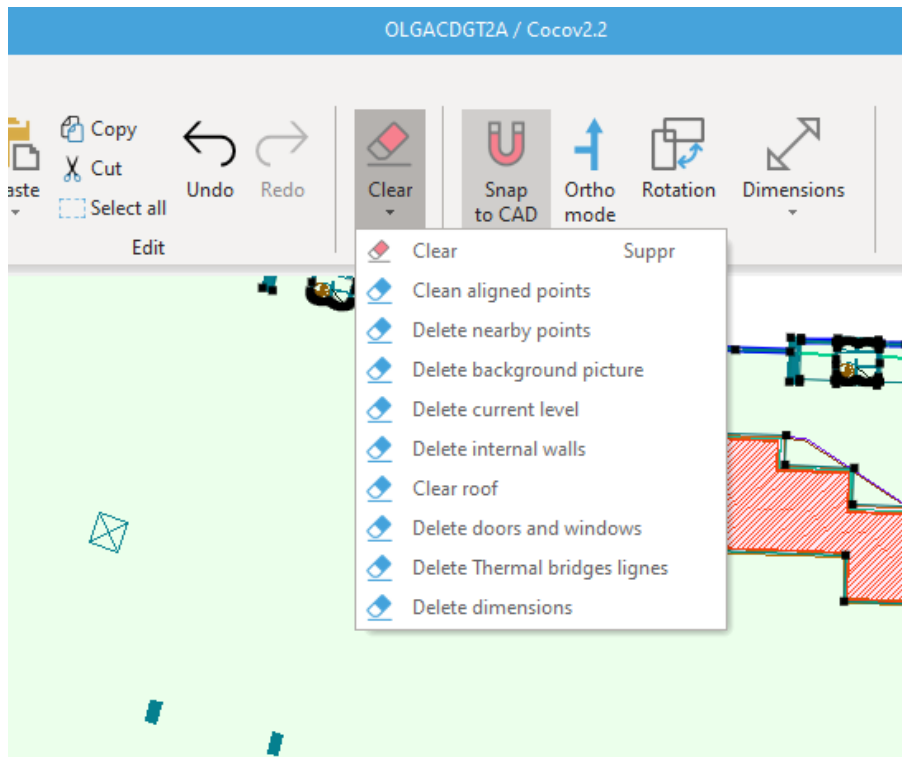


Figure 4-39: The interface of cleaning aligned points.

However, it is important to note that this operation may introduce new structural errors, as shown in the figure below. Therefore, it is essential to carefully review and resolve all resulting errors after the cleaning process.

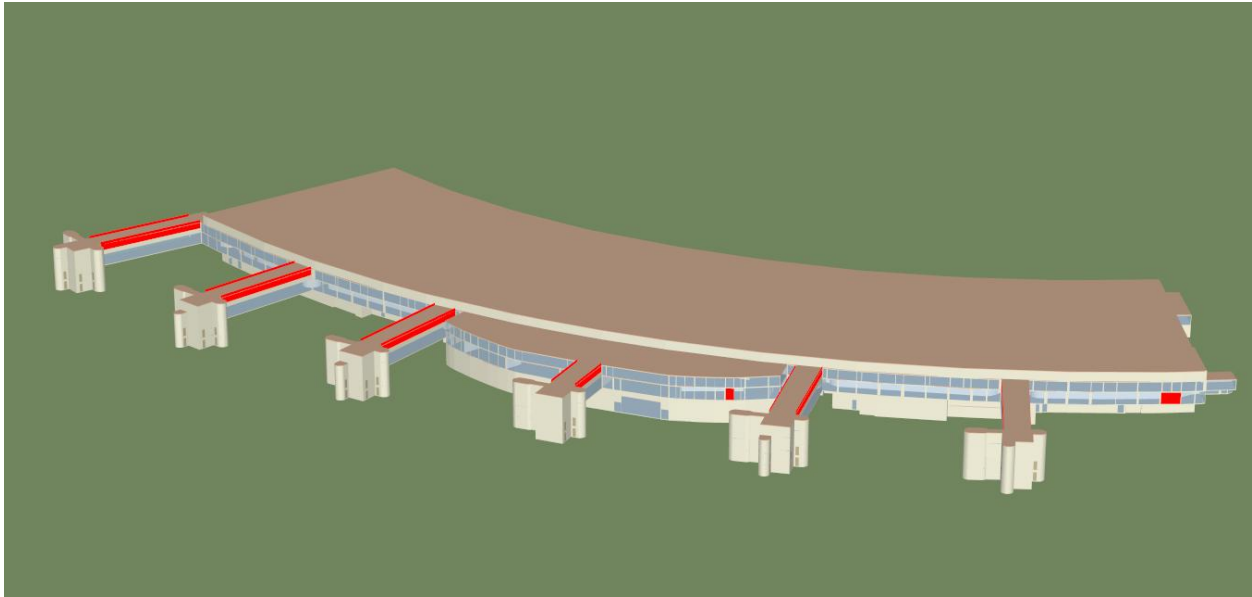


Figure 4-40: The errors in the 3D view.

After that, a manual review of the entire model was conducted to identify and replace the remaining small wall segments that were not automatically detected by Pleiades Modeler. As a result of these efforts, the simulation time was reduced to 58 minutes. However, this duration is still relatively long for running optimisation calculations efficiently.

4.3.1.3 Replacing curved parts with straight lines

Inspired by the simulation speed improvement resulting from the reduction of connection points, we observed that a significant number of small connection points were concentrated in the curved sections of the model. Therefore, the final proposal was to replace most of these curved parts with straight lines, as illustrated in Figure 4-41. We began with the internal walls, followed by the external walls. The replacement was carried out following the principle that the total surface area enclosed by the new straight lines remains equivalent to the original curved design. This ensures that the modification does not significantly affect the heat transfer calculations.

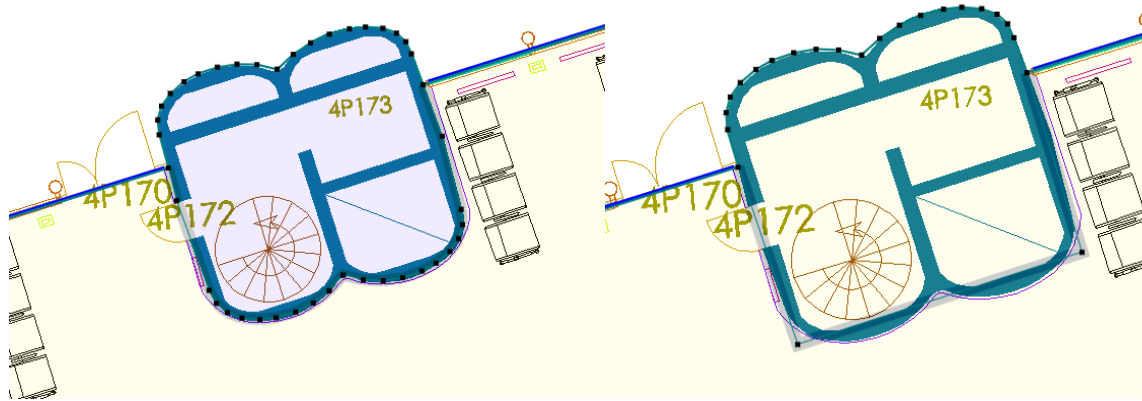


Figure 4-41: Before (left) and after (right) replacing the curved parts with straight lines.

The simulation time was finally reduced to 5 minutes and 19 seconds after all these efforts were taken into account. Besides, it took 10 seconds to generate the 3D model. This represents a significant improvement compared to the original model, making optimisation calculations much more feasible.

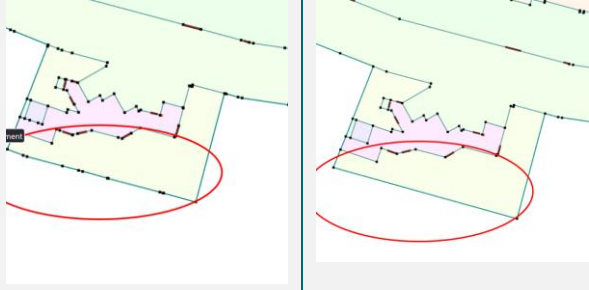
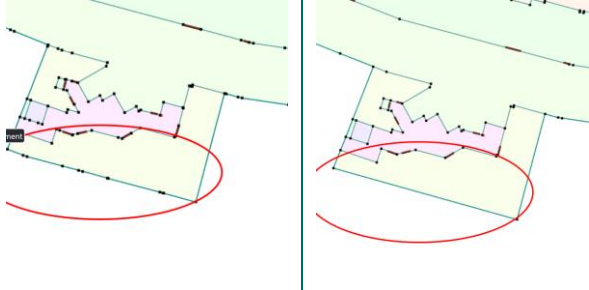
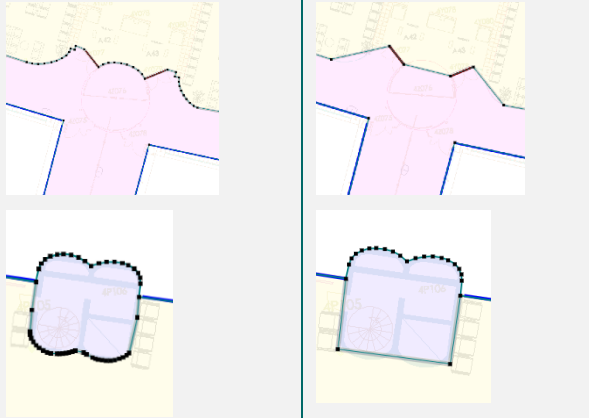

4.3.2 Accuracy verification of the simplified model

The simplification strategies used in different versions and their simulation time and results are summarised in Table 4-3.

Table 4-3: Summary of simplifications between different versions.

Version name	Simulation time	Key simplifications	Examples (Before)	Examples (After)	Simulation results
v2	3h41min	Original dedicated model			Annual heating loads: 5781 MWh (171 kWh/m ²) Annual cooling loads: 1510 MWh (45 kWh/m ²)
v2.1	3h33min	Remove small rooms in one thermal zone			Annual heating loads: 5781 MWh (171 kWh/m ²) Annual cooling loads: 1510 MWh



					(45 kWh/m ²)
v2.2	1h27min	Delete aligned points automatically			Annual heating loads: 5774 MWh (171 kWh/m ²) Annual cooling loads: 1505 MWh (45 kWh/m ²)
v2.3-2	58min	Delete aligned points manually			Annual heating loads: 5828 MWh (170 kWh/m ²) Annual cooling loads: 1537 MWh (45 kWh/m ²)
v3	47min	Replace inner curved parts with straight lines			Annual heating loads: 5795 MWh (169 kWh/m ²) Annual cooling loads: 1535 MWh (45 kWh/m ²)
v3.0	30min	Simplify the complex layouts while maintaining the same area to reduce the connection points			Annual heating loads: 5752 MWh (168 kWh/m ²) Annual cooling loads: 1533 MWh (45 kWh/m ²)



v3.1	5min19s	Replace more inner curved parts and some outer curved parts			<p>Annual heating loads: 5730 MWh (168 kWh/m²)</p> <p>Annual cooling loads: 1531 MWh (45 kWh/m²)</p>
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A comparison of the simulated results between the simplified version (v3.1) and the detailed version (v2) is shown in Figure 4-42. As illustrated, the discrepancy between the simplified and complex models is negligible in terms of heating, cooling, and electricity demand. This confirms that the simplification process is valid and does not compromise the accuracy of the simulation results.

After the correction and simplification actions listed above, the heated/cooled area of the building is 38,615 m². This will be used to express energy consumption ratios in kWh/m².

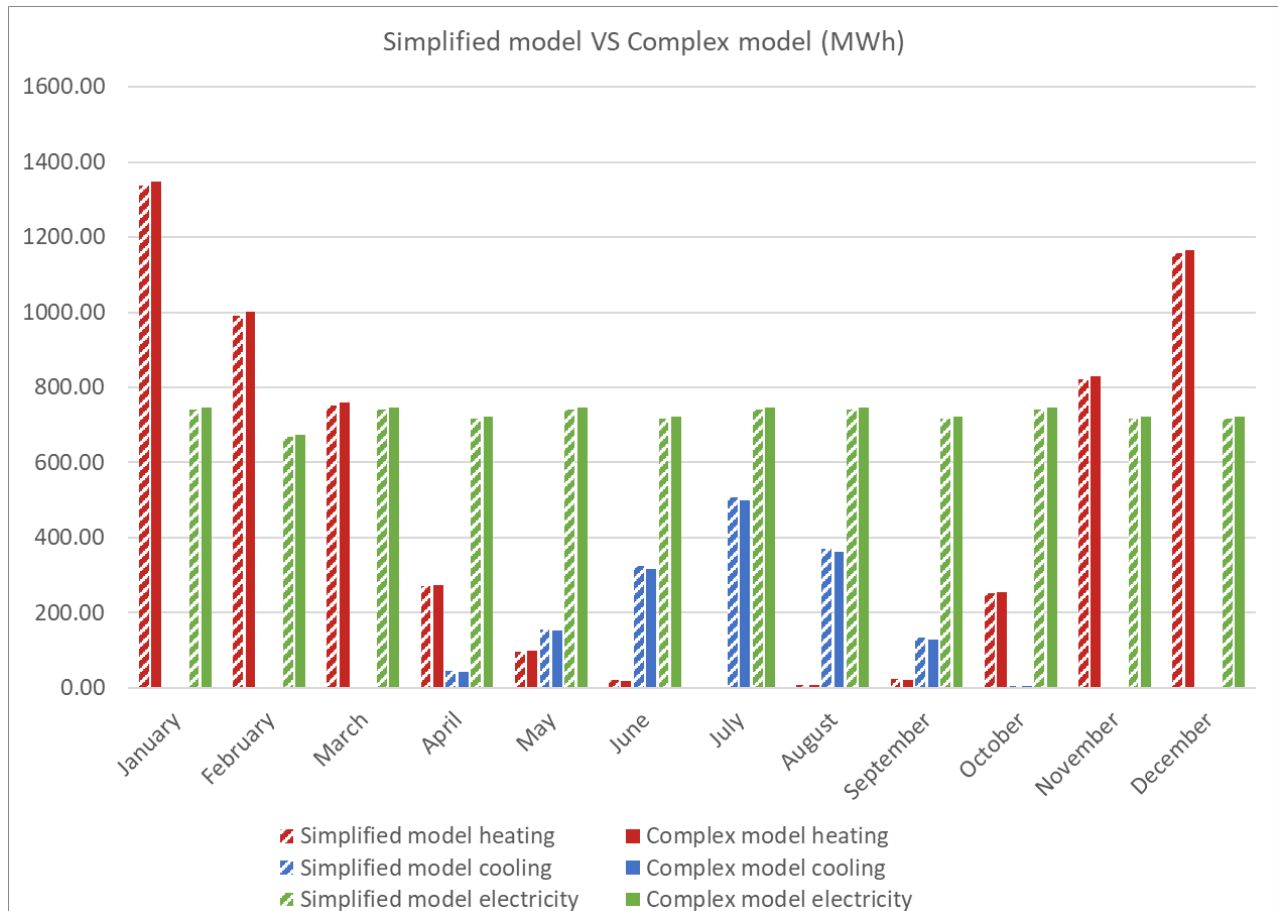


Figure 4-42: Comparison of simulated results between simplified model and complex model.

4.4 Calibration of the model

After simplifying the model, the next step is to make sure that the model is accurate enough for the subsequent optimisation of the annual heating loads.

4.4.1 Screening of the measurements data and selecting a reference year

Firstly, a reference year needs to be selected from the available measured data spanning 2019 to 2024. To assess the reliability of the data, measurements from sensors T2A and T2B were compared. For instance, the 2019 data appeared biased (see Figure 4-43), as T2A consistently showed lower values than T2B, despite T2A being uninsulated.

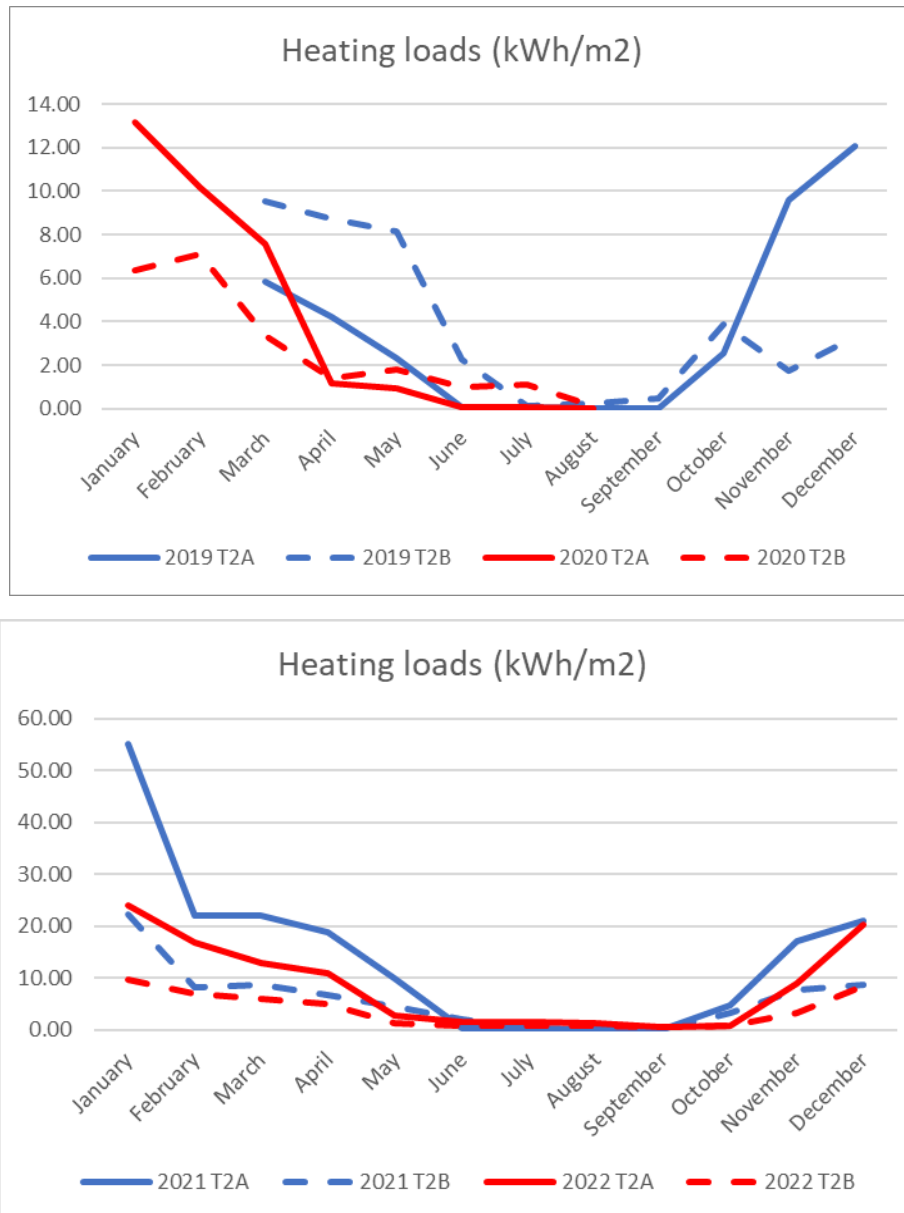


Figure 4-43: Measured heating loads of T2A and T2B from 2019 to 2022.

Based on analysis of the measurements data provided by ADP, the year 2021 was finally chosen as the reference year for two main reasons. One is that its data is consistent with terminal 2B measurements compared to other years. The other reason is that the climate conditions in 2021 closely align with typical degree-day values, which are critical for assessing heating demand, as they reflect the energy needed for space heating. Therefore, the 2021 measurements were adjusted based on degree-days and adopted as the reference for subsequent comparisons.



Figure 4-44 presents a comparison between the simulated results of the simplified model and the measured data from the reference year 2021. A noticeable discrepancy is observed, particularly in electricity consumption, where the simulation results are on average 46.7 % higher than the measured values. To address this issue, several calibration strategies, outlined in the following section, are applied to improve the accuracy of the final model.

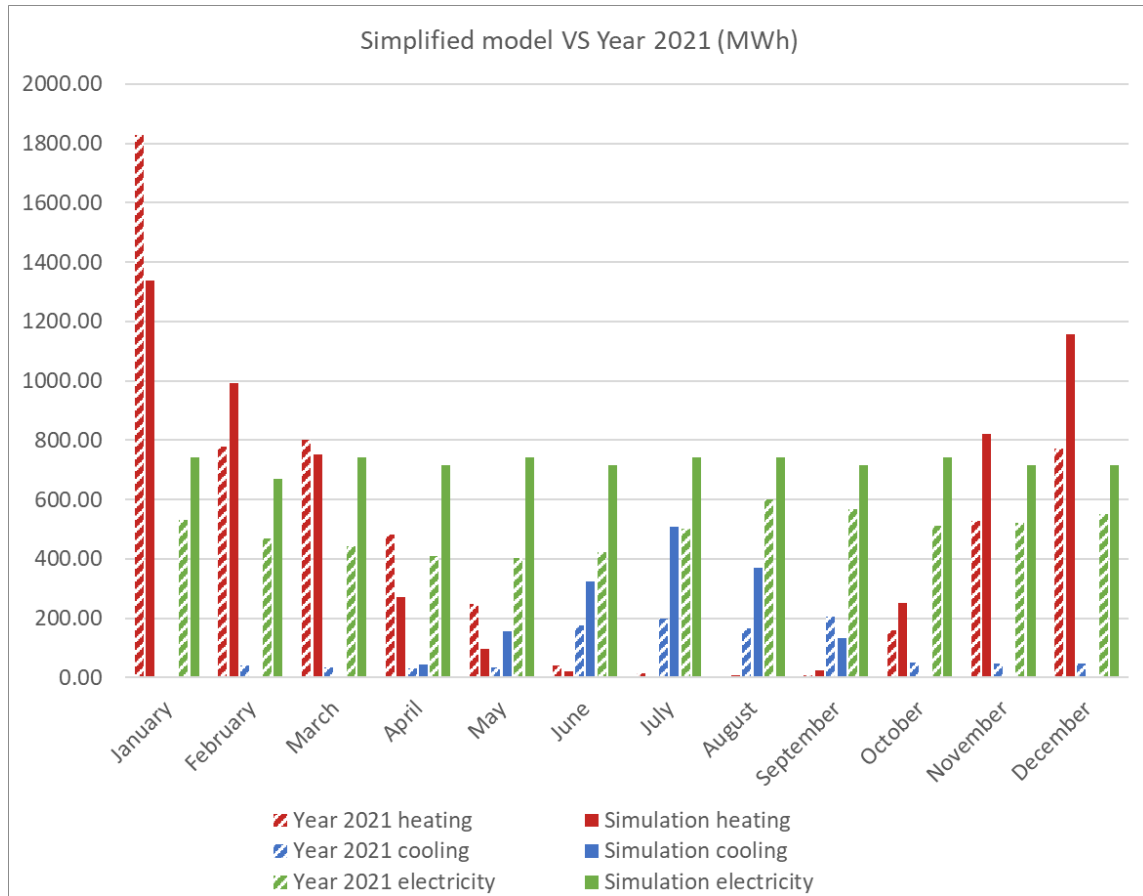


Figure 4-44: Comparison between the simulated results of the simplified model and the measured data from the reference year 2021.

4.4.2 Calibration strategies

Following discussions with ADP during the progress meeting, we reached a consensus regarding the missing information and data in the model. Based on that, several calibrations were implemented to enhance the simulation accuracy of the terminal model.



4.4.2.1 Roof windows

The model was improved by refining the description of level 5. One unique aspect of Level 5, compared to other levels, is the presence of six roof windows on the top (see Figure 4-45).

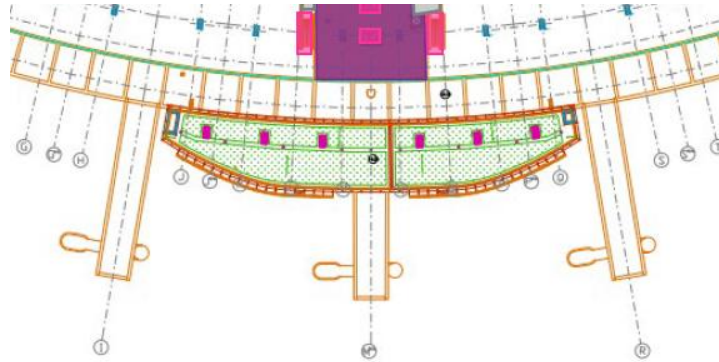


Figure 4-45: The roof windows displayed in the DWG file.

These can be defined by clicking on the "Roof Characteristics" button in the middle left and selecting the corresponding rectangles to set them as external sloped glazing, as shown in Figure xxx. The window type was defined as double glazing. Finally, the roof windows can be viewed in the 3D model, as shown in Figure 4-46.

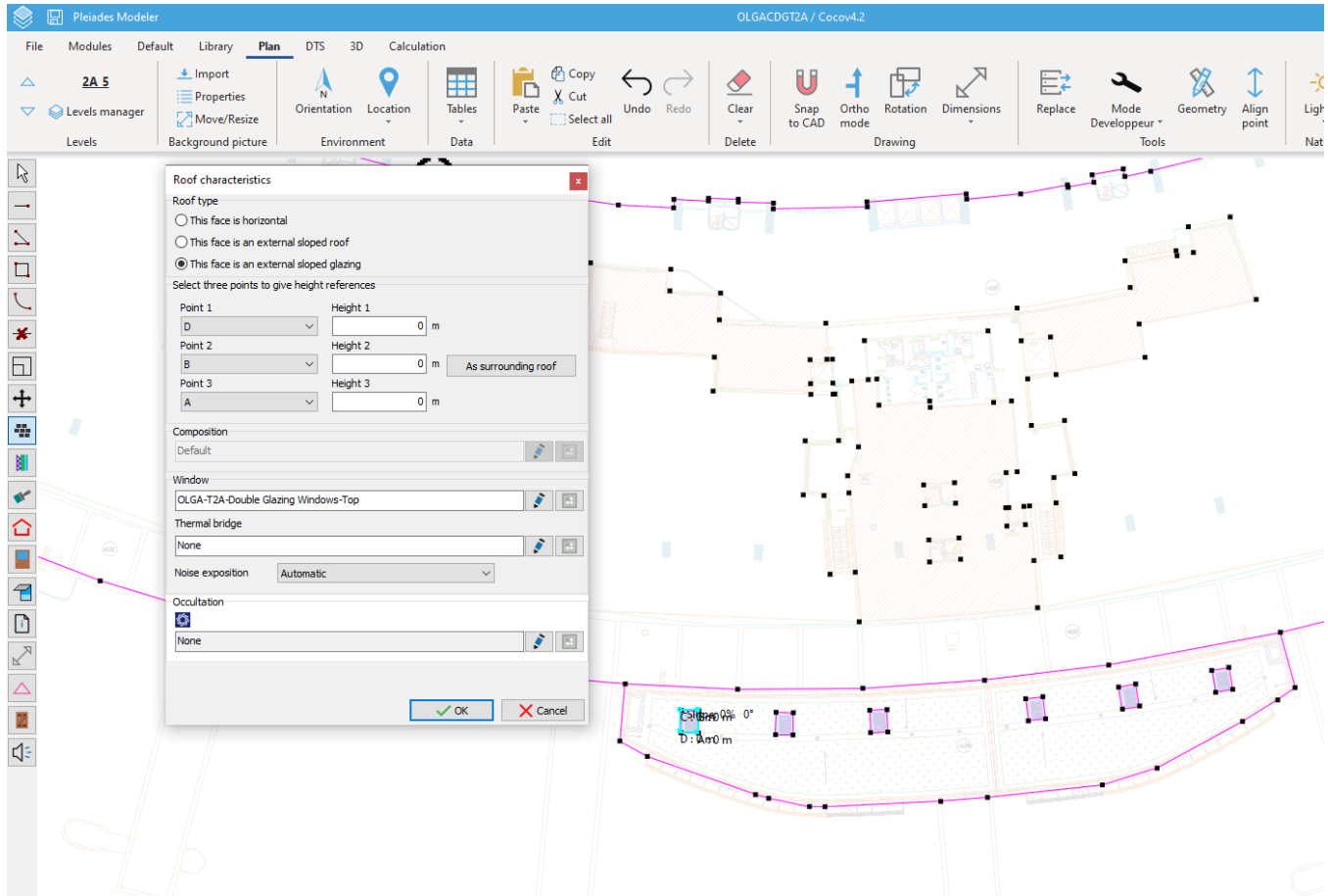


Figure 4-46: The interface of setting the roof windows.

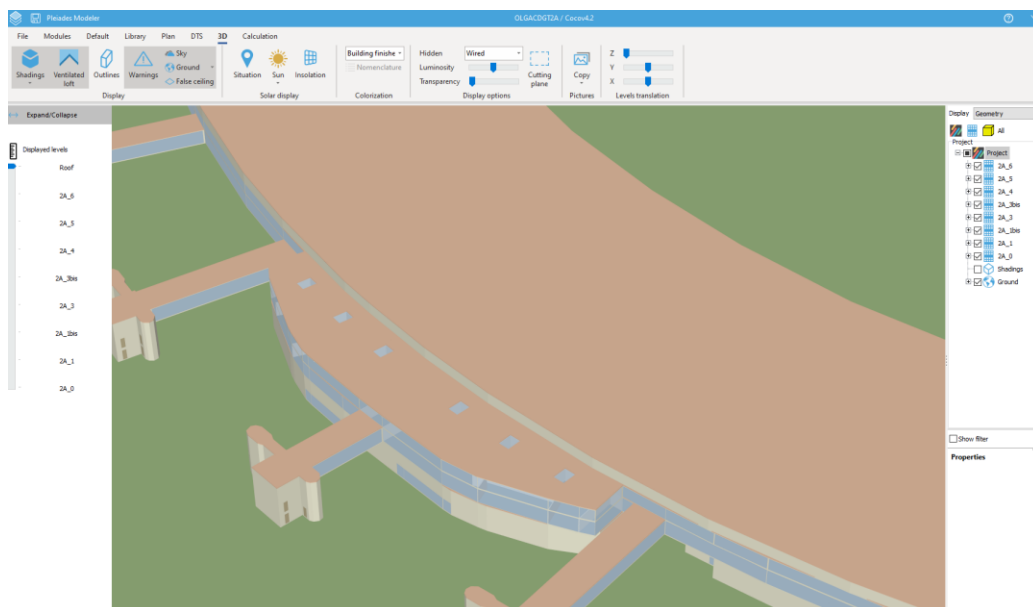




Figure 4-47: The roof windows in the 3D view.

4.4.2.2 Schedule scenarios

To ensure the accuracy of the model, several schedule scenarios were adjusted to better reflect real-world conditions. Occupancy, internal heat gains, and ventilation scenarios were all modified to ensure that the building's energy consumption, particularly the annual heating loads, align closely with measured values. The final schedules are presented in Section 4.2.3.2.

This is particularly the case for internal gains, which are directly related to the electricity consumption. Measurements were considered to adapt the internal gains scenario so that the annual values are corresponding. Specifically, the simulated annual internal gains were 133 kWh/m², while the measured value was 157 kWh/m². As a result, the internal gains values in the scenario were scaled by a factor of 157/133 to align the simulation results with the measured data.

4.4.3 Comparison of simulation results and measurements

Figure 4-48 shows the comparison between the measurement from the reference year (corrected according to the degree-days so that they correspond to the same degree-days as the reference year considered in the simulation) and the simulation results after calibration. It is evident that the calibrated model aligns more closely with the measured data compared with the model before calibration. The detailed values can be found in Table 4-4. To be specific, the discrepancies between simulation and measurements (annual values) are reduced to just 0.13 % for annual heating loads and 4.0 % for electricity. They are higher for cooling, which induced a supplementary modelling study (see next §).

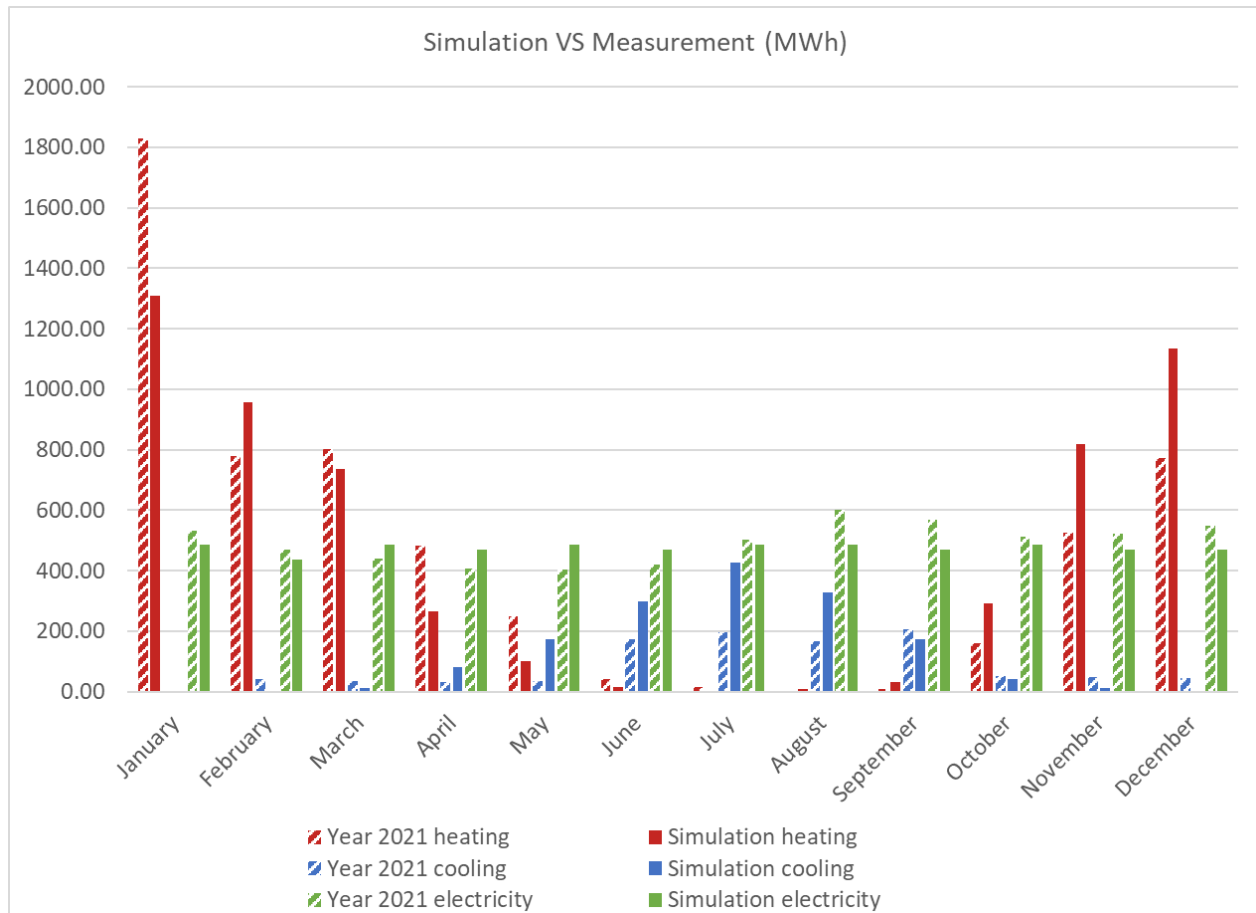


Figure 4-48: Comparison of the measurements and simulation results after calibration.

Table 4-4: Detailed values of the measurements and simulation results after calibration.

	Heating	Cooling	Electricity
Simulation (MWh / kWh/m ²)	5,672 / 147	1,556 / 40	5,689 / 147
Measurement (MWh / kWh/m ²)	5,665 / 147	1,029 / 27	5,927 / 153
Discrepancy (%)	0.13	51.2	4

4.4.4 Free ventilative cooling

As cooling loads are not the primary focus of this project and account for a relatively smaller proportion of CO₂ emissions compared to heating and electricity, they were not prioritised during the calibration phase. However, a preliminary optimisation study revealed that under improved



insulation scenarios, while annual heating loads are significantly reduced, annual cooling loads increase substantially—at times even exceeding heating demands. To address this issue, a solution involving conditional natural ventilation was proposed and incorporated into the model prior to commencing the final optimisation process. The principle is to model opening of windows if inside temperature is too high and outside temperature is lower (e.g. during summer nights), which creates a cooling effect thanks to natural ventilation.

In this project, the heating and cooling set points are set at 22 °C and 26 °C, respectively. Based on these values, the conditions for activating natural ventilation are defined as follows (see Figure 4-49): natural ventilation is triggered when the outdoor air temperature is lower than the current zone temperature minus 1 °C, and the zone temperature exceeds 24 °C.

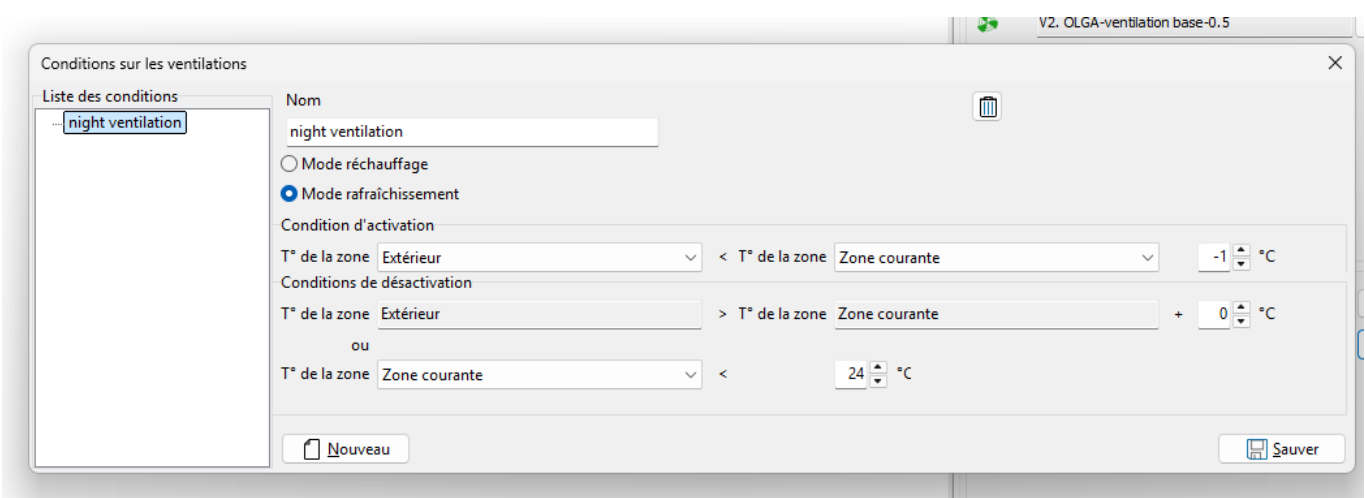
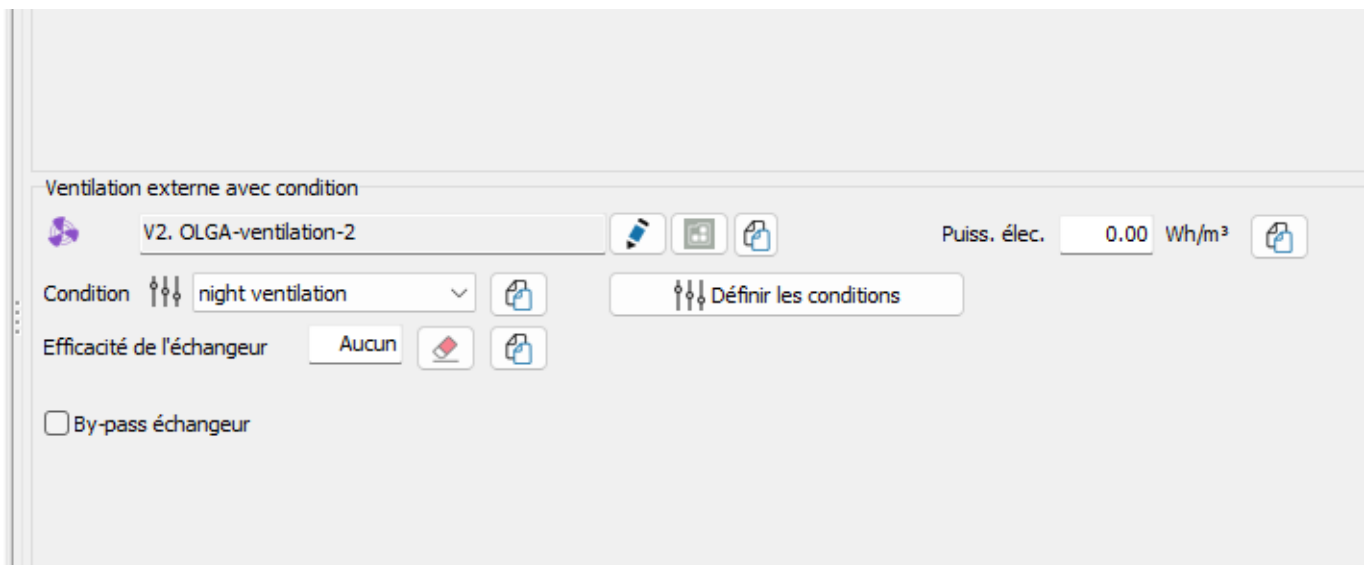




Figure 4-49: The interface of setting free ventilation cooling.

Figure 4-50 presents the simulated results of the model before and after the implementation of natural ventilation, with detailed values provided in Table 4-5. Appropriate ventilation significantly reduces the cooling loads—from 1,556 MWh to 763 MWh—representing a total reduction of 51 %. Meanwhile, the annual heating loads increased slightly, from 5,454 MWh to 5,672 MWh, corresponding to a 4 % increase.

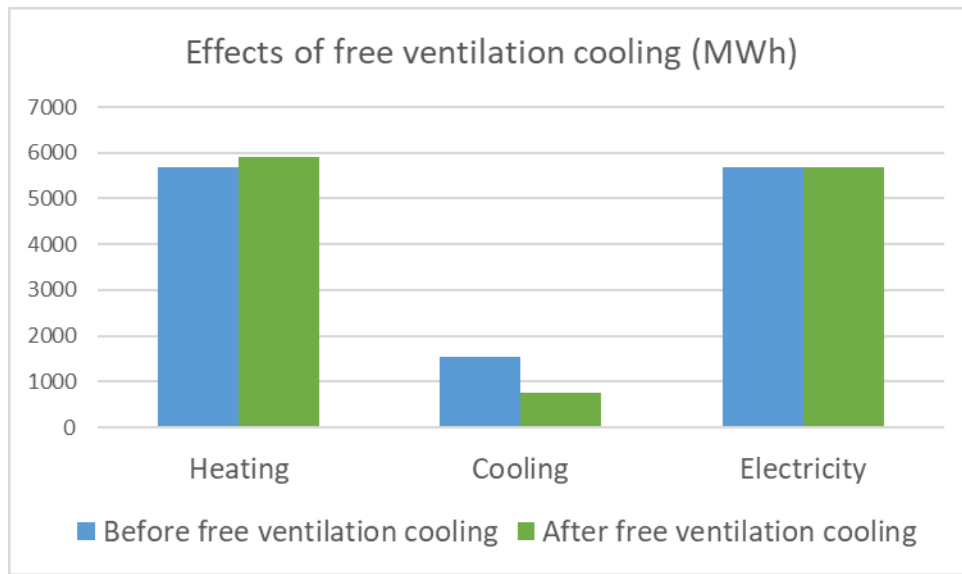


Figure 4-50: Effects of free ventilation cooling.

Table 4-5: Detailed results before and after night

	Heating	Cooling	Electricity
Before night ventilation (MWh / kWh/m ²)	5,672 / 147	1,556 / 40	5,689 / 147
After night ventilation (MWh / kWh/m ²)	5,900 / 153	763 / 20	5,689 / 147

Measured cooling energy consumption (1,029 MWh) could be explained by some natural ventilation occurring because of opened doors for passengers and luggage.



4.5 Optimisation calculation

Innovative parts of this research project are the application of optimisation and life cycle assessment to complex buildings like airport terminals. The first step, as presented above, is to develop models that integrate the complexity of such buildings (e.g. large number of functions, complex geometry) while requiring reasonable computation time. This was achieved by simplifying the description, but also using a model reduction technique (Peuportier and Blanc-Sommereux, 1990).

The optimisation problem consists in identifying design parameters which minimize energy consumption, environmental impacts and renovation cost. In such a multi-objective problem, the concept of Pareto front is used. First, minimising the heating load is prioritised because heat generation, provided 75% by gas, emits more CO₂ than cooling which consumes low carbon electricity in the French context. A set of non-dominated solutions is defined including the lowest heating load for a given renovation cost (and the lowest renovation cost for a given heating load). Then LCA is performed in order to check that these identified optimal solutions correspond also to low environmental impacts.

A solution is a set of design parameters. The considered design parameters are the insulation thickness in different elements (façades with different orientations, floors, roof) and glazing types on the different façades. Insulation thicknesses may vary between 0 and 30 to 40 cm, which results in 79,580 billion possible solutions. Such a large number of simulations would not be feasible, therefore a genetic algorithm was used.

4.5.1 Genetic optimisation algorithm

The genetic optimisation algorithm used in this study (AMAPOLA module of Pleiades software tool) considers that a renovation solution can be characterised by a chromosome containing a number of genes having a number of alleles, as displayed in Figure 4-51. The algorithm allows the user to identify the optimal solutions for one project offering the best compromises between different controlled elements such as investment cost, operating cost, energy consumption, comfort, regulatory level, and environmental balance while minimising calculation times. In this project, the two controlled elements are investment costs and annual heating loads.

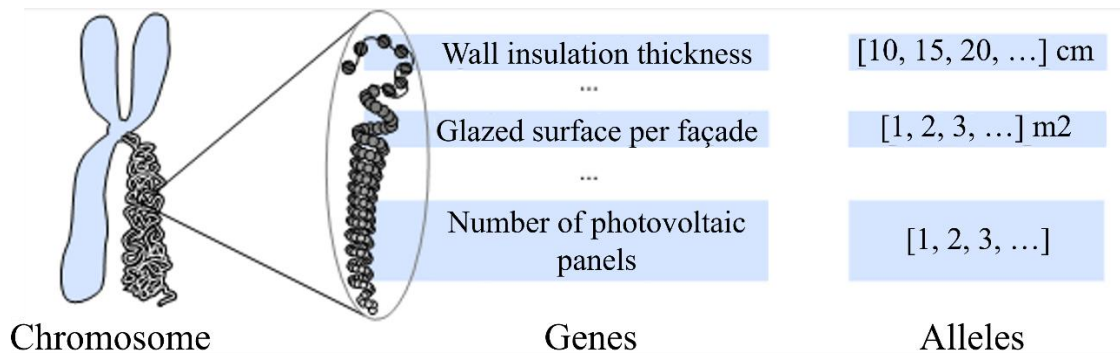


Figure 4-51: Illustration of the genetic characterisation used in AMAPOLA.

As for the genes and alleles, several wall compositions and their related insulation thickness have been chosen in this project. Particularly, the walls and windows are categorised by their orientations to take into account the effects of both heat transfer and solar gains for a more precise optimisation. Two types of floors are considered because marble is added in passenger spaces (“floor nobles”). The detailed information can be found in Table 4-6.

Table 4-6: Optimisation parameters of this project.

	Orientation	Genes	Alleles
External façades	North	Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
	South	Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
	West	Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
	East	Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
Floors -nobles		Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
Floors -no nobles		Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 28, 29, 30] cm
Roof		Thickness of insulation layers	[0.001, 1, 2, 3, 4, ..., 38, 39, 40] cm
Windows -double glazing	North	Types of window glazing	[double glazing windows, low-emissivity double glazing windows, triple glazing windows]



	South	Types of window glazing	[double glazing windows, low-emissivity double glazing windows, triple glazing windows]
	West	Types of window glazing	[double glazing windows, low-emissivity double glazing windows, triple glazing windows]
	East	Types of window glazing	[double glazing windows, low-emissivity double glazing windows, triple glazing windows]
	Top	Types of window glazing	[double glazing windows, low-emissivity double glazing windows, triple glazing windows]
Windows -single glazing	North	Types of window glazing	[Single glazing windows, low-emissivity double glazing windows, triple glazing windows]
	South	Types of window glazing	[Single glazing windows, low-emissivity double glazing windows, triple glazing windows]

In this project, glass wool (named “laine de verre”) was chosen as the insulation material for all constructions due to its low investment cost, and its associated costs at various thicknesses remain consistent with those specified in Section 3.6. Regarding windows, the original terminal model included two types of glazing: single glazing and a basic double glazing. However, the double-glazed window exhibited relatively poor insulation performance. Therefore, an alternative low-emissivity double-glazing option—BBC Double Vitrage Peu Émissif Argon—with improved thermal insulation was chosen for this project. Table 4-7 shows the thermal parameters of the windows used in this project.

Table 4-7: Thermal parameters of the windows used in the project.

	Single glazing window in T2A	Double glazing window in T2A	Low-emissivity double glazing window	Triple glazing window	Unit
Uw vertical	5.6	2.8	1.695	1.095	W/(m2.K)
Uw horizontal	5.6	2.8	1.738	1.112	W/(m2.K)



Solar factor	0.83	0.75	0.549	0.533	-
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4.5.2 Configurations in COMFIE and AMAPOLA

4.5.2.1 Distinguish the orientations in COMFIE

As the original terminal model lacks insulation layers and does not differentiate between orientations, certain adjustments must first be implemented in the thermal simulation model (COMFIE) to ensure that the genes defined in the previous section can be recognised by AMAPOLA.

The windows and external walls should be redefined based on their orientation. This can be done by following these steps: First, create new compositions for the external walls in different orientations (duplicating the default composition is acceptable). Then, replace the default composition (e.g., north) with the one corresponding to another orientation, applying the filter for the relevant orientation as shown in Figure 4-52. The same process applies to the windows, as shown in Figure 4-53.

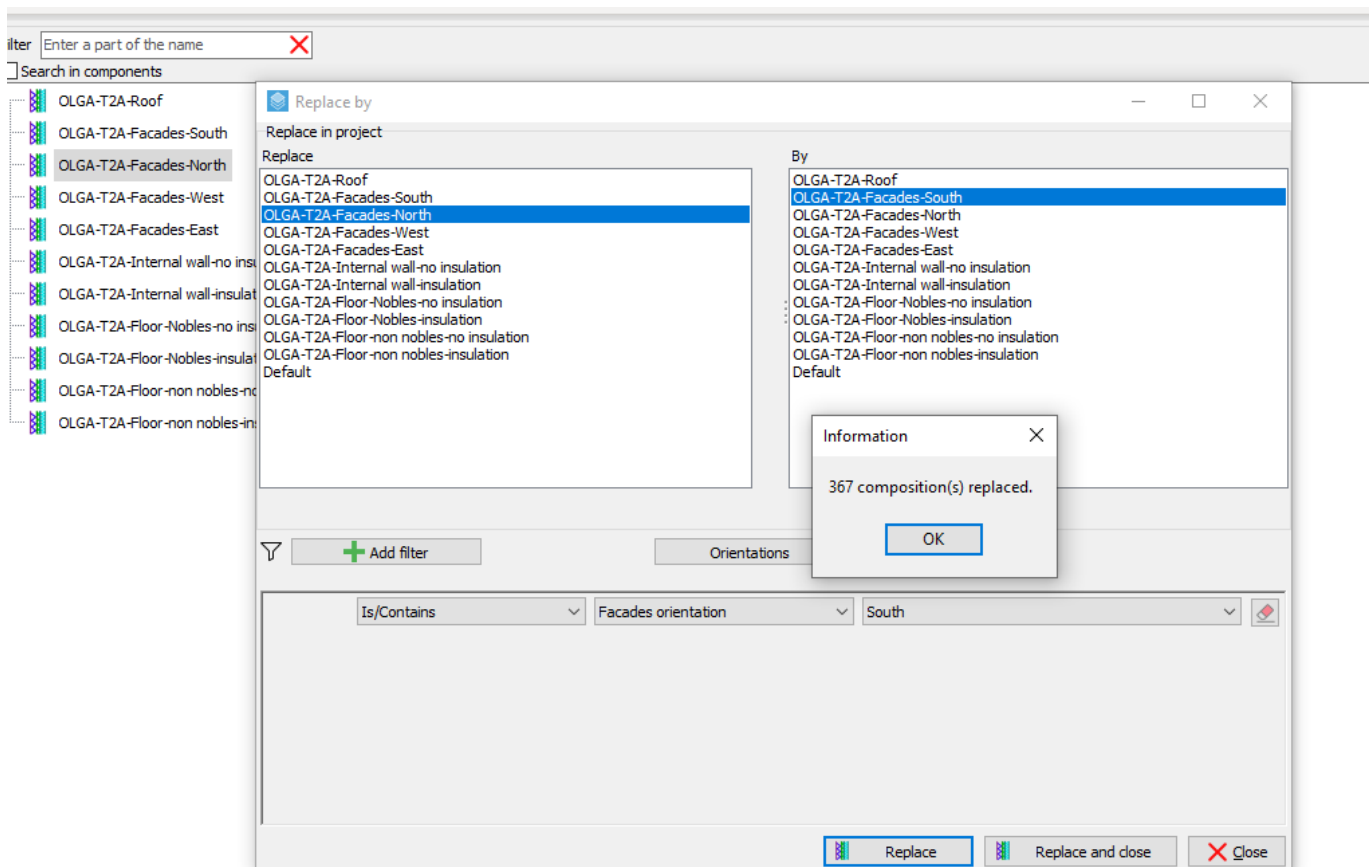




Figure 4-52: The interface for distinguishing the orientation of façades.

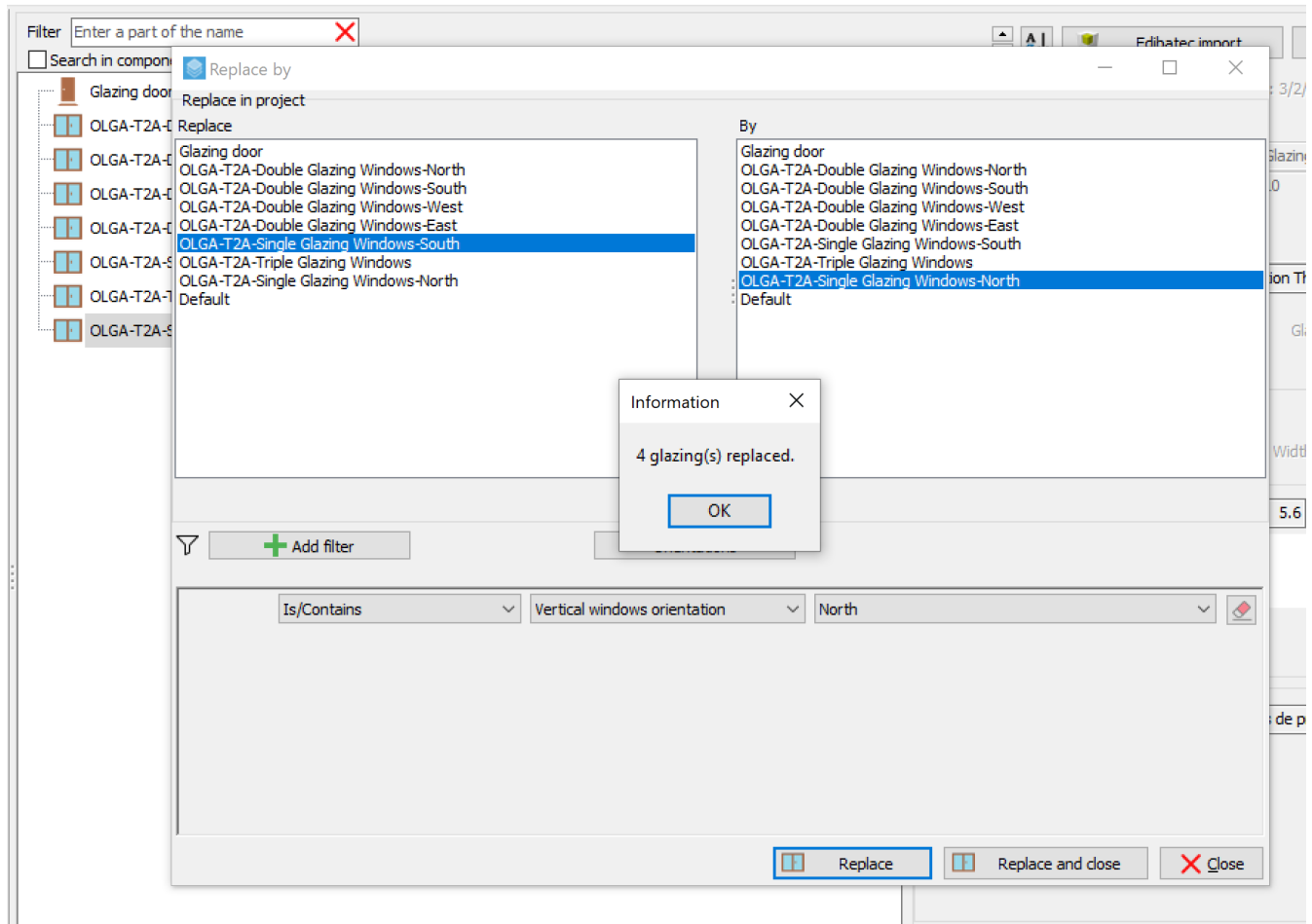


Figure 4-53: The interface for distinguishing the orientation of windows.

4.5.2.2 Optimisation parameters in AMAPOLA

Based on the information provided in Section 4.4.1, genes and their corresponding alleles can then be defined in AMAPOLA, as shown in the figures below.



Pleiades Editeur OLGACDGT2A / Cocov5.1-night ventilation

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Systèmes constructifs

Matériaux/éléments

Taille des menuiseries

Menuiseries

Systèmes photovoltaïques

Éclairages

Masques intégrés

Etats de surface

Composition	N°	Type	Composant	Epais	Nb cas	
<input type="checkbox"/>	OLGA-T2A-Roof	1	M	Béton lourd	15.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Roof	2	M	Laine de verre	0.001	41
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	1	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	2	E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Sout	3	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	4	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	1	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	2	E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Nort	3	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	4	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	1	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	2	E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Wes	3	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	4	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-East	1	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-East	2	E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-East	3	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-East	4	M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Internal wall-	1	M	Enduit extérieur	2.000	0
<input type="checkbox"/>	OLGA-T2A-Internal wall-	2	E	Parpaing de 15	15.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	1	M	Béton lourd	10.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	2	M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	3	M	Marbres	2.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	1	M	Béton lourd	10.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Floor-Nobles	2	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	3	M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	4	M	Marbres	2.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	1	M	Béton lourd	10.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	2	M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	1	M	Béton lourd	10.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Floor-non no	2	M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Floor-non no	3	M	OLGA-T2A-Chape	5.000	0

Coût de la composition 0 €/m²

Cas original

Type	Composant	Epaisseur	€/m ²
M	Laine de verre	0.001	0

Nombre de cas simulés 31

Type	Composant	Epaisseur	€/m ²
M	Laine de verre	0.001	0.000
M	Laine de verre	1.000	0.558
M	Laine de verre	2.000	0.950
M	Laine de verre	3.000	1.342
M	Laine de verre	4.000	1.734
M	Laine de verre	5.000	2.126
M	Laine de verre	6.000	2.518
M	Laine de verre	7.000	2.910
M	Laine de verre	8.000	3.302
M	Laine de verre	9.000	3.694
M	Laine de verre	10.000	4.086
M	Laine de verre	11.000	4.478
M	Laine de verre	12.000	4.870
M	Laine de verre	13.000	5.262
M	Laine de verre	14.000	5.654
M	Laine de verre	15.000	6.046
M	Laine de verre	16.000	6.438
M	Laine de verre	17.000	6.830
M	Laine de verre	18.000	7.222
M	Laine de verre	19.000	7.614
M	Laine de verre	20.000	8.006
M	Laine de verre	21.000	8.398
M	Laine de verre	22.000	8.790
M	Laine de verre	23.000	9.182
M	Laine de verre	24.000	9.574
M	Laine de verre	25.000	9.966
M	Laine de verre	26.000	10.358
M	Laine de verre	27.000	10.750
M	Laine de verre	28.000	11.142
M	Laine de verre	29.000	11.534
M	Laine de verre	30.000	11.926

Figure 4-54: Interface of AMAPOLA for setting optimisation parameters.

If the parameters increase in equal increments, it is possible to simply enter the first three values and click on the grey icon to the right of the third value (see Figure 4-55). The software will then automatically generate the remaining values.



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Composition	N°	Type	Composant	Epais	Nb cas
<input type="checkbox"/>	OLGA-T2A-Roof	1 M	Béton lourd	15.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Roof	2 M	Laine de verre	0.001	41
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	1 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	2 E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Sout	3 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Sout	4 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	1 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	2 E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Nort	3 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Nort	4 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	1 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	2 E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Wes	3 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Wes	4 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-East	1 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-East	2 E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-East	3 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-East	4 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Internal wall-	1 M	Enduit extérieur	2.000	0
<input type="checkbox"/>	OLGA-T2A-Internal wall-	2 E	Parpaing de 15	15.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	1 M	Béton lourd	10.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	2 M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	3 M	Marbres	2.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	1 M	Béton lourd	10.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Floor-Nobles	2 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	3 M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-Nobles	4 M	Marbres	2.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	1 M	Béton lourd	10.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	2 M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Floor-non no	1 M	Béton lourd	10.000	0
<input checked="" type="checkbox"/>	OLGA-T2A-Floor-non no	2 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Floor-non no	3 M	OLGA-T2A-Chape	5.000	0
<input type="checkbox"/>	OLGA-T2A-Facades-Top	1 M	Aluminium (générique)	0.100	0
<input type="checkbox"/>	OLGA-T2A-Facades-Top	2 E	Lame d'air > 1.3 cm	1.500	0
<input checked="" type="checkbox"/>	OLGA-T2A-Facades-Top	3 M	Laine de verre	0.001	31
<input type="checkbox"/>	OLGA-T2A-Facades-Top	4 M	Aluminium (générique)	0.100	0

Coût de la composition 0 €/m²

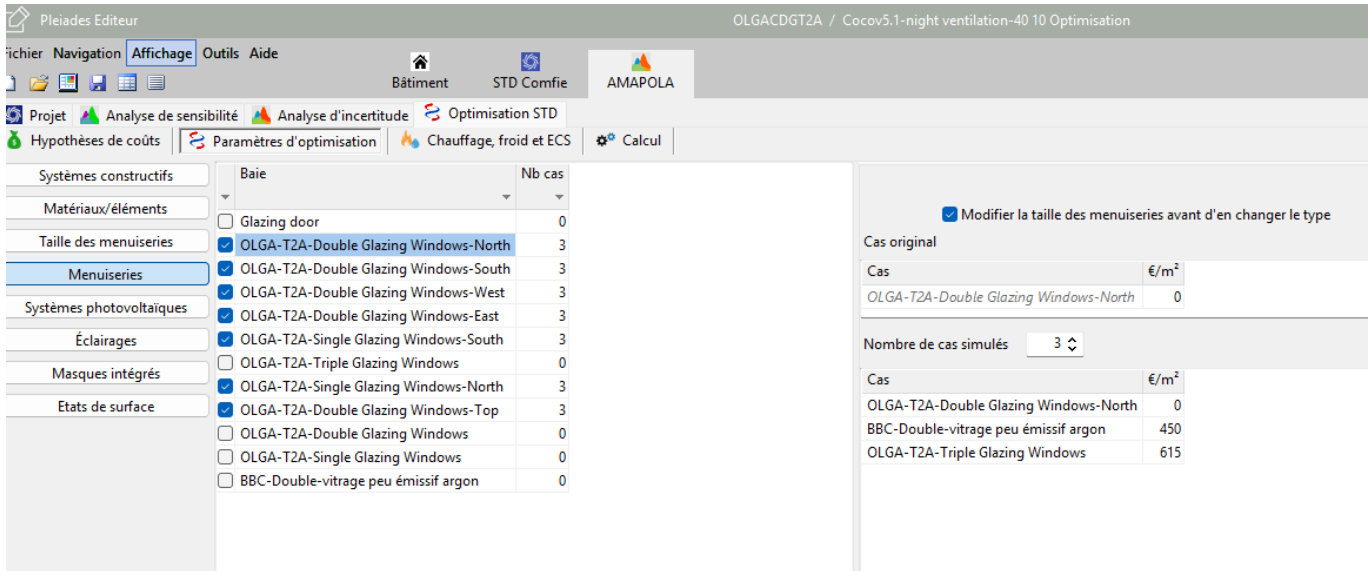
Cas original

Type	Composant	Epaisseur	€/m ²
M	Laine de verre	0.001	0

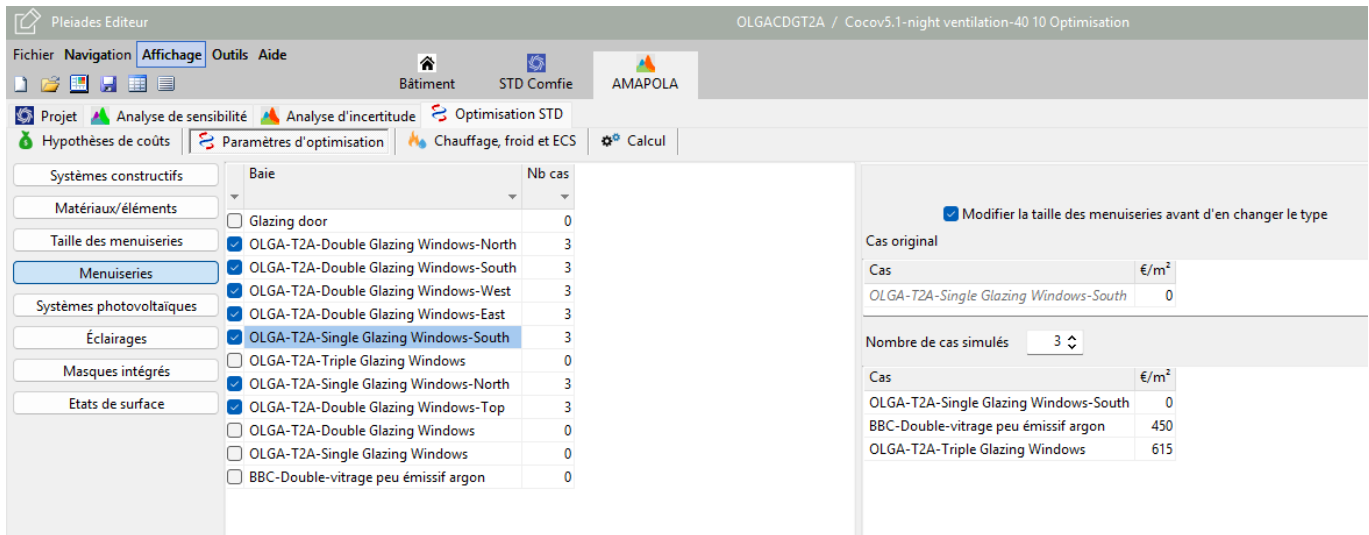
Nombre de cas simulés 31

Type	Composant	Epaisseur	€/m ²
M	Laine de verre	0.001	0.000
M	Laine de verre	1.000	0.558
M	Laine de verre	2.000	50.000
M	Laine de verre	3.000	0.000
M	Laine de verre	4.000	0.000
M	Laine de verre	5.000	0.000
M	Laine de verre	6.000	0.000
M	Laine de verre	7.000	0.000
M	Laine de verre	8.000	0.000
M	Laine de verre	9.000	0.000
M	Laine de verre	10.000	0.000
M	Laine de verre	11.000	0.000
M	Laine de verre	12.000	0.000
M	Laine de verre	13.000	0.000
M	Laine de verre	14.000	0.000
M	Laine de verre	15.000	0.000
M	Laine de verre	16.000	0.000
M	Laine de verre	17.000	0.000
M	Laine de verre	18.000	0.000
M	Laine de verre	19.000	0.000
M	Laine de verre	20.000	0.000
M	Laine de verre	21.000	0.000
M	Laine de verre	22.000	0.000
M	Laine de verre	23.000	0.000
M	Laine de verre	24.000	0.000
M	Laine de verre	25.000	0.000
M	Laine de verre	26.000	0.000
M	Laine de verre	27.000	0.000
M	Laine de verre	28.000	0.000
M	Laine de verre	29.000	0.000
M	Laine de verre	30.000	0.000

Figure 4-55: Interface of setting the optimisation parameters.



(a)



(b)

Figure 4-56: Interface of setting optimisation parameters for (a) double glazing windows and (b) single glazing windows.

4.5.3 Optimisation results

4.5.3.1 Pareto front and parallel coordinates

With the genes and alleles defined in the previous section, AMAPOLA is able to perform genetic algorithm optimisation. This process mimics natural selection through genetic crossbreeding of



buildings (reproduction) and mutations (evolution), driven by the objective function of cost and performance (adaptation). The algorithm selects the best-performing ‘offspring’ in each generation, gradually converging towards increasingly optimal solutions. In this project, the default settings of 40 individuals and 10 generations were used for the optimisation process, as seen in the figure below.

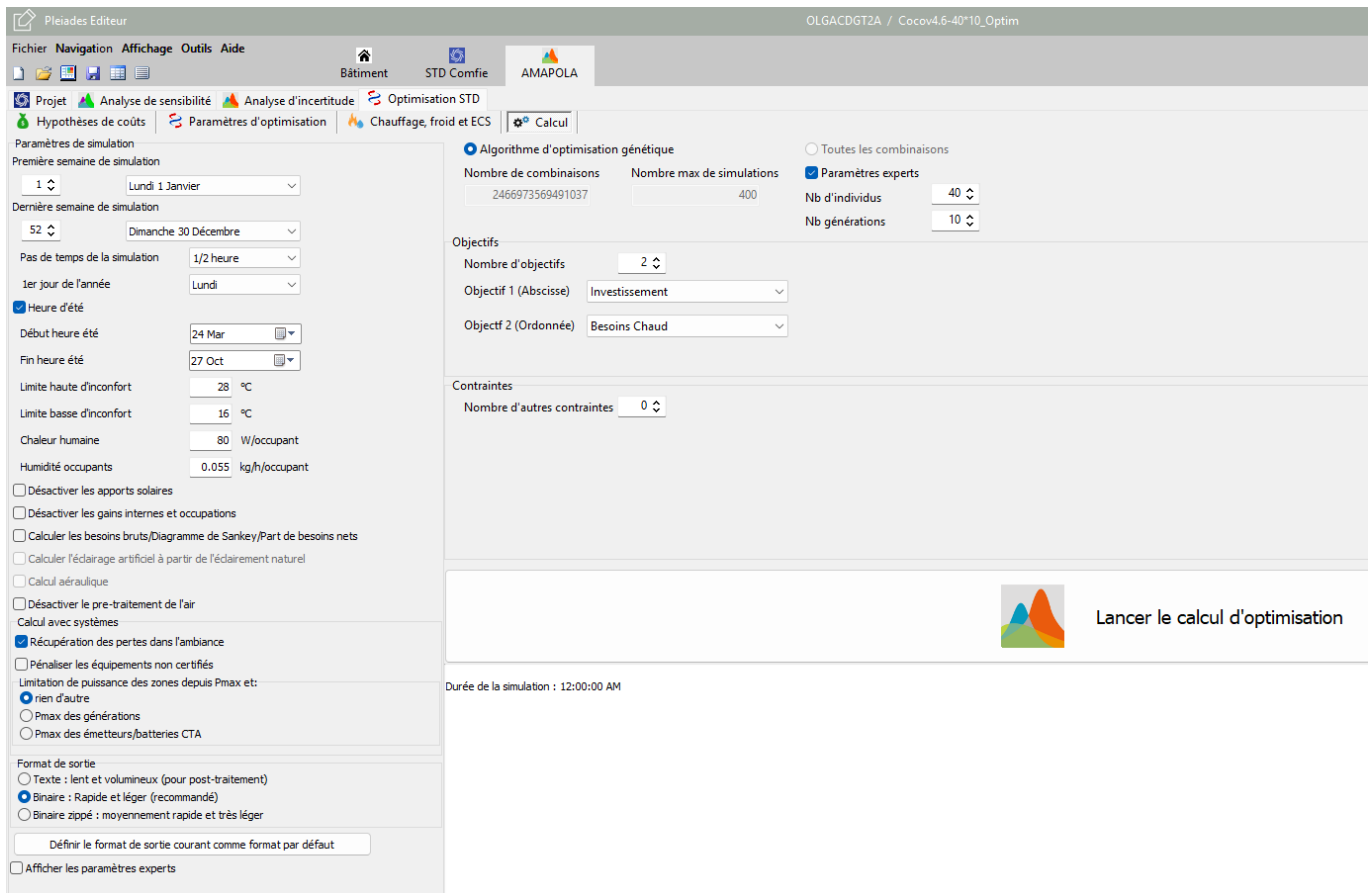


Figure 4-57: The interface of setting the generations and individuals for optimisation.

After clicking on “launch the optimisation calculation” button, the Amapola window will appear, as shown in the figure below. It should be noted that the optimisation calculations can only be started after clicking on the “Démarrer” (start) button.

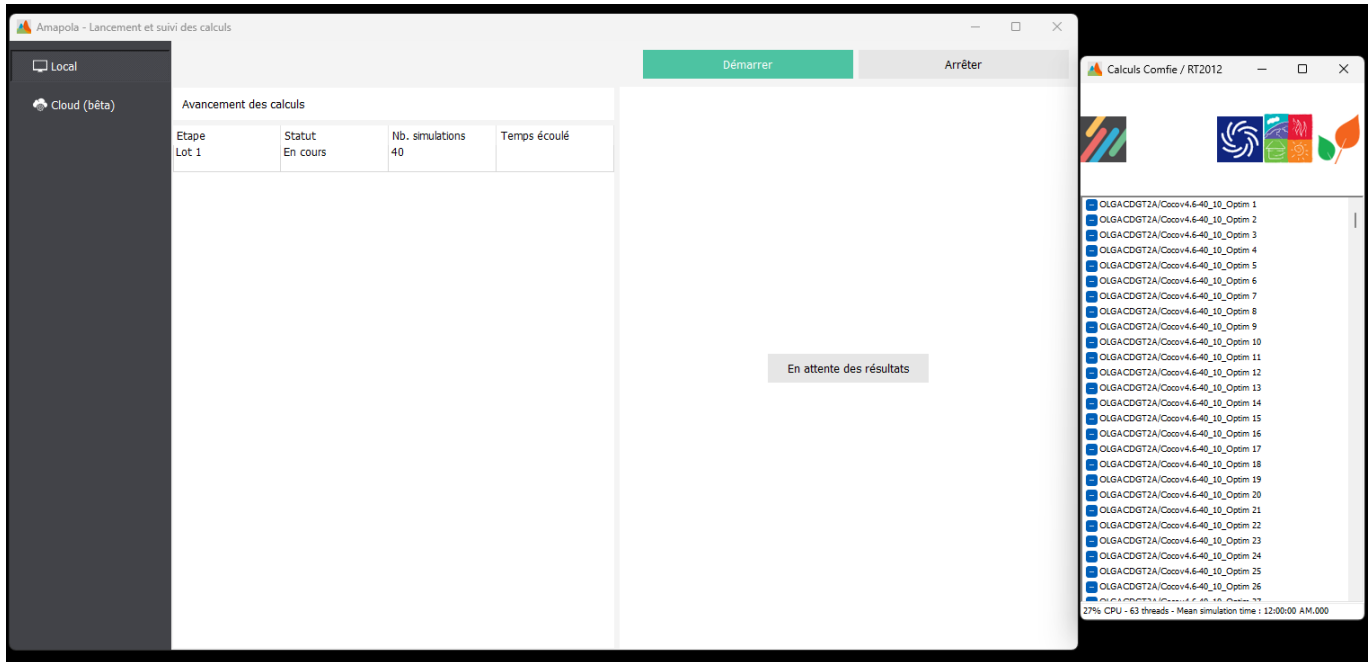


Figure 4-58: The interface of launching the optimisation process.

The iterative process between generations is shown in the figure below. Investment costs and heating loads are shown for all solutions of the successive generations, as well as the Pareto front (red diamond points).

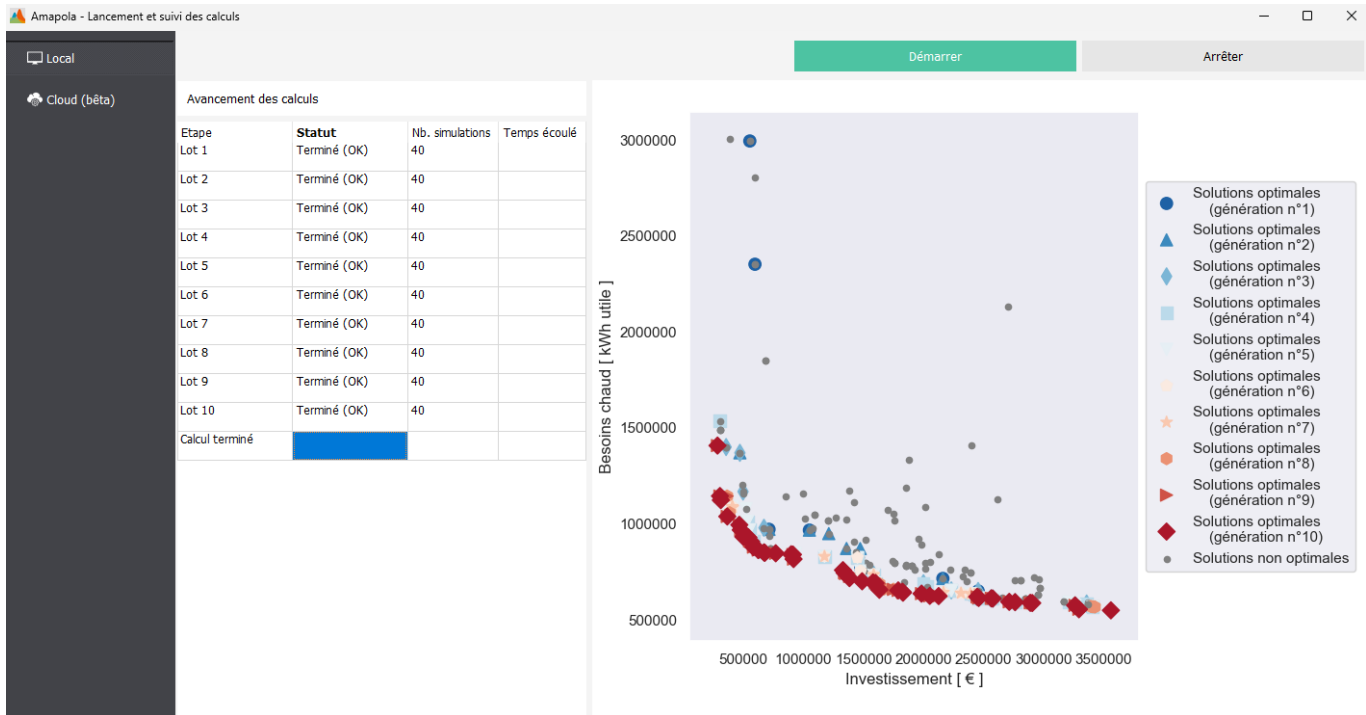


Figure 4-59: The interface of AMAPOLA after optimisation process.

After reading the files, the software displays the results on the 'Pleiades Results' interface. The Pareto front, which presents the final optimal solutions, and the parallel coordinate plot, which provides detailed visualisation of how each solution performs across multiple variables, are shown at the bottom of the interface. In addition, the results tables at the top can be exported to Excel for easier data handling.

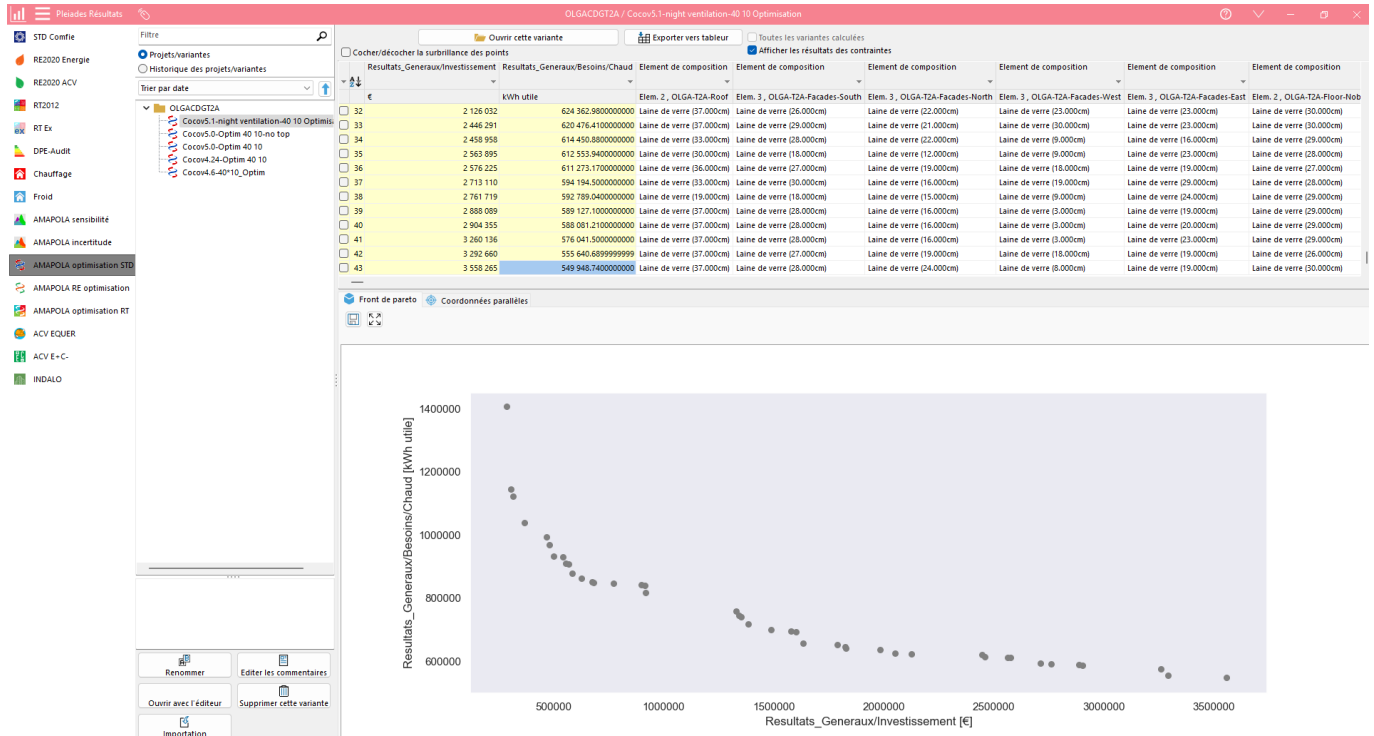


Figure 4-60: Pareto front of the optimisation calculation.

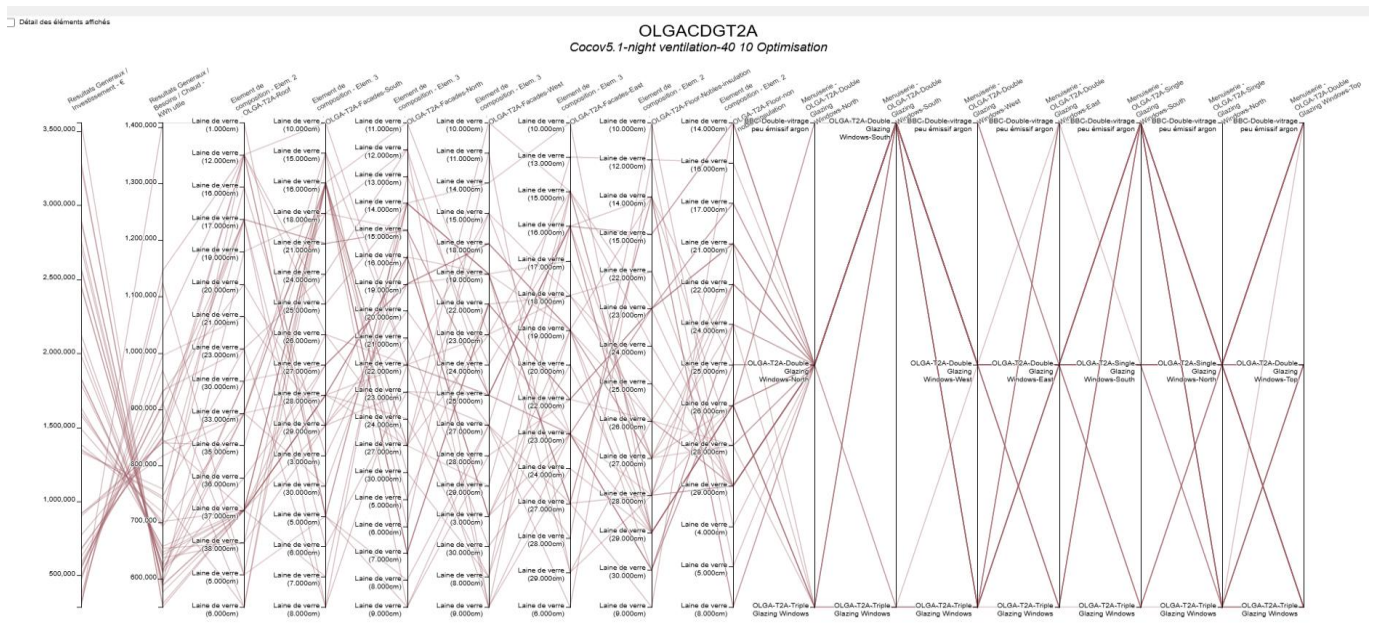


Figure 4-61: Parallel coordinates of the optimisation calculation.



4.5.3.2 Convergence of the optimisation calculations

It is of course not possible to run the 80,000 billion simulations in order to validate the optimisation. The genetic algorithm (NSGA II) was validated on a simpler case where 4 million simulations were performed. Ideally, convergence should be checked by evaluating an “hypervolume” (Knowles et Corne, 2002), which should approach 1 when the number of generations is sufficient to reach convergence (Branke et al., 2008). But we had not enough time in this study addressing a very complex building. We sent a suggestion to the Pleiades software editor to include an automatic calculation of the hypervolume, and hope that this will be possible. To verify whether the optimisation calculations have converged, a dynamic simulation was carried out using the best insulation scenario and compared with the optimisation results that produced the lowest annual heating loads. The best insulation scenario refers to the case in which all single and double glazing windows are replaced with triple glazing, and all insulation layers are applied at their maximum thickness. To this end, a new variant was created to adjust the insulation layer thickness and window types accordingly. The new compositions with the beat insulation were created at first in the library, as shown in the figures below.

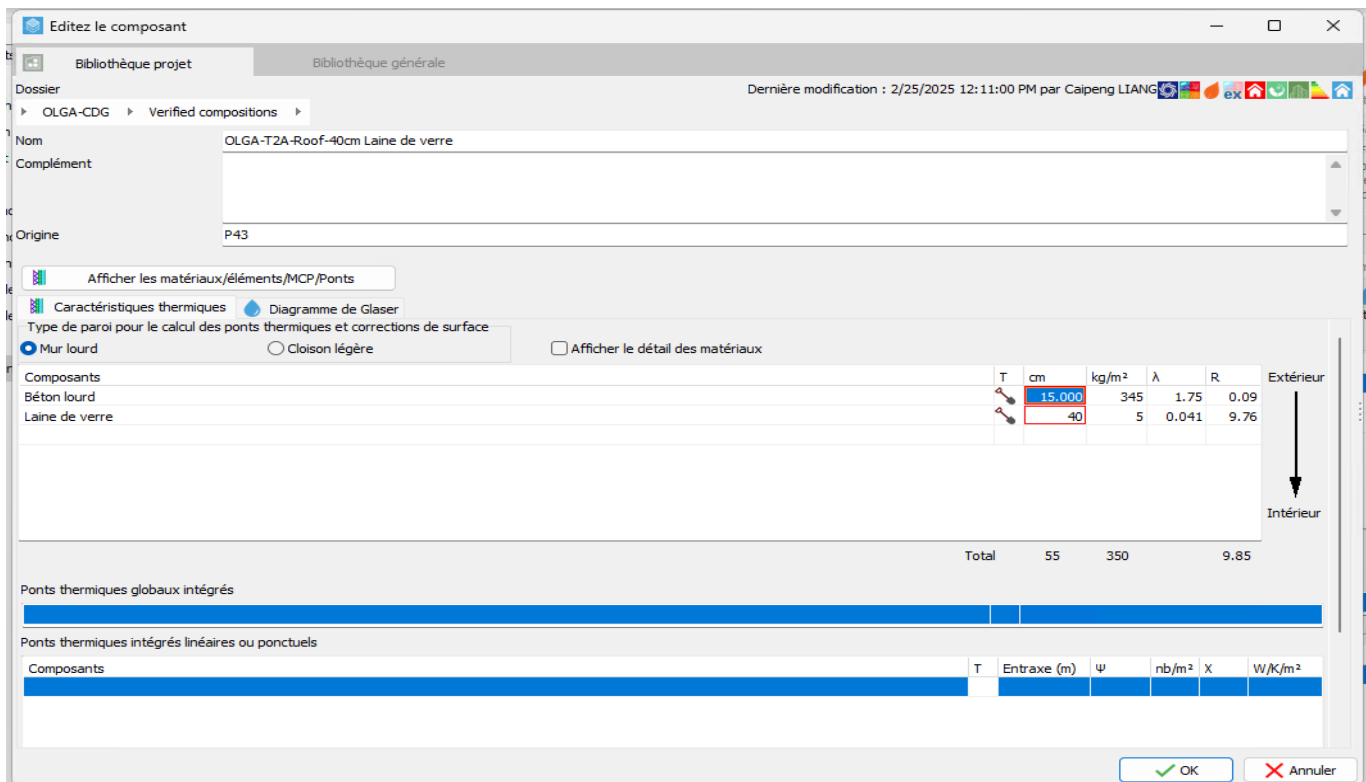


Figure 4-62: The interface of configuring the new composition.

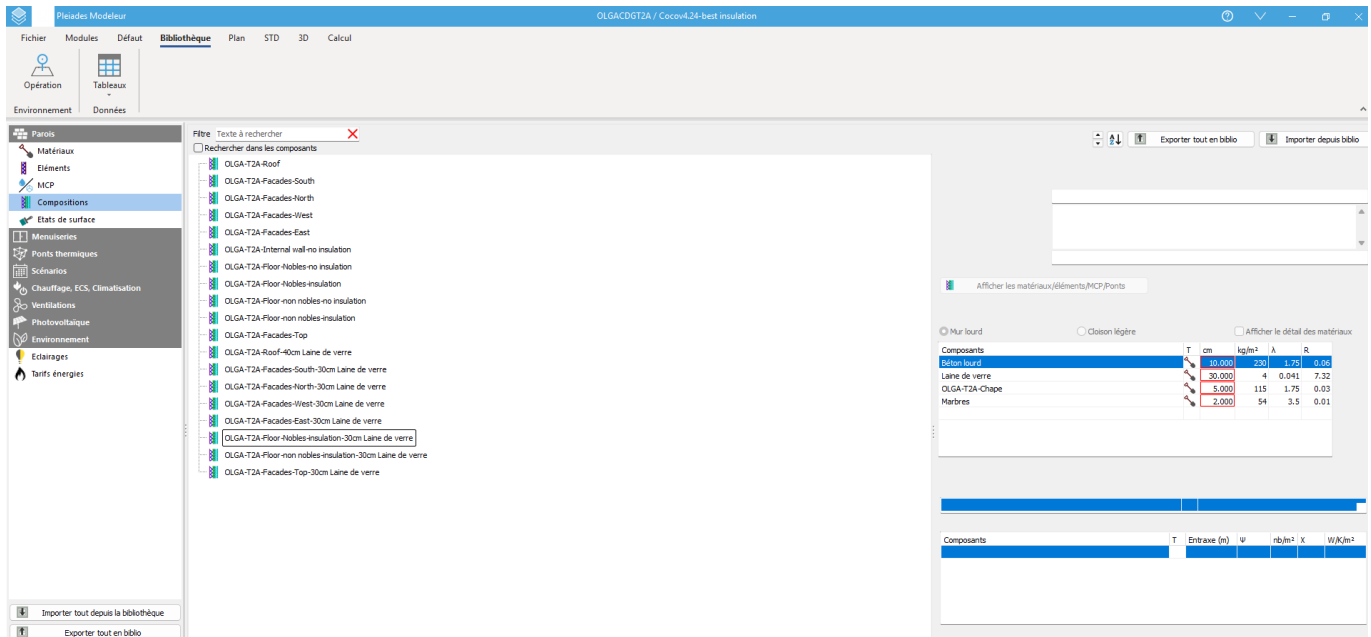


Figure 4-63: The interface of the new library.

Then the original compositions were replaced with those incorporating the thickest insulation layers, as shown in the figure below. The same applies to the windows, which were substituted with triple glazing.

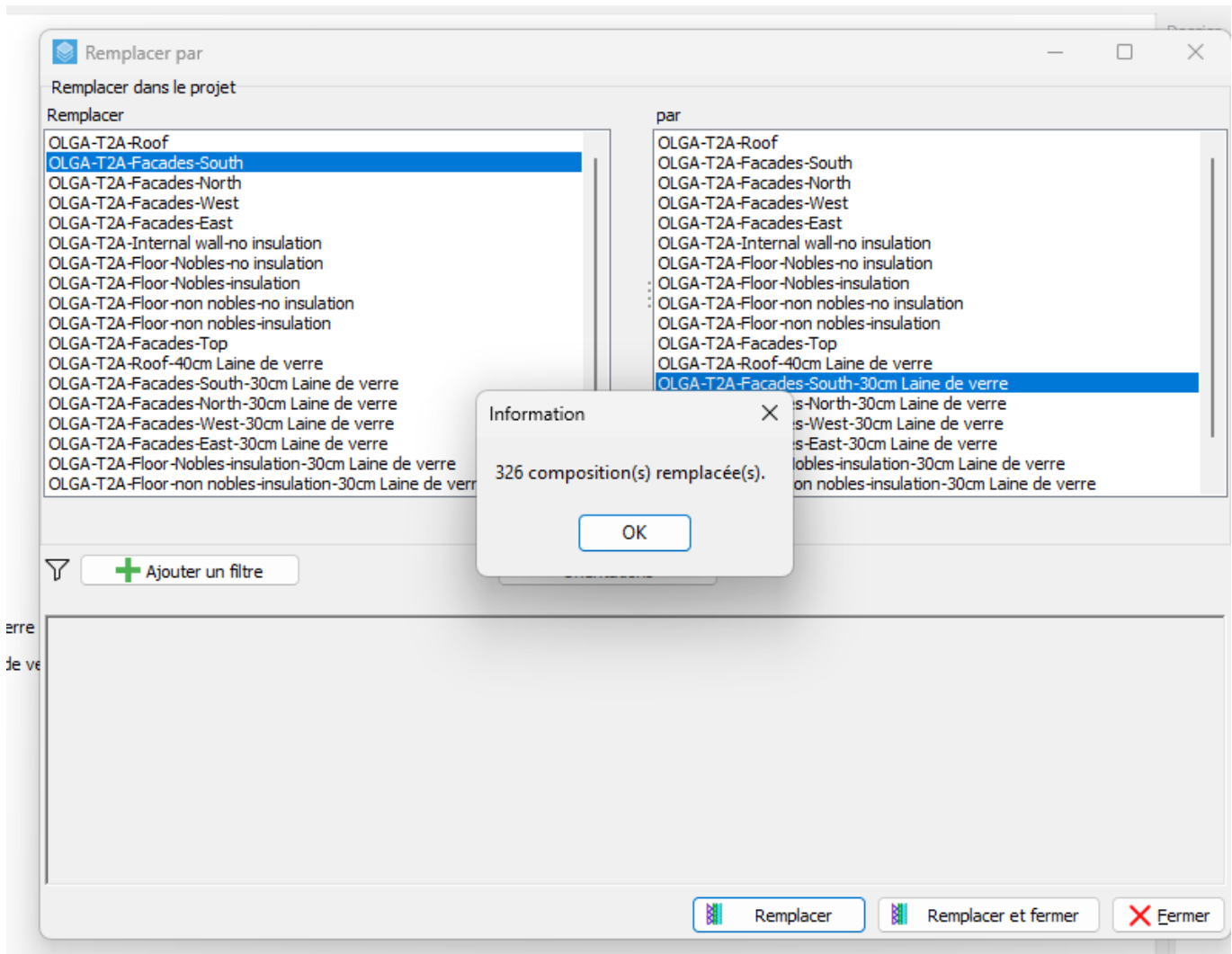


Figure 4-64: The interface of replacing façades in the project.

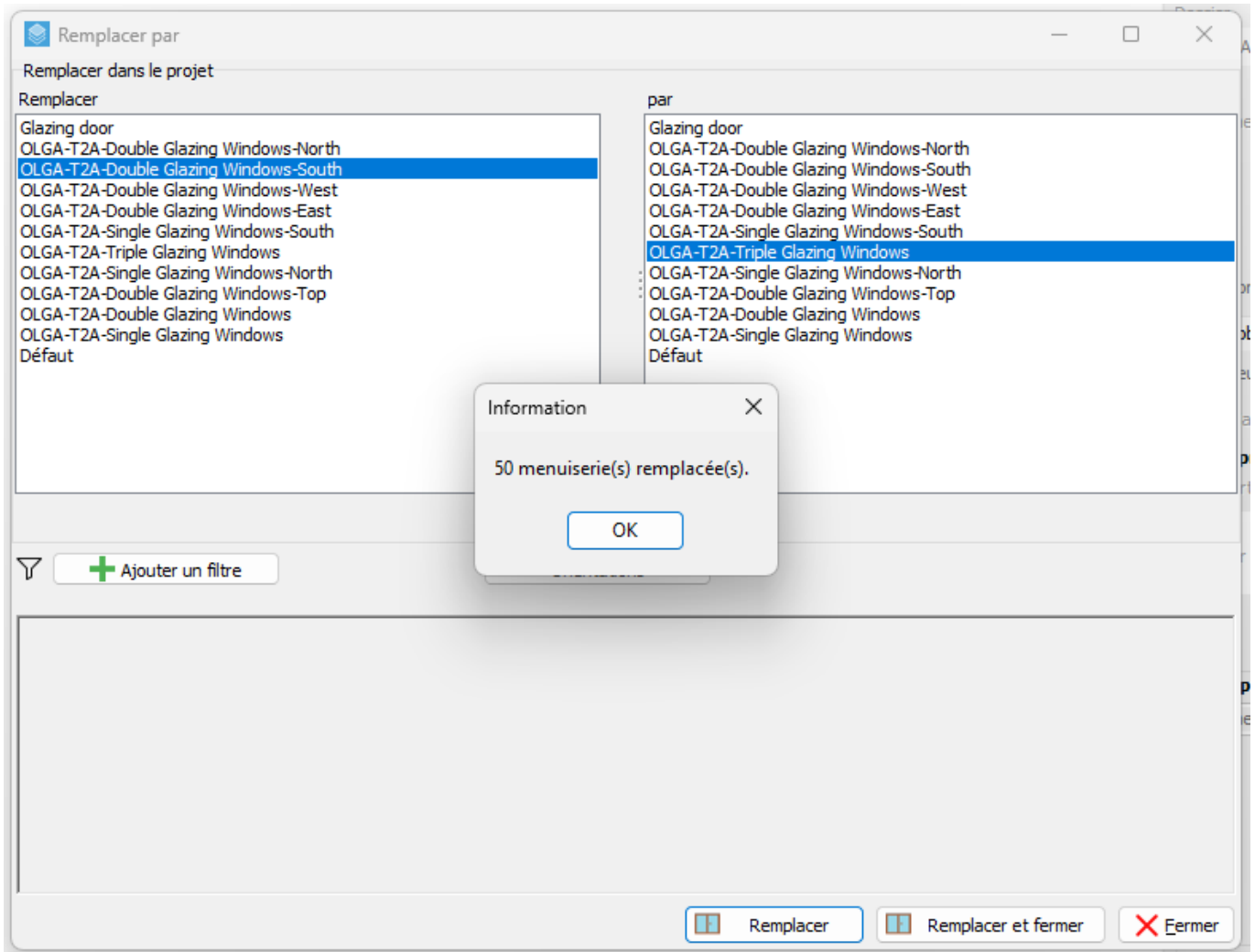


Figure 4-65: The interface of replacing windows in the project.

After replacing all construction elements, including the roof, façades, floors and windows, the simulation can be run to obtain the results. It should be noted that some errors may occur following the replacements due to the increased thickness of the insulation layers.

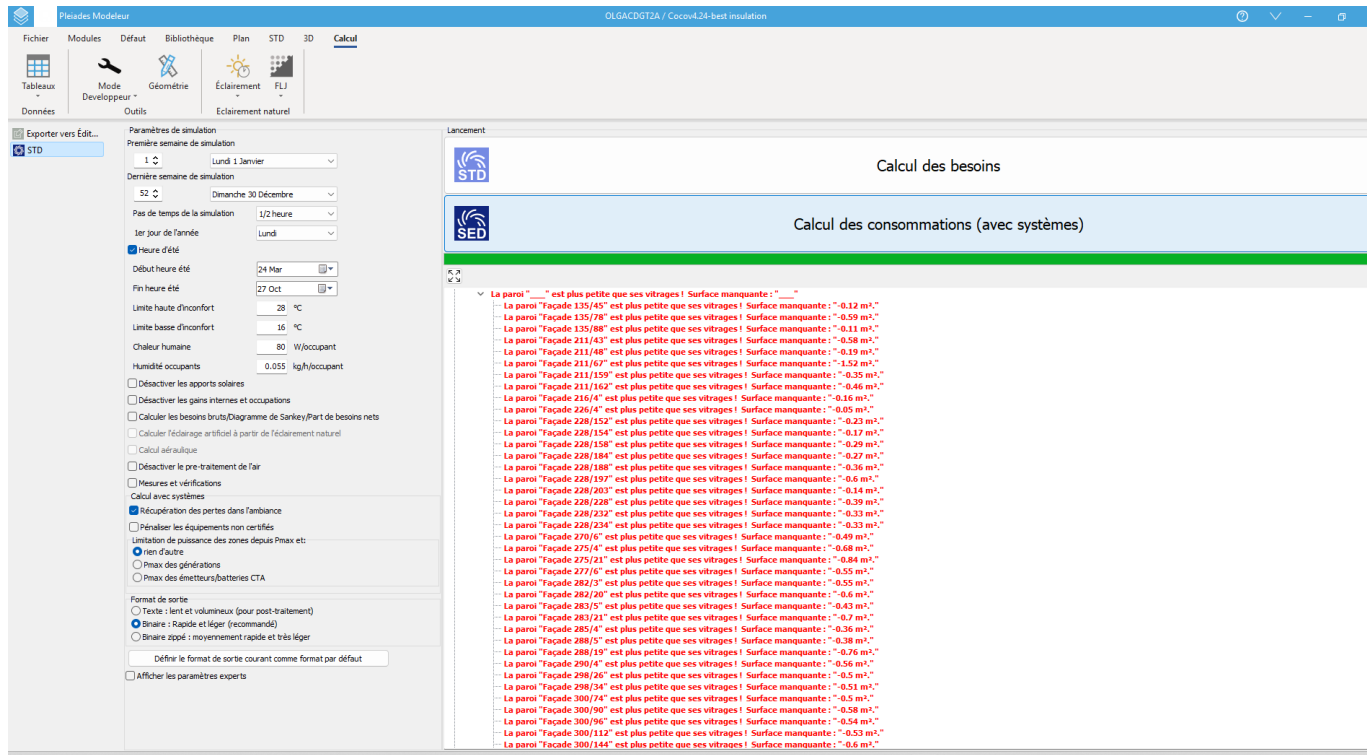
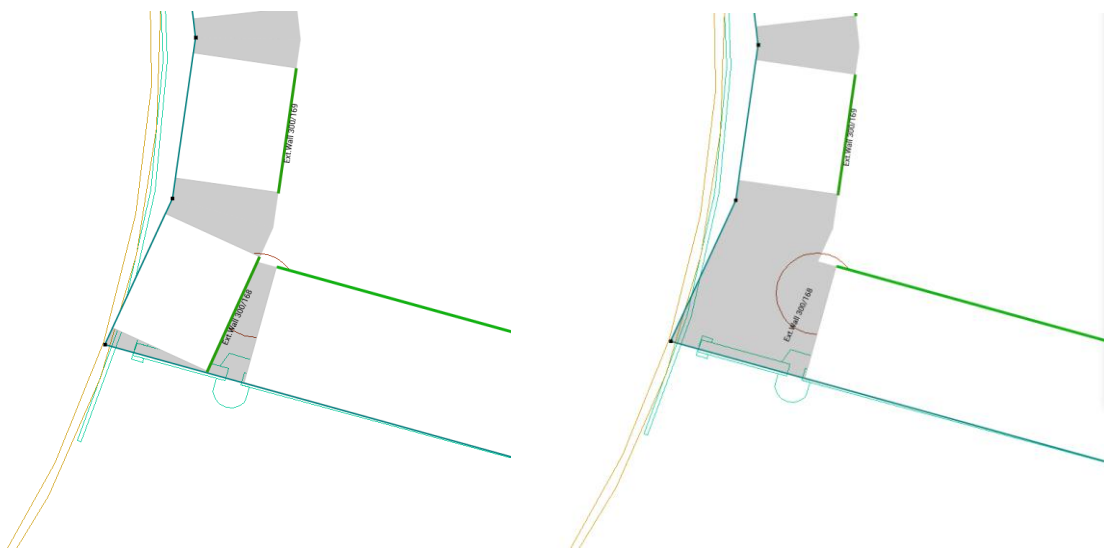


Figure 4-66: The interface of errors when launching the dynamic simulation.

For example, in the figure below, the grey area representing the wall has increased due to the thicker insulation, leading to overlaps between the wall and the surrounding windows. In most cases, this error can be resolved by reducing the size of the windows.



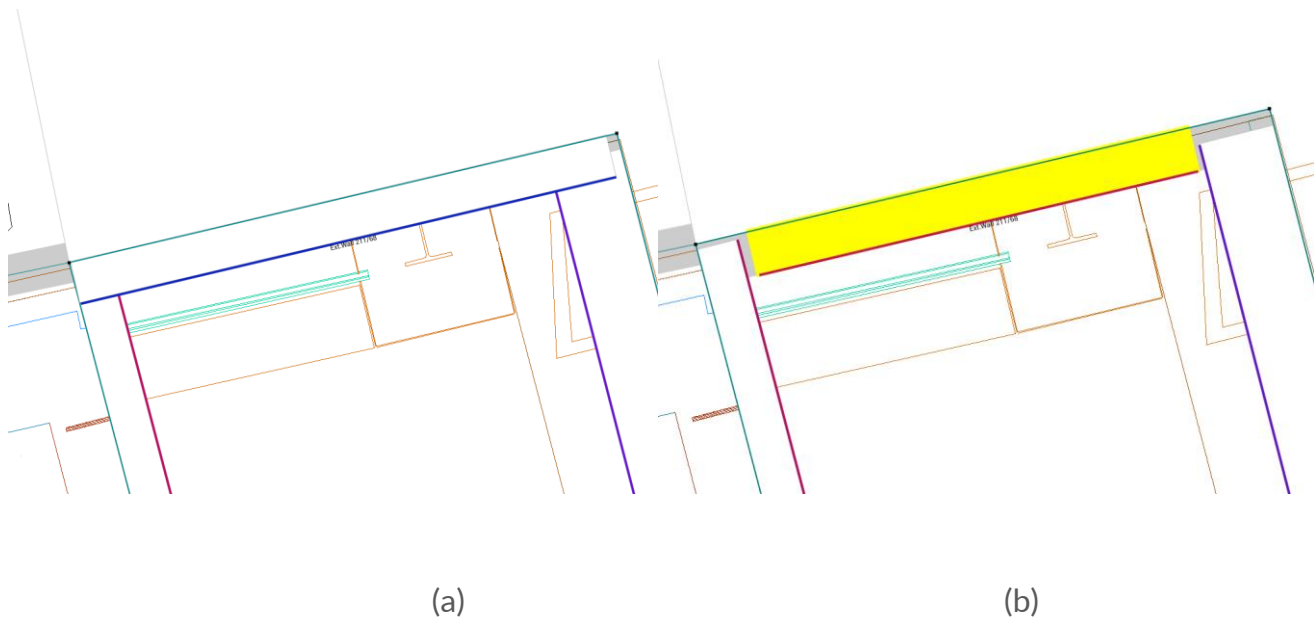


Figure 4-67: (a) Before and (b) after the adjustment to deal with errors.

After making the necessary adjustments in the plan view, the dynamic simulation can be run again to obtain the results under the best insulation conditions. Following the same procedure, the simulation results for the lowest heating load solution of the Pareto front can also be obtained. Table 4-8 presents a comparison of the results for three conditions. It can be observed that under the best optimised conditions, the annual heating loads in the simulated results are slightly higher than those in the optimisation results, which may be due to the window adjustments made in the model to address the overlaps. Additionally, the heating loads under the best optimised conditions and the best insulation conditions are within the same magnitude, with only a small discrepancy of 6%. Therefore, the optimisation calculation is considered to have converged.

Table 4-8: Comparison of the heating loads for three insulation conditions.

V5.1 (with night ventilation)	Insulation conditions	Annual heating loads
The lowest heating load in the optimisation results	37 cm insulation for roof. 28 cm/24 cm/8 cm/19 cm insulation for façades south/north/west/east. 30 cm/24 cm insulation for floors nobles/non-nobles. All triple glazing except bad double glazing east and single glazing north;	14.24 kWh/m ²



Simulated results with the same parameters as the lowest heating load optimised solution	Same as above	16.35 kWh/m ²
Simulated results with the best insulation parameters	40 cm insulation for roof. 30 cm insulation for other compositions. All triple glazing;	15.36 kWh/m ²

4.5.3.3 Selection of three renovation scenarios

Beyond a scenario without renovation (no investment cost but high energy consumption) and the best insulation (but most expensive) scenario, it is useful to identify a limited number of intermediate solutions of the Pareto front that can be further evaluated and discussed with decision makers. We can see in the graph below that the heating load (vertical axis) does not decrease linearly in terms of the investment cost (horizontal axis). The decrease is fast until a “turning point” and then slower. This means that increasing the investment is less efficient after a turning point.

Based on these optimisation calculations, two cases at the turning point, as marked in Figure 4-68 (red circles), are selected as the final scenarios to be analysed in the next section, considering the trade-off between cost and performance. The one with a lower investment is point n°14 in the Pareto front, the second one is n°26. Detailed information regarding the thickness of insulation layers for different compositions and the types of windows across all three renovation scenarios and the case without renovation is displayed in Table 4-9.

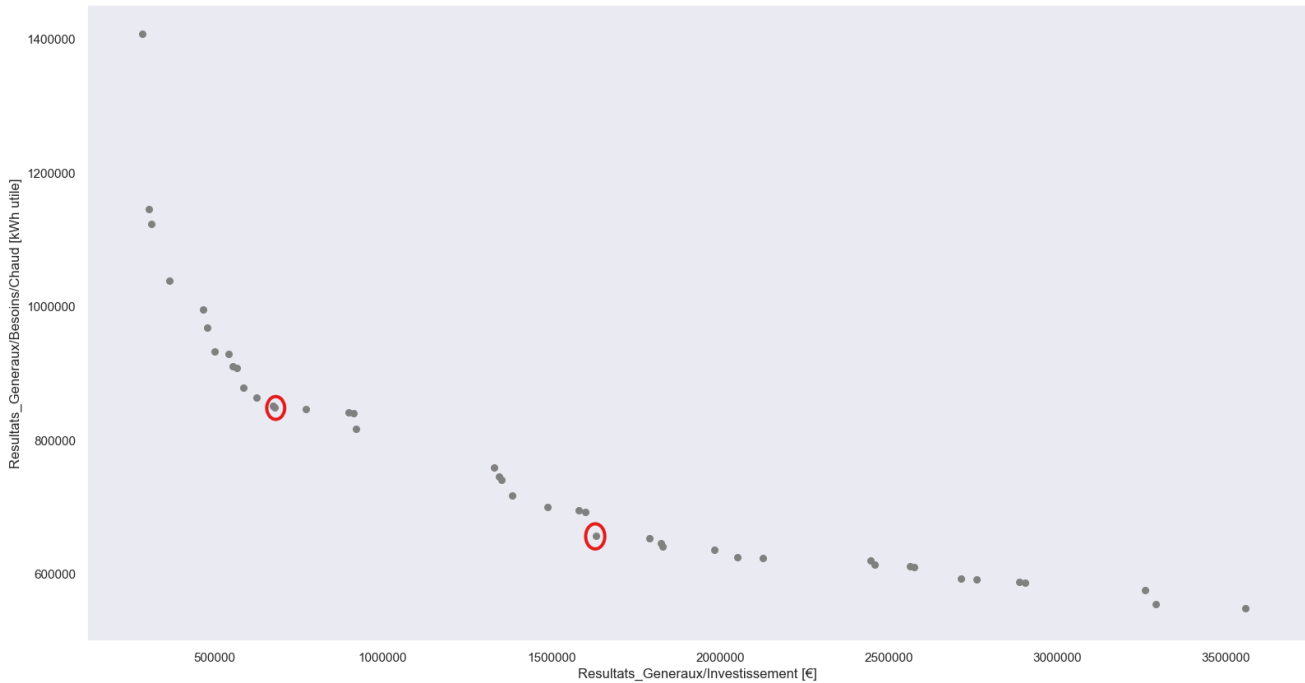


Figure 4-68: The two selected optimised scenarios in the pareto front.

Table 4-9: detailed information of the three scenarios.

Nb.Case	Insulation layers	Windows type
Original model (no renovation)	Roof: 0.01 cm; South façades: 0.01 cm; North façades: 0.01 cm; West façades: 0.01 cm; East façades: 0.01 cm; Floor-nobles: 0.01 cm; Floor-non nobles: 0.01 cm	Default double glazing windows + single glazing windows
Optimised point 14	Roof: 12 cm; South façades: 26 cm; North façades: 27 cm; West façades: 15 cm; East façades: 23 cm; Floor-nobles: 30 cm; Floor-non nobles: 25 cm	Double glazing windows-Top: BBC-Double-vitrage peu emissive argon; Others keep the same as the default settings
Optimised point 26	Roof: 37 cm; South façades: 16 cm; North façades: 27 cm; West façades: 29 cm; East façades: 15 cm; Floor-nobles: 28 cm; Floor-non nobles: 29 cm	Single glazing windows-South: BBC-Double-vitrage peu emissive argon; Double glazing windows-Top: Triple glazing windows; Others keep the same as the default settings



Best insulation	Roof: 40 cm; South façades: 30 cm; North façades: 30 cm; West façades: 30 cm; East façades: 30 cm; Floor-nobles: 30 cm; Floor-non nobles: 30 cm	Triple glazing windows everywhere
------------------------	---	-----------------------------------

The investment cost and performance of the different scenarios are compared in Figure 4-69 and Figure 4-70. Regarding investment, the cost increases with better insulation. It should be noted that the cost of renovation scenarios is an estimated value, and the actual cost is likely to be higher than the value presented in the figure below.

In terms of performance, it can be observed that all three renovation scenarios have significantly reduced the heating loads, while the cooling loads have increased slightly. Specifically, the annual heating loads are 24 kWh/m² for Optimised 14, 19kWh/m² for Optimised 26, and 15 kWh/m² for the Best Insulation scenario, respectively, compared to 153 kWh/m² without renovation.

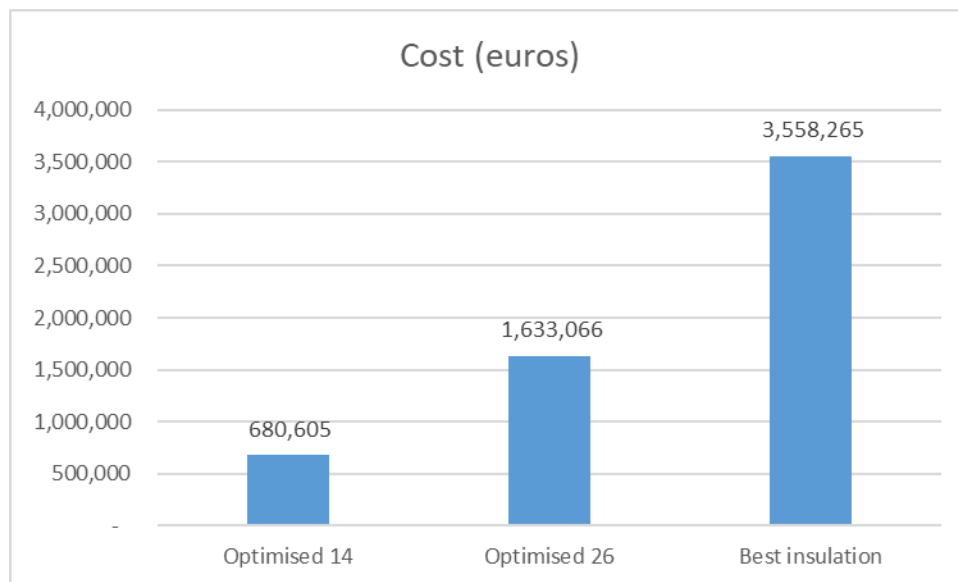


Figure 4-69: Costs of different scenarios.

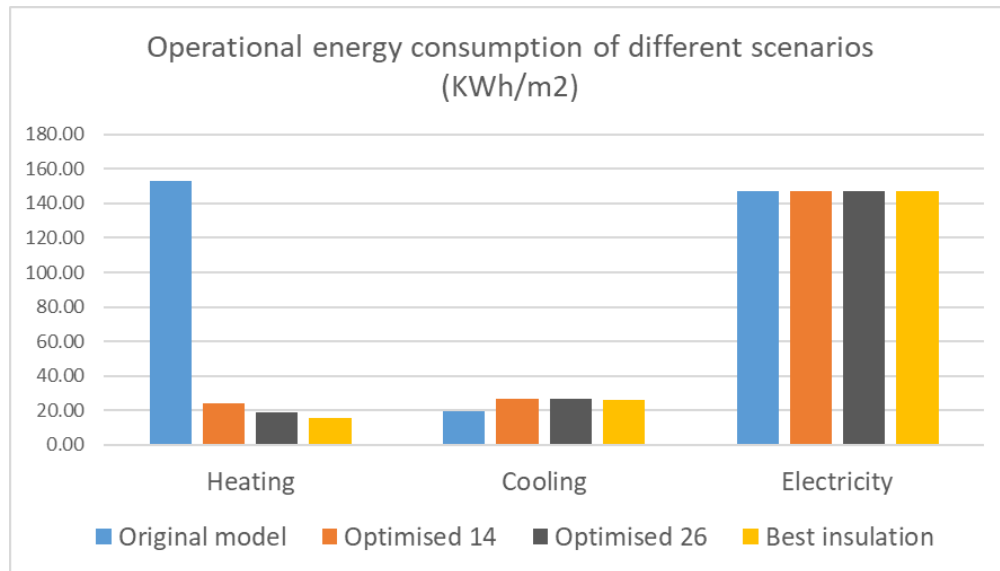


Figure 4-70: Operational energy consumption of different scenarios.

4.6 Environmental impact assessment

4.6.1 Goal and scope

The main goal of LCA for this study is to evaluate the environmental impacts such as CO₂ emission of the renovation scenarios for Terminal 2A. The evaluation scope covers the entire life cycle of the building (which is assumed to be 50 years after renovation), consisting of the renovation works, the use stage, the replacement of components (depending on the lifespan of building materials and components) and the deconstruction stage.

The system boundaries include the processes related to building operation, e.g. district heating using gas and wood for heating and domestic hot water (DHW), upstream processes (e.g. materials fabrication) and downstream processes (e.g. landfill or recycling of materials at end-of-life).

Because the project is related to renovation of existing terminals, materials corresponding to foundations and structure are not accounted for, and neither equipment like computers or other devices. Focusing on the environmental impacts of the building, the daily transportation of the persons and waste generation by users are not considered. The functional unit is the entire Terminal 2A of airport CDG located near Paris over a lifespan of 50 years, considering the functions of the different spaces and their related use scenarios (heating and cooling temperatures, occupancy



scenarios, interval gains, ventilation). Environmental indicators are then evaluated for an average 1 m² area over one year in order to be compared with benchmarks.

4.6.2 Link with thermal simulation

4.6.2.1 Utilisation stage

Before performing LCA, the dynamic simulation needs to be implemented in order to get the operational energy consumption results in Pleiades Modeler. Taking the optimised point 14 as an example, a variant was created based on the original model (v5.1 with night ventilation) by adding thicker insulation layers and replacing the window types as optimised in the AMAPOLA module.

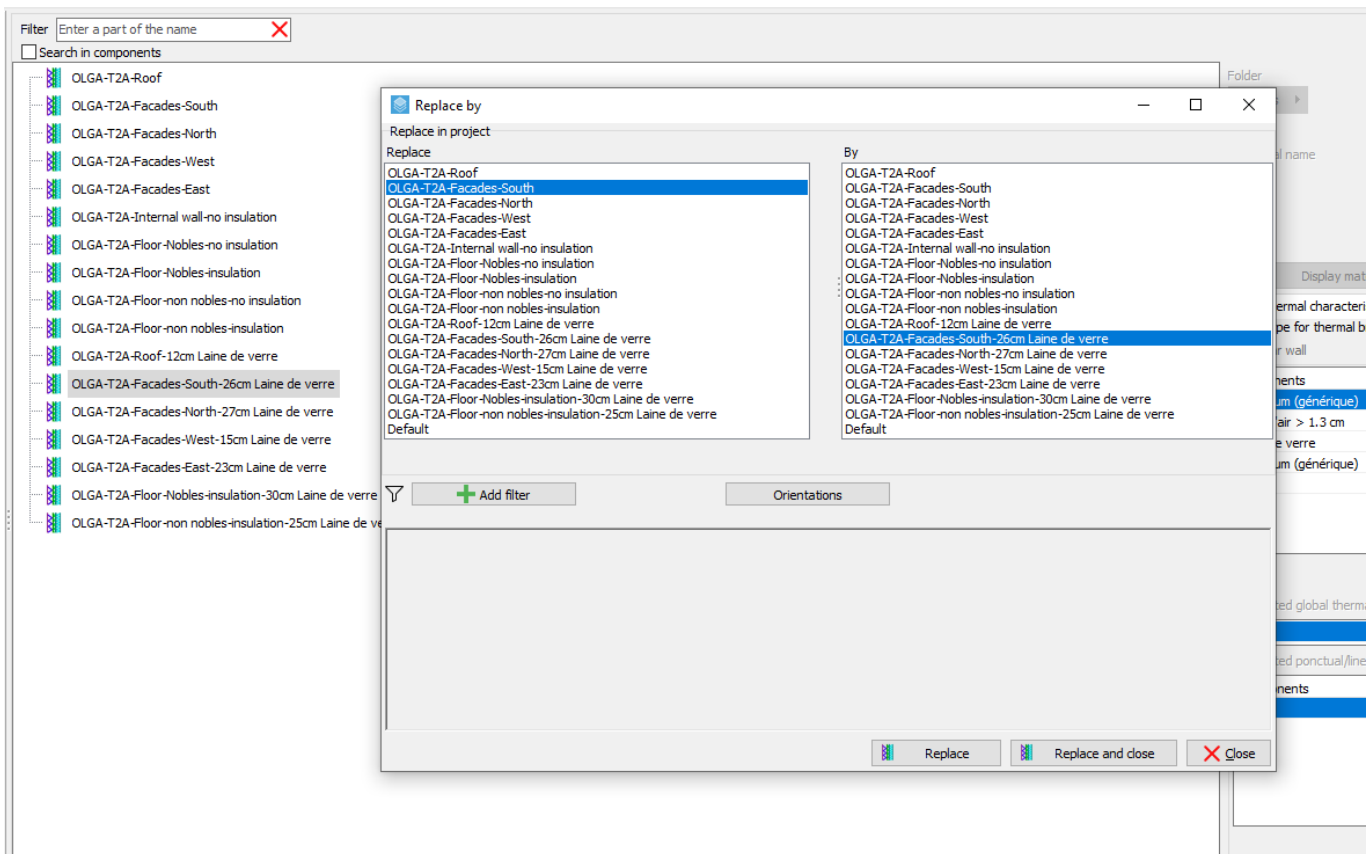


Figure 4-71: The interface of replacing compositions in the project library.

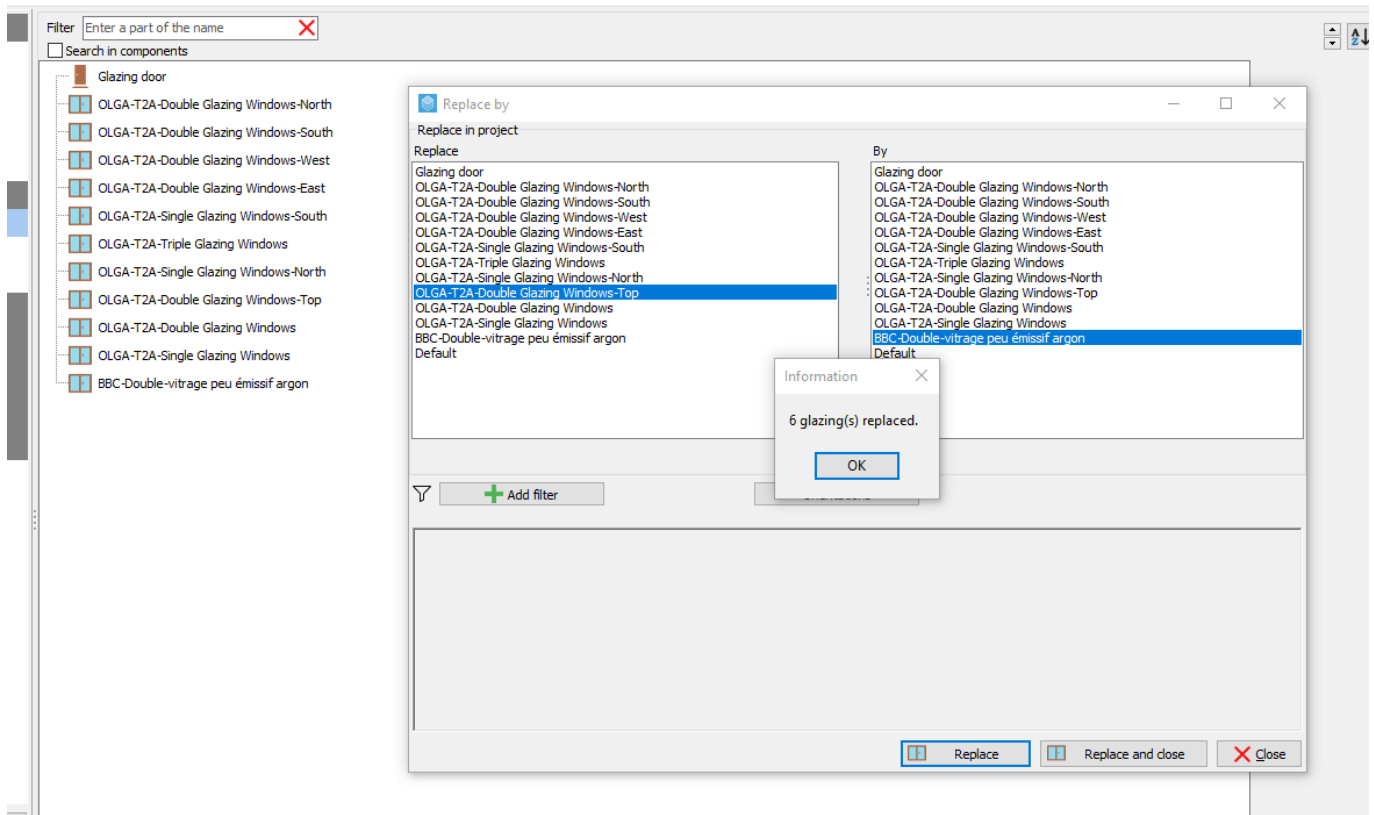


Figure 4-72: The interface of replacing windows in the project library.

Then the dynamic simulation can be performed in order to get the heating and cooling loads. Likewise, some overlapped areas caused by thicker insulation layers need to be first corrected to avoid errors.

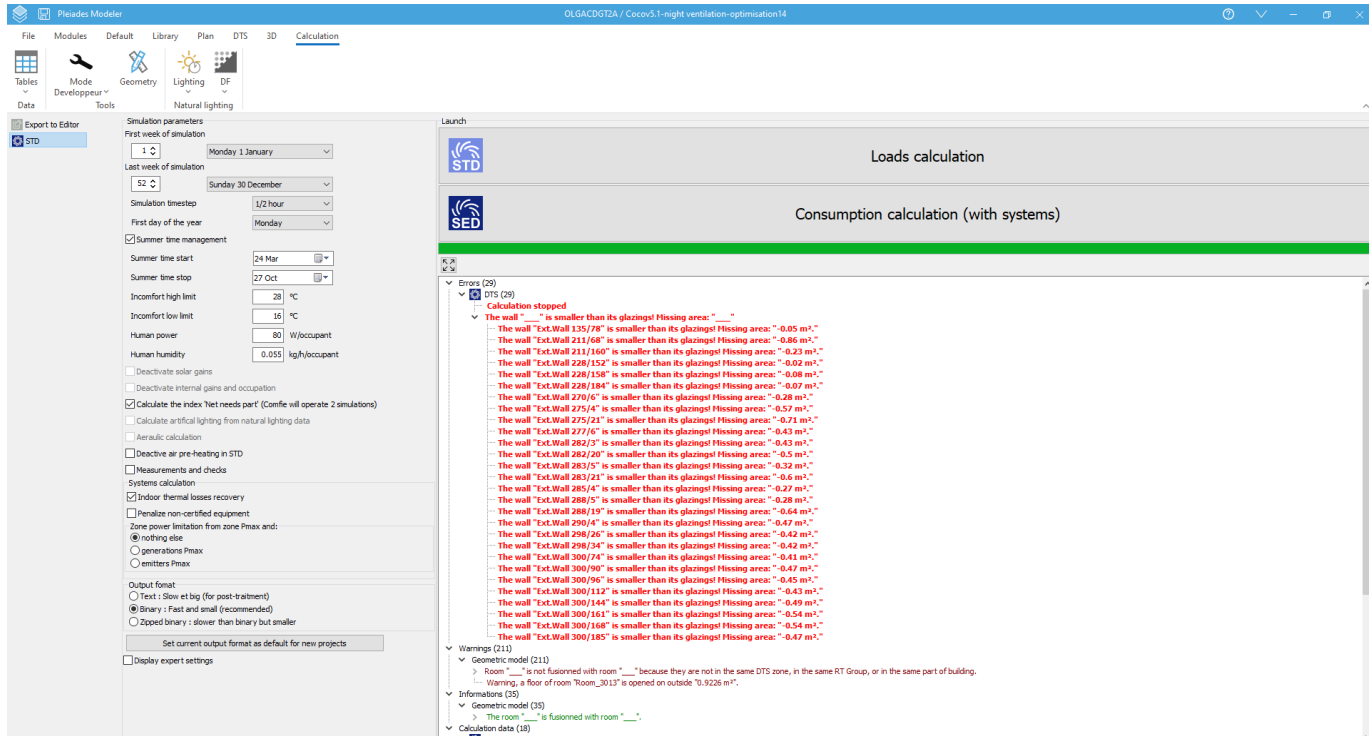


Figure 4-73: The interface of simulation errors after adding insulation layers.

The thermal model includes all characteristics of walls, floors and roof, allowing quantification of materials which is needed for the LCA

4.6.2.2 LCA calculation

After completing the STD simulation, the project can be opened in Pleiades LCA to carry out the Life Cycle Assessment (LCA) using Equer model (Polster et al., 1996). The quantity of each material is calculated using the LCA tool EQUER of Pleiades and the corresponding elements from the ecoinvent database are used for the evaluation. In this study, ecoinvent version 3.8.1 was applied.

Default environmental impact values are considered for painting, and no impact for air layers. Materials are defined in wall compositions in the thermal simulation model, for instance “Parpaing de 15” corresponds to 15 cm thick concrete blocks. It is therefore needed to select the appropriate dataset in the ecoinvent database, e.g. concrete blocks. This is the purpose of a “project match” window, allowing users to associate datasets to materials for fabrication and end of life stages.

The amounts of materials of Terminal 2A are summarised in the following table, indicating also the associations with ecoinvent datasets.



Table 4-10: Materials in Terminal 2A under four scenarios and corresponding LCI items in ecoinvent.

Name	LCI item in ecoinvent	Mass				Unit
		No renovation	Best insulation	Optimised 14	Optimised 26	
Aluminium (générique)	Aluminium	74,176	74,737	75,137	75,056	kg
BBC-Double-vitrage peu émissif argon	Aluminium double-glazing			33.85	1,711	m ²
Béton lourd	Concrete	20,777,057	20,646,518	20,667,059	20,685,628	kg
Default		230,119	229,775	230,080	230,172	m ²
Enduit extérieur	Exterior plaster	694,322	701,212	701,217	700,772	kg
Glazing door	Glazing door	700.36	700.36	700.36	700.36	m ²
Laine de verre	Glass wool	8.19	267,066	185,642	239,892	kg
Lame d'air > 1.3 cm	Air gap	206.05	207.60	208.71	208.49	kg
Marbres	Marble	2,100,425	2,087,990	2,090,381	2,092,492	kg
OLGA-T2A-Chape	Concrete screed	7,134,138	7,099,6123	7,105,972	7,113,020	kg
OLGA-T2A-Double Glazing Windows-East	Aluminium double-glazing	329.86		320.92	321.50	
OLGA-T2A-Double Glazing Windows-North	Aluminium double-glazing	1,566		1,549	1,558	
OLGA-T2A-Double Glazing Windows-South	Aluminium double-glazing	839.58		847.41	838.42	



OLGA-T2A-Double Glazing Windows-Top	Aluminium double-glazing	33.85				
OLGA-T2A-Double Glazing Windows-West	Aluminium double-glazing	312.91		282.12	303.35	
OLGA-T2A-Single Glazing Windows-North	Aluminium single-glazing	42.29		41.81	41.81	
OLGA-T2A-Single Glazing Windows-South	Aluminium single-glazing	1,716		1,736		
OLGA-T2A-Triple Glazing Windows	Aluminium triple-glazing		4,793		33.85	m ²
Parpaing de 15		3,982,143	4,021,658	4,021,688	4,019,133	kg

In the assumptions, the weight of fabricated materials is considered to be 5 % higher than the quantity required, to account for on-site processing, damaged elements, and surplus purchases. Materials are assumed to be transported by truck over a distance of 100 km from factories. The lifespans of building elements are defined as follows: 10 years for finishes (e.g. painting), 20 years for equipment, 30 years for windows and doors, and 50 years for the building structure. Materials and equipment are replaced at the end of their service life during the renovation stage. The distance from material factories to the construction site is assumed to be 100 km, and also from the site to recycling facilities (but 20 km to landfill and incineration). These assumptions can be set in the software interface, as shown below.

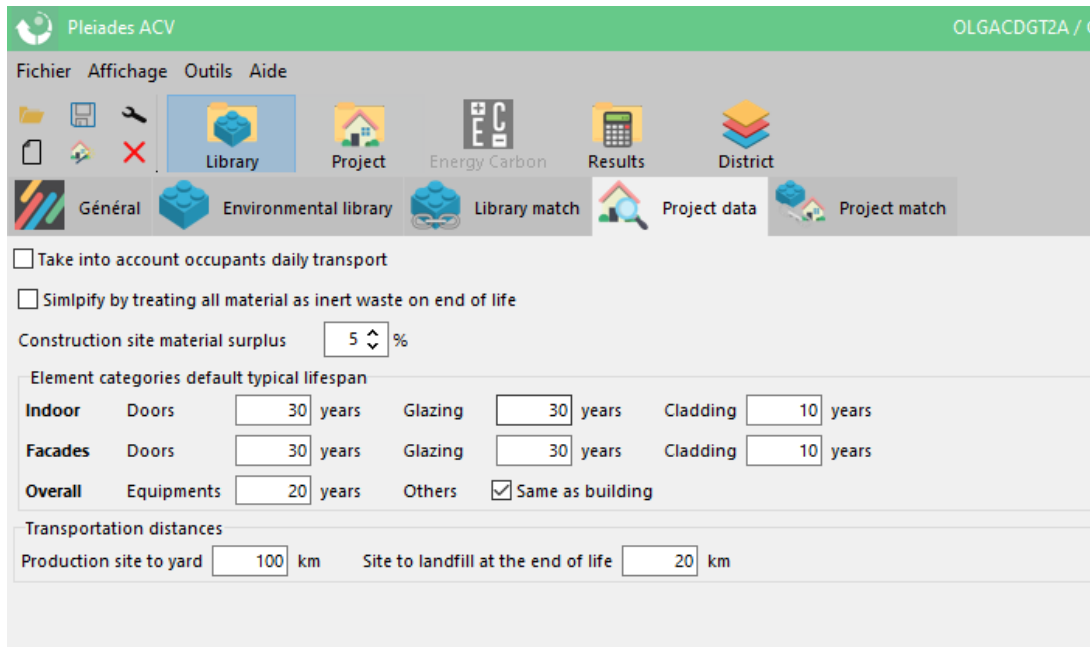


Figure 4-74: Interface of assumption settings in Pleiades LCA.

The total number of occupants, resulting from ratios of m^2 per person for different uses, is 5,611 and the useful (net) area (SURT) is assumed to be 57,793 m^2 for Terminal 2A. These could be set in the interface below.

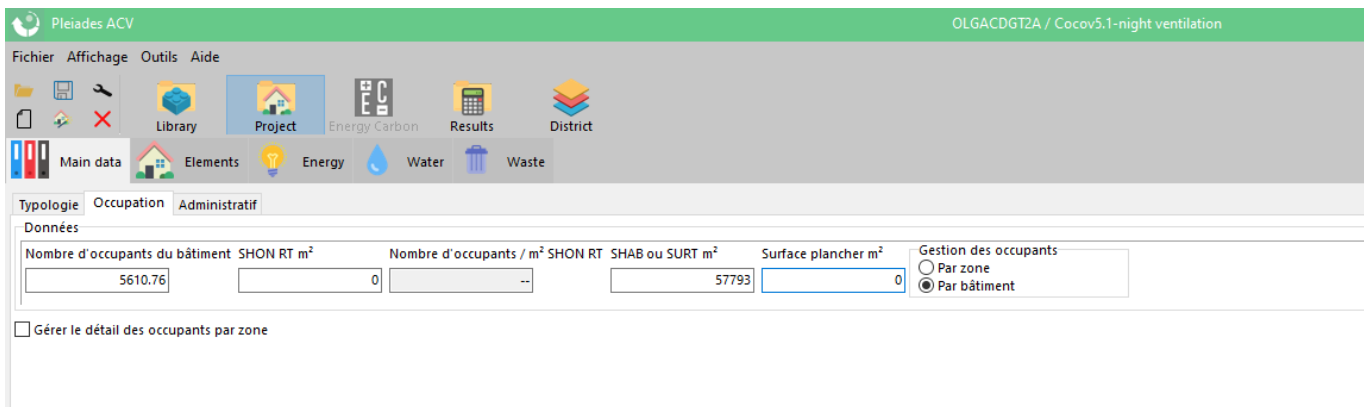


Figure 4-75: Interface of occupant number and useful (net) area settings in Pleiades LCA.

Regarding energy consumption, four main uses are considered: heating, cooling, domestic hot water (DHW), and specific electricity (including lighting and ventilation). Heating and DHW are supplied by district heating, which is based on a heat generation mix of 75 % natural gas and 25 % wood. Cooling is provided by a heat pump powered by electricity, with an Energy Efficiency Ratio (EER) of 4. Specific electricity is supplied from the electricity grid, with a network loss of 9 %. The electricity mix is



assumed to consist of 64 % nuclear, 10 % hydro, 10 % natural gas, 10 % wind, 5 % solar, and 1 % renewable thermal. Data on French electricity production and imports is provided by the French transmission system operator RTE. These parameters can be set in the interface below.

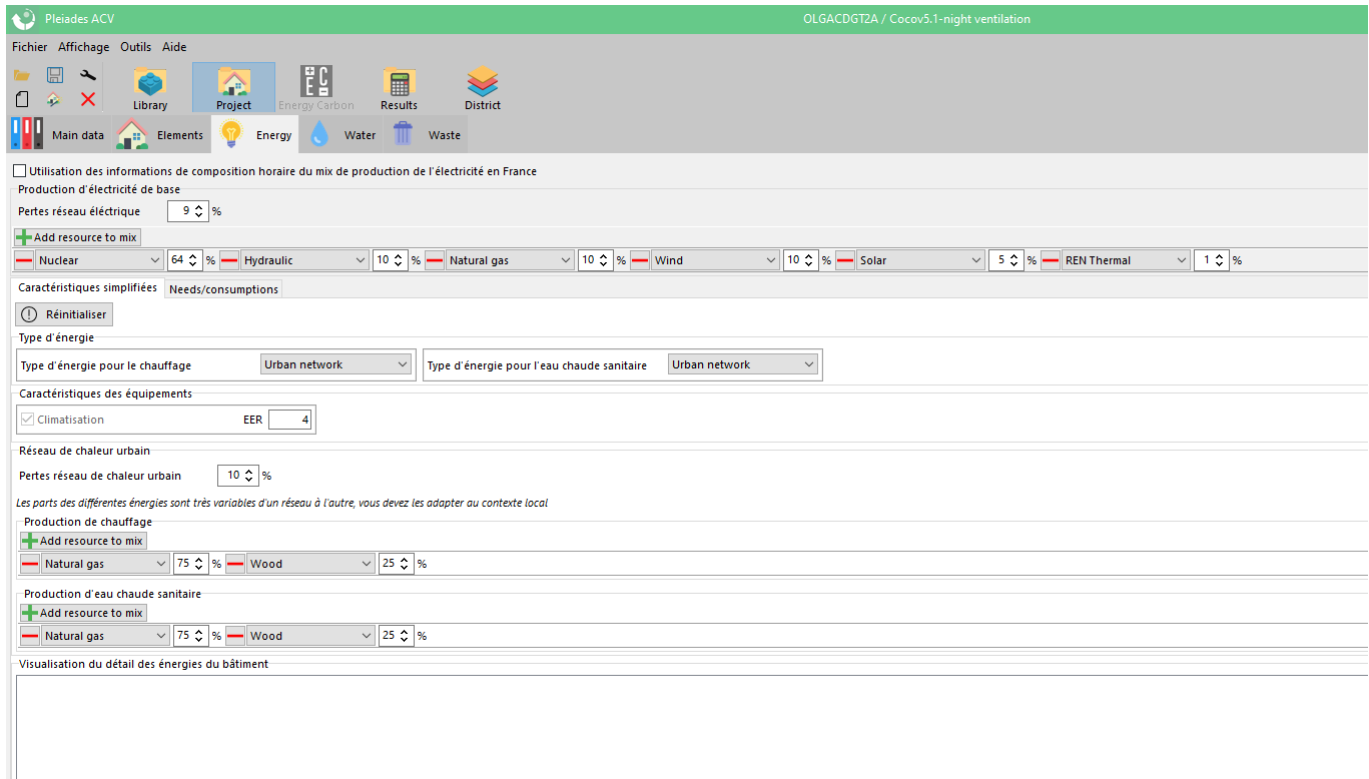


Figure 4-76: Interface of energy settings in Pleiades LCA.

The water network leakage is set at 20 % (average in French cities), and the hot and cold water consumptions are set at 1 liter/day/person and 10 liters/day/person. The daily transportation of the persons and waste generation are not included in this study. These could be set in the interface below.





Figure 4-77: Interface of water consumption settings in Pleiades LCA.

A distance of 20 km is assumed from the site to the landfill during the deconstruction stage, the distance is the same to the incineration site. The distance to the recycling centre is assumed to be 100 km.

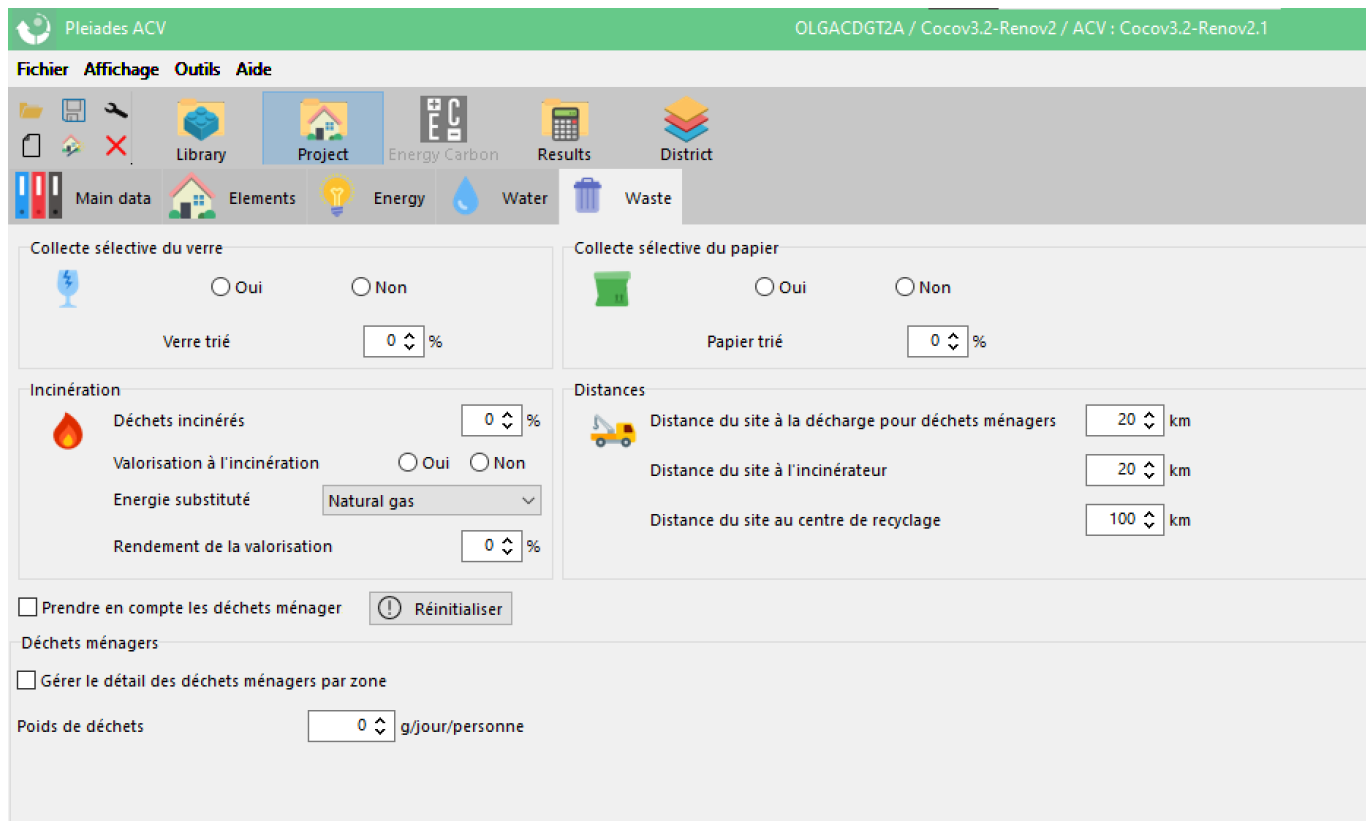


Figure 4-78: Interface of waste settings in Pleiades LCA.

To evaluate the impacts of the renovation works, two LCAs must be conducted for each optimisation scenario: one assessing the impacts of the removal of old materials, and the other evaluating the impacts of the construction of new materials. For the first part, the LCA should be performed using the original model (before renovation): only the end of life of the disposed elements (old glazing) is considered, and all other processes (e.g. fabrication) are not accounted for. For the second part, LCA should be carried out using the renovated model (after renovation), i.e. the model with the corresponding optimised insulation parameters. Fabrication processes are accounted for regarding the added insulation materials and new glazing.

In the LCA of the scenario without renovation, only impacts from the use stage until deconstruction are considered because there is no renovation work.



4.6.2.2.1 Optimised point 14

For optimised 14, only double glazing windows on the top are replaced with the low-emissivity double glazing windows. Therefore, to quantify the impacts of renovation works, only elimination of the default double glazing windows on the top is considered. The corresponding associations are displayed in the figure below.

Type	Composition	Name	Lifes...	Production	Elimination	Elimination : Avoided impact
		OLGA-TZA-Chape	--	No match	No match	n/a
		Béton lourd	--	No match	No match	n/a
		OLGA-TZA-Double Glazing Windows-East	--	No match	No match	n/a
		OLGA-TZA-Double Glazing Windows-Top	--	No match	Aluminium double vitrage - m2 - recyclage	No match
		Default	--	No match	No match	n/a
		Parpas de 15	--	No match	No match	n/a
		Enduit extérieur	--	No match	No match	n/a
		OLGA-TZA-Single Glazing Windows-South	--	No match	No match	n/a
		OLGA-TZA-Single Glazing Windows-North	--	No match	No match	n/a
		Glazing door	--	No match	No match	n/a
		OLGA-TZA-Double Glazing Windows-North	--	No match	No match	n/a
		Marbres	--	No match	No match	n/a
		Laine de verre	--	No match	No match	n/a
		OLGA-TZA-Double Glazing Windows-South	--	No match	No match	n/a
		Aluminium (générique)	--	No match	No match	n/a
		Lame d'air > 1,3 cm	--	No match	No match	n/a
		OLGA-TZA-Double Glazing Windows-West	--	No match	No match	n/a

Figure 4-79: Project match window for Optimised 14 scenario before renovation.

The production of low-emissivity double glazing and the insulation layer of glass wool (laine de verre) should also be considered in the impacts of renovation work. Glass wool (laine de verre) is supposed to be landfilled at end of life. The corresponding associations are displayed in the figure below. It should be noted that this part was conducted using the optimised model after renovation.

Type	Composition	Name	Lifes...	Production	Elimination
		OLGA-TZA-Chape	--	No match	No match
		Béton lourd	--	No match	No match
		OLGA-TZA-Double Glazing Windows-East	--	No match	No match
		Default	--	No match	No match
		Parpas de 15	--	No match	No match
		Enduit extérieur	--	No match	No match
		BBC-Double-vitrage peu émissif argon	100	Aluminium double vitrage	No match
		OLGA-TZA-Single Glazing Windows-South	--	No match	No match
		OLGA-TZA-Single Glazing Windows-North	--	No match	No match
		Glazing door	--	No match	No match
		OLGA-TZA-Double Glazing Windows-North	--	No match	No match
		Marbres	--	No match	No match
		Laine de verre	100	Laine de verre	Déchet inerte - kg - décharge
		OLGA-TZA-Double Glazing Windows-South	--	No match	No match
		Aluminium (générique)	--	No match	No match
		Lame d'air > 1,3 cm	--	No match	No match
		OLGA-TZA-Double Glazing Windows-West	--	No match	No match

Figure 4-80: Project match window for Optimised 14 scenario after renovation.



4.6.2.2.2 Optimised point 26

For optimised 26, double glazing on the top (roof) and single glazing on the south façade are replaced with triple glazing and low-emissivity double glazing respectively. Therefore, the elimination of these two should be considered in the impacts of renovation works.

Composition	Name	Lifespan	Production	Elimination	Elimination: Avoided impact
	OLGA-TZA-Chape	--	No match	No match	n/a
	Béton lourd	--	No match	No match	n/a
	OLGA-TZA-Double Glazing Windows-East	--	No match	No match	n/a
	OLGA-TZA-Double Glazing Windows-East	--	No match	Aluminium double vitrage - m2 - recyclage	No match
	Default	--	No match	No match	n/a
	Parpaing de 15	--	No match	No match	n/a
	Enduit extérieur	--	No match	No match	n/a
	OLGA-TZA-Single Glazing Windows-South	--	No match	Aluminium simple vitrage - m2 - recyclage	No match
	OLGA-TZA-Single Glazing Windows-North	--	No match	No match	n/a
	Glazing door	--	No match	No match	n/a
	OLGA-TZA-Double Glazing Windows-North	--	No match	No match	n/a
	Marbres	--	No match	No match	n/a
	Laine de verre	--	No match	No match	n/a
	OLGA-TZA-Double Glazing Windows-South	--	No match	No match	n/a
	Aluminium (générique)	--	No match	No match	n/a
	Lame d'air > 1,3 cm	--	No match	No match	n/a
	OLGA-TZA-Double Glazing Windows-West	--	No match	No match	n/a

Figure 4-81: Project match window for Optimised 26 scenario before renovation.

Production of low-emissivity double glazing, triple glazing and the insulation layer glass wool (laine de verre) should also be considered in the impacts of renovation works. The corresponding associations are displayed in the figure below. This part was conducted using the optimised model after renovation.

Composition	Name	Lifespan	Production	Elimination
	OLGA-TZA-Chape	--	No match	No match
	Béton lourd	--	No match	No match
	OLGA-TZA-Double Glazing Windows-East	--	No match	No match
	Default	--	No match	No match
	Parpaing de 15	--	No match	No match
	Enduit extérieur	--	No match	No match
	OLGA-TZA-Triple Glazing Windows	100	Aluminium triple vitrage	No match
	BBC-Double-vitrage peu émissif argon	100	Aluminium double vitrage	No match
	OLGA-TZA-Single Glazing Windows-North	--	No match	No match
	Glazing door	--	No match	No match
	OLGA-TZA-Double Glazing Windows-North	--	No match	No match
	Marbres	--	No match	No match
	Laine de verre	100	Laine de verre	Déchet inerte - kg - décharge
	OLGA-TZA-Double Glazing Windows-South	--	No match	No match
	Aluminium (générique)	--	No match	No match
	Lame d'air > 1,3 cm	--	No match	No match
	OLGA-TZA-Double Glazing Windows-West	--	No match	No match

Figure 4-82: Project match window for Optimised 26 scenario after renovation.

4.6.2.2.3 Best insulation

For best insulation, all double glazing and single glazing are replaced with triple glazing, so the elimination of all these windows is supposed to be considered in the impacts of renovation works.



Composition	Name	Lifespan	Production	Elimination	Elimination: Avoided impact
OLGA-TZA-Chape		--	No match	No match	n/a
Béton lourd		--	No match	No match	n/a
OLGA-TZA-Double Glazing Windows-East		--	No match	Aluminium double vitrage - m2 - recyclage	No match
OLGA-TZA-Double Glazing Windows-Top		--	No match	Aluminium double vitrage - m2 - recyclage	No match
Default		--	No match	No match	n/a
Parpaing de 15		--	No match	No match	n/a
Enduit extérieur		--	No match	No match	n/a
OLGA-TZA-Single Glazing Windows-South		--	No match	Aluminium simple vitrage - m2 - recyclage	No match
OLGA-TZA-Single Glazing Windows-North		--	No match	Aluminium simple vitrage - m2 - recyclage	No match
Glazing door		--	No match	No match	n/a
OLGA-TZA-Double Glazing Windows-North		--	No match	Aluminium double vitrage - m2 - recyclage	No match
Marbres		--	No match	No match	n/a
Laine de verre		--	No match	No match	n/a
OLGA-TZA-Double Glazing Windows-South		--	No match	Aluminium double vitrage - m2 - recyclage	No match
Aluminium (générique)		--	No match	No match	n/a
Lame d'air > 1.3 cm		--	No match	No match	n/a
OLGA-TZA-Double Glazing Windows-West		--	No match	Aluminium double vitrage - m2 - recyclage	No match

Figure 4-83: Project match window for Best Insulation scenario before renovation.

As for the model after renovation, the production of triple glazing and the insulation layer glass wool (laine de verre) should be considered in the impacts of renovation work.

Composition	Name	Lifespan	Production	Elimination
OLGA-TZA-Chape		--	No match	No match
Béton lourd		--	No match	No match
Glazing door		--	No match	No match
Default		--	No match	No match
Parpaing de 15		--	No match	No match
Enduit extérieur		--	No match	No match
Marbres		--	No match	No match
Laine de verre		100	Laine de verre	Déchet inerte - kg - décharge
OLGA-TZA-Triple Glazing Windows		100	Aluminium triple vitrage	No match
Aluminium (générique)		--	No match	No match
Lame d'air > 1.3 cm		--	No match	No match

Figure 4-84: Project match window for Best Insulation scenario after renovation.

4.6.3 Impact assessment

Eight impact indicators have been selected to evaluate the environmental impacts of Terminal 2A, as listed in the table below. Beside climate change, resource depletion is considered (primary energy, water, and minerals) as well as waste (radioactive and others), and two damage indicators (human health and ecosystems).

Table 4-11: The 8 indicators selected in the study.

Climate change (kg CO2 eq.)
Abiotic depletion potential, minerals and metals (kg Sb eq.)
Total primary energy use, without raw material (MJ)
Net water consumption (m3)



Eliminated wastes, total (kg)
Eliminated radioactive wastes (kg)
Total damage, ecosystem quality, ReCiPe2016 - H (species.yr)
Total damage, human health, ReCiPe2016 - H (DALY)

4.6.4 Interpretation of results

4.6.4.1 CO₂ emissions

The CO₂ emissions for the different scenarios are presented first, as climate change is one of the most pressing concerns. Figure 4-85 illustrates the total climate change impacts for the four scenarios. As shown in the figure, emissions from the use stage contribute significantly to the overall impact, whereas emissions from the renovation works are much lower. Furthermore, thanks to the improved insulation conditions applied in the three renovation scenarios, emissions during the use stage are significantly reduced due to lower operational energy consumption. In comparison, the increase in emissions resulting from the renovation works is almost negligible.

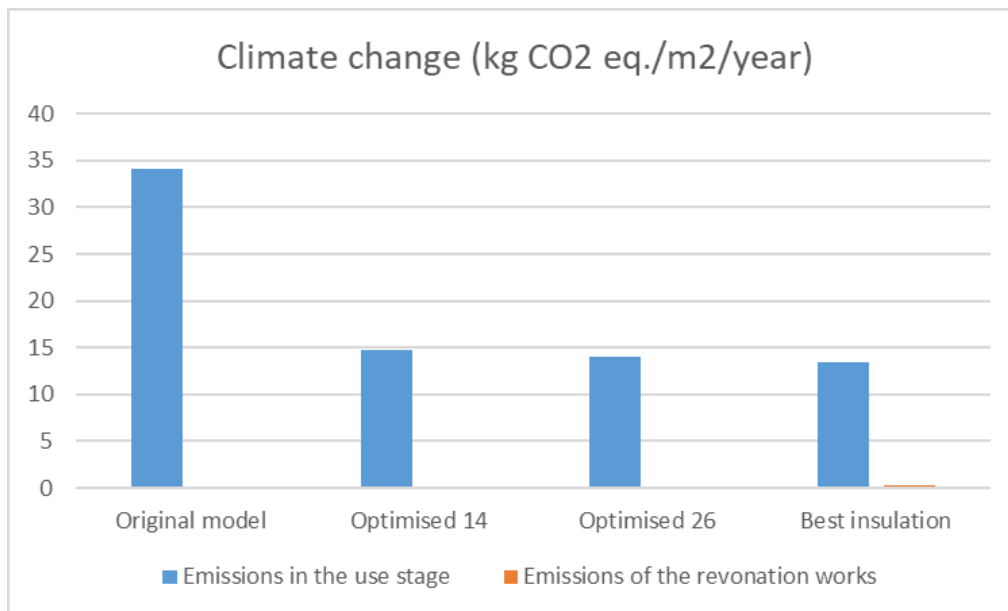


Figure 4-85: Total climate change impacts for the four scenarios.

Figure 4-86 provides a more detailed view of the emissions associated with the renovation works across the selected scenarios. It is clear that emissions from renovation increase in line with



improvements in insulation conditions. Although the deconstruction of old materials also increases slightly with increased insulation, it is consistently the construction of new materials that accounts for most of the renovation-related impacts. Specifically, the construction stage contributes 99.96 % of emissions under the Optimised 14 scenario and 96.02 % under the Best Insulation scenario.

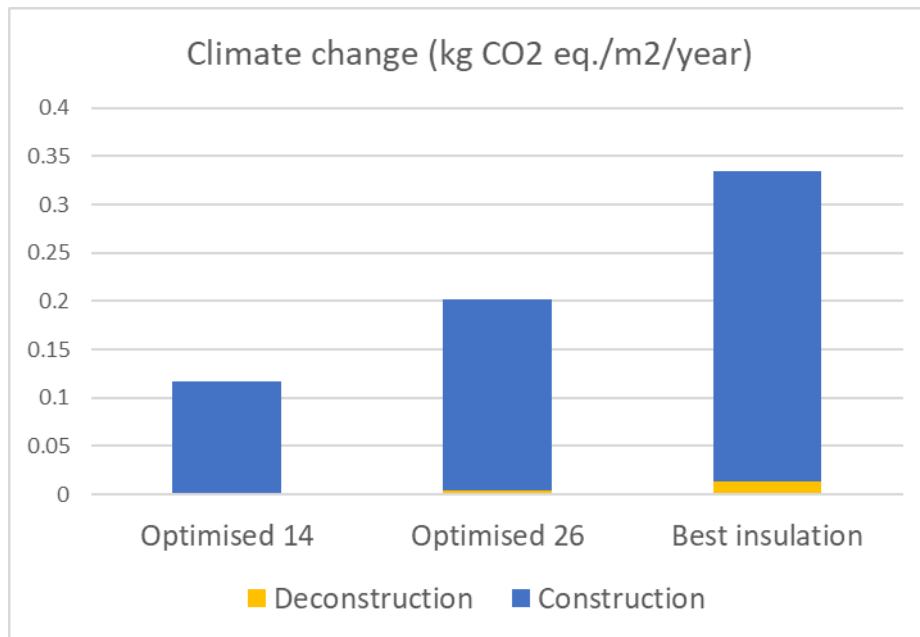


Figure 4-86: Climate change of renovation works across the three selected scenarios.

4.6.4.2 Impacts over the whole life cycle

Figure 4-87 presents a comparison of the total impacts across all indicators for the four scenarios. Each axis of the radar graph corresponds to an environmental indicator. The scenario without renovation is considered as a reference, and the three scenarios with renovation are expressed as relative values compared to the reference. For instance, the climate change indicator with renovation corresponds to around 40% of the reference value (without renovation), i.e. renovation reduces GhG emissions by around 60%.

As shown in the figure, the improved insulation conditions result in a reduction in total impacts for all three selected scenarios across nearly all indicators, with the exception of abiotic depletion potential. On average, the reductions are 28 % for Optimised 14 and Optimised 26, and 29 % for the Best insulation scenario. While the differences between the original model and the three insulated scenarios are substantial, the differences among the three insulated scenarios themselves are relatively minor. The Best Insulation scenario achieves an average reduction of 5 % in total impacts across all indicators compared to Optimised 14, and 2 % compared to Optimised 26. The abiotic



potential indicator increases with renovation due to the need of resources to produce new glazing and insulation, but this increase is very small compared to the reduction of e.g. GhG emissions.

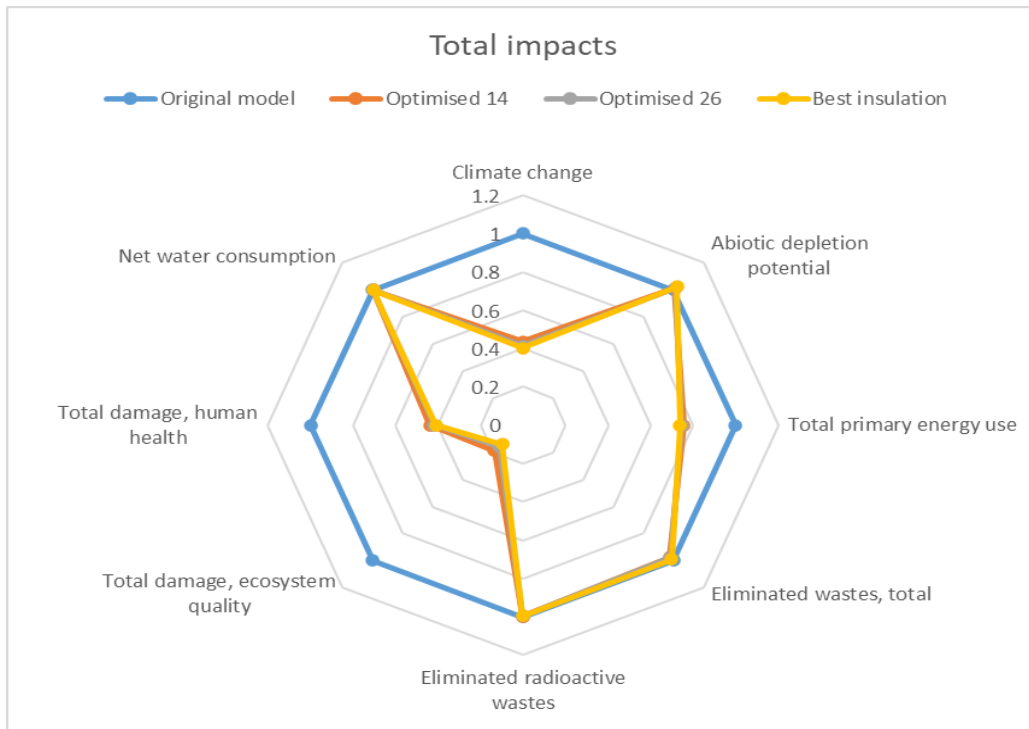


Figure 4-87: Comparison of total impacts for the four scenarios.

Regarding the contribution to total impacts across all indicators, taking the Optimised 14 scenario as an example, it can be observed that the use stage is the dominant contributor for all indicators, with an average share of 99 %.

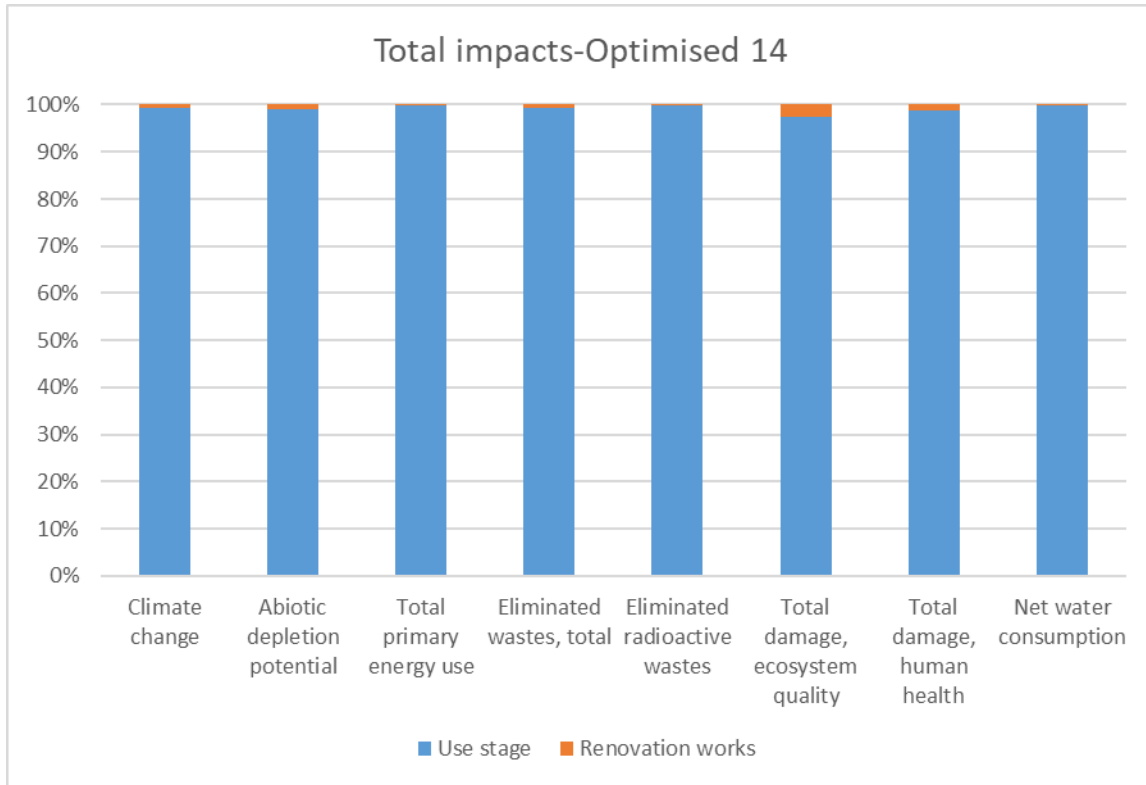


Figure 4-88: Contribution of total impacts for Optimised 14.

4.6.4.3 Impacts of the use stage

The impacts of the use stage for the four different scenarios are shown in Figure 4-89. As can be seen, due to the significant reduction in operational energy consumption—particularly for heating, as discussed in Section 4.4.3.3—the impacts during the use stage have been reduced across nearly all indicators, though to varying extents. On average, the reduction in impacts during the use stage is 28 % for Optimised 14, 29 % for Optimised 26, and 30 % for the Best Insulation scenario.

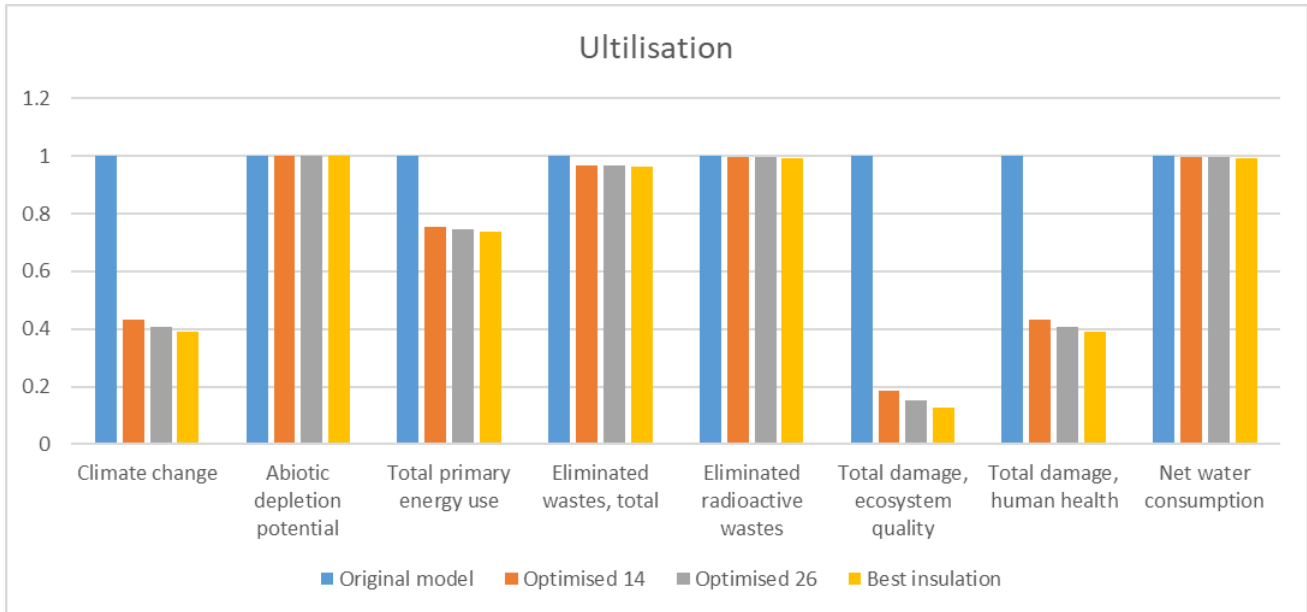


Figure 4-89: Impacts of the use stage.

4.6.4.4 Impacts of renovation works

Figures 4-90 to 4-92 illustrate the impacts of the renovation works for the three selected scenarios individually. Regardless of the scenario, the construction of new materials consistently accounts for the majority of renovation impacts across all indicators. Specifically, the share of impacts from the construction of new materials is 99.9 % for Optimised 14, 96.7 % for Optimised 26, and 93.7 % for the Best Insulation scenario. However, as the insulation conditions are improved, the proportion of impacts resulting from the deconstruction of old materials also appears to increase.

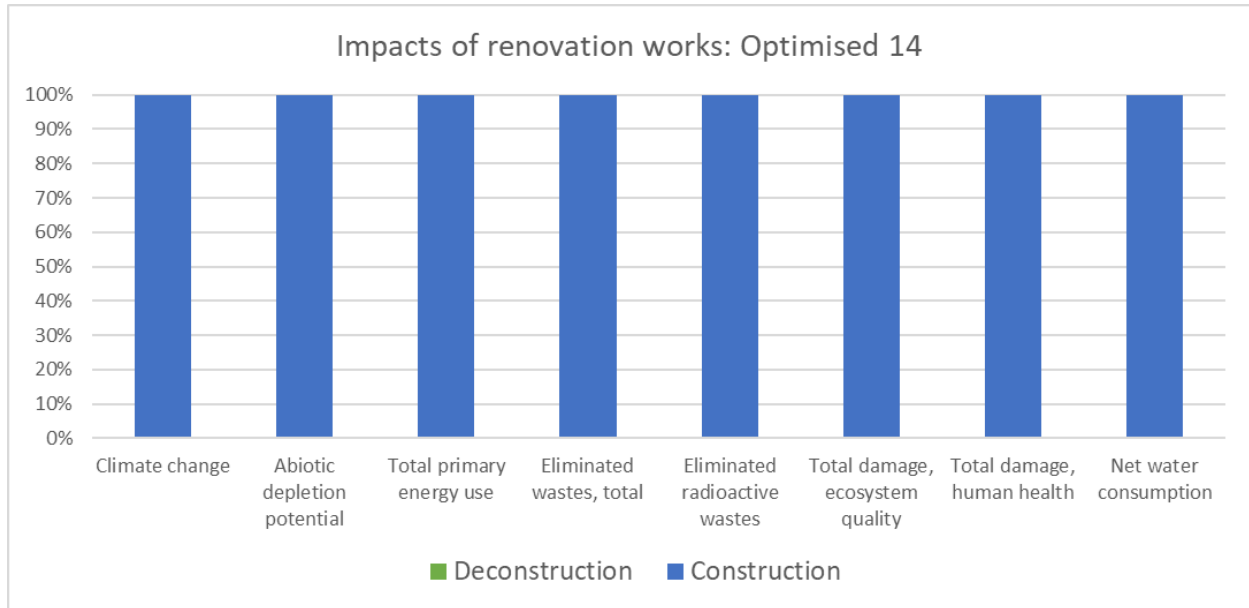


Figure 4-90: The share of impacts of renovation works for Optimised 14 scenario.

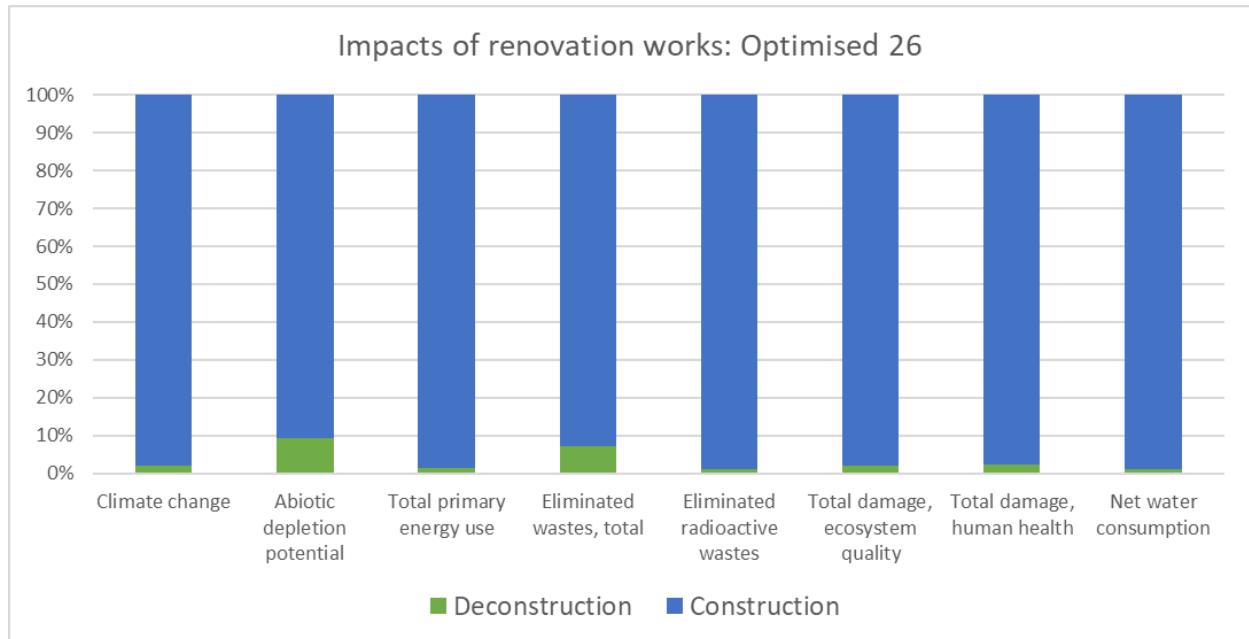


Figure 4-91: The share of impacts of renovation works for Optimised 26 scenario.

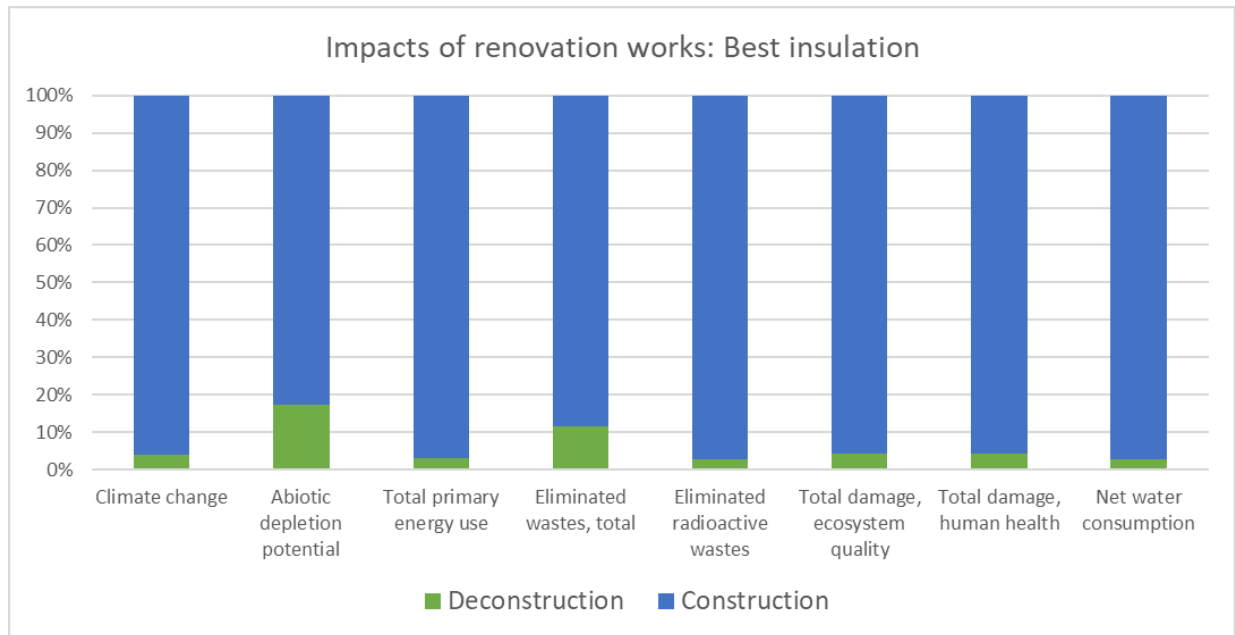


Figure 4-92: The share of impacts of renovation works for the Best Insulation scenario.

4.7 Comparison with decarbonation of the district heating network

It is planned to reduce the GhG emissions of heat generation by reducing the % of gas and implementing heat pumps and a geothermal system. The initial mix is 75% gas and 25% wood, leading to 230 g CO₂ eq./kWh heat including 10% losses in the district heating pipes and 10% in the distribution system. The planned future mix will be: 40% gas, 24% wood, 21% geothermal, 15% Heat pumps, leading to 150 g CO₂ eq./kWh heat (including the same losses).

The LCA of the building before and after renovation were performed again using this new district heating system, in order to compare different scenarios as shown in the graph below.

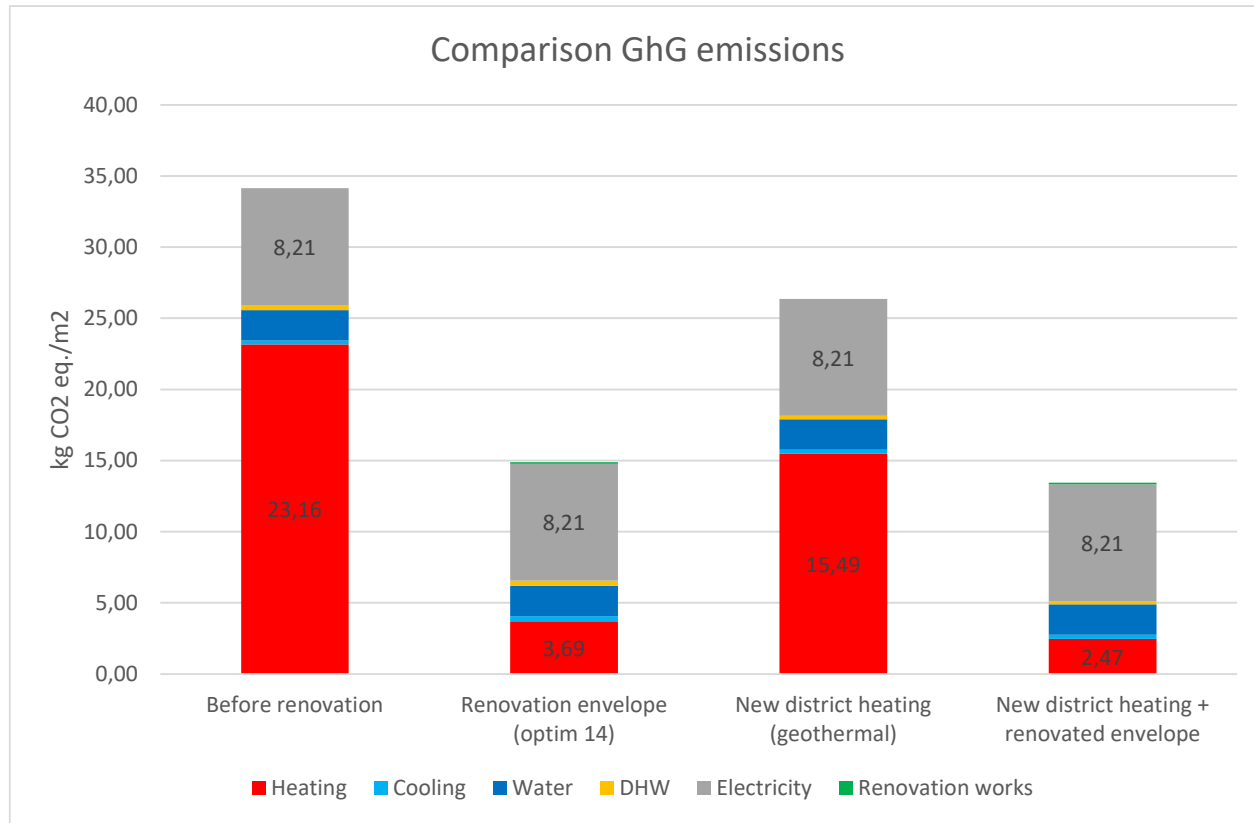


Figure 4-93: Comparison of scenarios for both envelope and district heating.

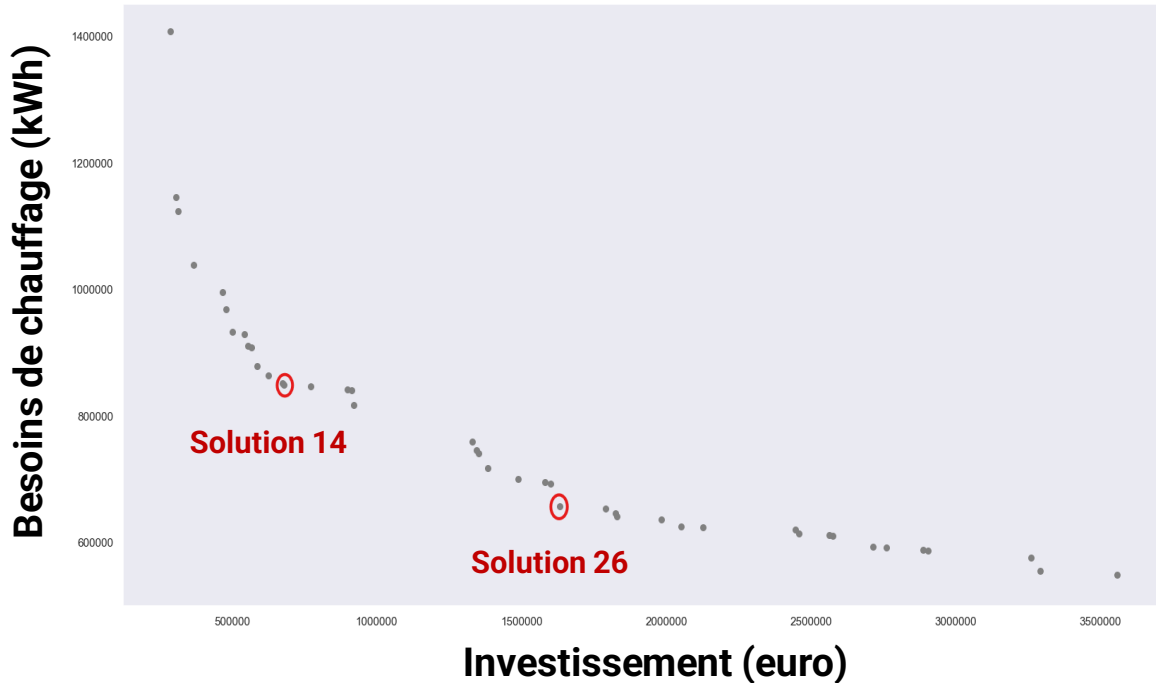
Renovating the envelope would allow a higher reduction of GhG emissions than modifying the district heating system. Improving both the performance of the envelope and the district heating system would not save much more GhG emissions than just renovating the envelope.

4.8 Meeting with decision makers

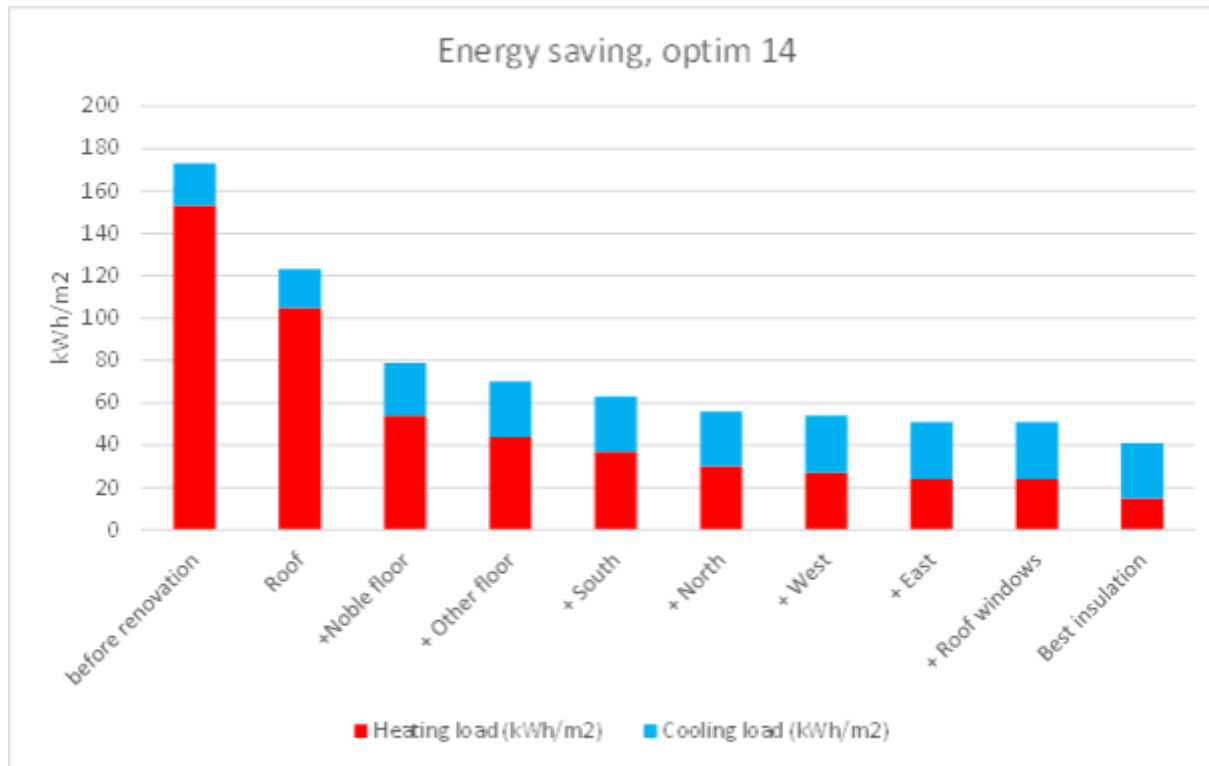
Optimisation led to various possible scenarios along a Pareto front, which were presented to decision makers. The Figure below shows possible optimised projects. Solution 14 focuses mainly on thermal insulation, while solution 26 integrates the replacement of the window associated with the insulation. Those two proposals could be considered as a minimum (solution 14) and a maximum (solution 26) thermal optimized project, avoiding both too weak performance and too high investment cost.



Front de Pareto



Some renovation measures may be difficult to realise because of practical reasons: some renovation works require closing a part of the airport, which is difficult to manage. It is therefore useful to analyse the effectiveness of each measure in order to help in the decision-making process. Simulation was performed, starting from the project before renovation and adding each measure one after the other. Additional results are shown on the next figure in the case of optimisation scenario n°14, also including the results of the best insulation case.



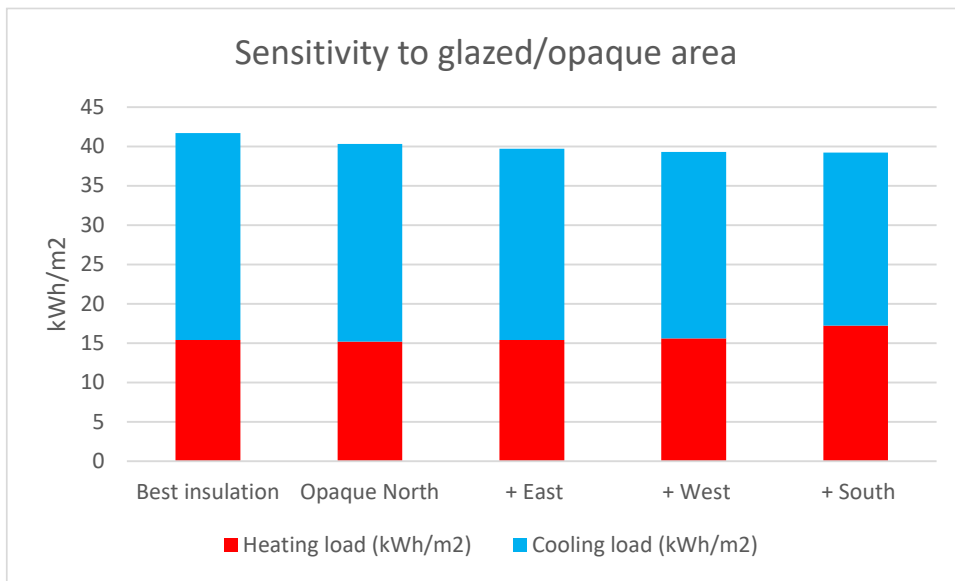
Insulating the roof reduces the heating load by one third, as well as insulating the floors of spaces occupied by passengers. Insulating other floors, façades, and replacing roof windows is less efficient.

The roof can be insulated in most parts (curved ceiling of technical spaces rather than horizontal roof) without disturbing the exploitation of the terminal, and this renovation measure is most efficient. It will therefore be prioritized if a renovation project can be planned. Insulating the floor is more problematic because a lot of networks are situated under the floor where the insulation layer would be placed. It can be acceptable only in some parts of the building. Insulating façades is less efficient and may generate an economic burden because work must be carried out in the restricted area under airside exploitation. It strategically should be done when conformity to regulations must be achieved or when some elements show damage, which begins to be the case at CDG. Wooden frame glazing could be preferable rather than aluminium in order to decrease the heat loss coefficient and reduce CO2 emissions. Free night extraction ventilative cooling could be tested in a small part of the building and be associated with free cooling regulation for the ventilation mechanical systems. Generalization could be foreseen if the results are satisfactory. Surrounding noise, indoor air quality and automation (manual opening is prohibited) are the specific points to be taken care of.

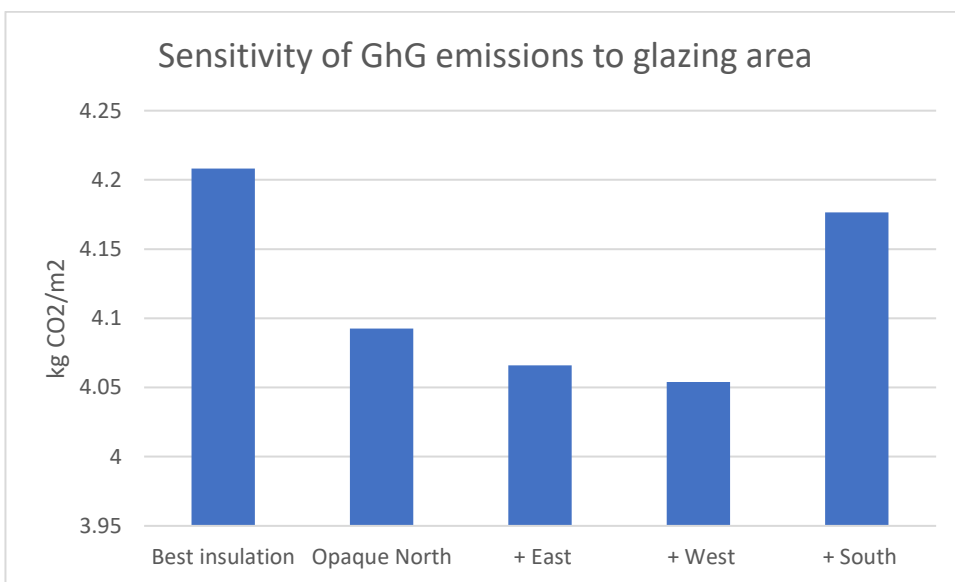
The meeting raised a new question, concerning the replacement of glazed surfaces with opaque surfaces depending on the orientation of the façades. New simulations were performed, starting with



the “best insulation” case (in which all transparent elements are triple glazed). The elements were replaced with opaque ones including 15 cm insulation, corresponding to a U value of 0.25 W/(m2.K) and a solar factor of 4%. North oriented glazing was first replaced, then also East, West, and South (i.e. all façades). The corresponding results are shown hereunder.



Opaque façades reduce the cooling load, but increase the heating load except for the North orientation. This is due to the reduction of solar gains. The overall variation remains small. The following graph shows that effects on heating and cooling may compensate when evaluating greenhouse gas emissions.





According to these results, corresponding to the new planned district heating system integrating geothermal energy, GhG emissions are reduced with opaque façades, except for South orientation because higher solar gains reduce the heating load and related emissions. The reduction is nevertheless only 4% when North, East and West façades are opaque compared to the “best insulation” case. It should also be noted that the GhG emissions are lower for the fabrication of opaque materials compared with glazing.

The optimization analysis has been applied only on the insulation and the cost of investment parameters. Other KPI could be evaluated if this approach would be implemented in refurbishment process by airport operators.

5 Prospects in terms of replication

This report was forwarded to our colleagues in charge of studying renovation projects in Zagreb and Cluj airports. Terminal buildings were modelled and it is possible to perform similar evaluations using thermal simulation, optimisation and life cycle assessment.

6 Conclusion and outlook

A methodology was developed to reduce GhG emissions of existing airport terminals by studying renovation projects. It consists of elaborating a building model, either following the BIM approach or a simplified modelling approach, performing thermal simulation, preferably calibrating the model using measured energy consumption data, implementing an optimisation algorithm to identify energy and cost-efficient renovation measures, and evaluating the environmental performance, and particularly the reduction of GhG emissions, using life cycle assessment.

The first test of this methodology on an ex-post case study (CDG Terminal 2B and BD link) showed the advantage of using AutoCAD format plans instead of BIM, both in terms of modelling efforts and computation time. Reducing the computation time by simplifying the geometry (e.g. reducing the level of detail and number of segments in the representation of rounded surfaces) and zoning (grouping rooms with the same use in larger zones) is essential in order to perform hundreds of simulation runs required by optimisation algorithms.



This return of experience benefited the ex-ante case study. The simplified methodology was used to elaborate a renovation project of CDG Terminal 2A. Results were presented to decision makers in order to study their relevance, particularly regarding the feasibility of renovating the envelope while the terminal is in use. Decarbonation of the district heating system by implementing a geothermal heat source and heat pumps was also studied.

Replication of this process will be studied in Zagreb and Cluj in order to check its relevance in various contexts.

7 References

Beaumont, M. A., Cornuet, J.-M., Marin, J.-M. et Robert, C. P., 2009. Adaptive approximate Bayesian computation. In : *Biometrika*. 1 décembre 2009. Vol. 96, n° 4, p. 983-990. DOI 10.1093/biomet/asp052.

Branke, J., Deb, K., Miettinen, K. et Slowinski, R., 2008. *Multiobjective optimization: Interactive and evolutionary approaches*. S.l. : Springer Science & Business Media.

Clarke, J. A. (2001). *Energy simulation in building design*. Butterworth-Heinemann.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W., Huang, Y., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J. et Glazer, J. (2001). EnergyPlus : creating a new-generation building energy simulation program. *Energy and Buildings*, 33(4):319–331.

Heo, Y., Choudhary, R. et Augenbroe, G. A., 2012. Calibration of building energy models for retrofit analysis under uncertainty. In : *Energy and Buildings*. avril 2012. Vol. 47, p. 550-560. DOI 10.1016/j.enbuild.2011.12.029.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M. et Nemecek, T., 2010. 3 : *Implementation of Life Cycle Impact Assessment Methods*. St Gallen, Switzerland. Ecoinvent.

Huijbregts M.A.J. et al., 2016. ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level - Report I : Characterization [en ligne]. Netherlands. National Institute for Public Health and the Environment. RIVM Report 2016-0104. Disponible à l'adresse : https://www.rivm.nl/en/Documents_and_publications/Scientific/Reports/2016/december/ReCiPe_2016_A_harmonized_life_cycle_impact_assessment_method_at_midpoint_and_endpoint_level_Report_I_Characterization.



IPCC, 2013. Anthropogenic and Natural Radiative Forcing. In : Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA : Cambridge University Press.

Kennedy, M. C. and O'Hagan, A., 2001. Bayesian calibration of computer models. In : Journal of the Royal Statistical Society: Series B (Statistical Methodology). août 2001. Vol. 63, n° 3, p. 425-464. DOI 10.1111/1467-9868.00294.

Knowles, J. et Corne, D., 2002. On metrics for comparing nondominated sets. In : Proceedings of the 2002 Congress on Evolutionary Computation. CEC'02 (Cat. No.02TH8600). S.l. : s.n. mai 2002. p. 711-716 vol.1.

Koellner, T. et Scholz, R. W., 2006. Assessment of land use impacts on the natural environment. In : The International Journal of Life Cycle Assessment. 9 décembre 2006. Vol. 13, n° 1, p. 32. DOI 10.1065/lca2006.12.292.2.

Morris, Max D. 1991. 'Factorial Sampling Plans for Preliminary Computational Experiments'. Technometrics 33 (April): 161-174. doi:10.2307/1269043.

Munaretto, F., Recht, T., Schalbart, P. and Peuportier, B., 2017. Empirical validation of different internal superficial heat transfer models on a full-scale passive house. Journal of Building Performance Simulation, doi: 10.1080/19401493.2017.1331376.

Oers, L. van et Guinée, J., 2016. The Abiotic Depletion Potential: Background, Updates, and Future. In : Resources. 2 mars 2016. Vol. 5, n° 1, p. 16. DOI 10.3390/resources5010016.

Palacios-Munoz B., Peuportier B., Gracia-Villa L., López-Mesad B., 2019. The importance of estimating lifespan in LCA of buildings: The case of refurbishment vs. new construction, Building and Environment, vol 160, <https://doi.org/10.1016/j.buildenv.2019.106203>

Peuportier, B. et Sommereux, I. B. (1990). Simulation tool with its expert interface for the thermal design of multizone buildings. International Journal of Sustainable Energy, 8(2):109-120.

Peuportier, B. Eco-design for buildings and neighbourhoods, Taylor & Francis Group, London, 286p, 2015

Polster, B., Peuportier, B., Blanc Sommereux, I., Diaz Pedregal, P., Gobin C. and Durand, E. Evaluation of the environmental quality of buildings - a step towards a more environmentally conscious design, Solar Energy vol. 57 n°3, pp 219-230, 1996



Recht T., Schalbart P., and Peuportier B., 2016. Ecodesign of a "plus energy" house using stochastic occupancy model, life cycle assessment and multi-objective optimisation, Hamza N and Underwood C. (Ed), Building Simulation & Optimization 2016, Newcastle

Seem, J. E. (1987). Modeling of Heat Transfer in Buildings. PhD thesis, University of Wisconsin, Madison.

Seppälä, J., Posch, M., Johannson, M. et Hettelingh, J.-P., 2006. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp). In : The International Journal of Life Cycle Assessment. 1 novembre 2006. Vol. 11, n° 6, p. 403-416. DOI 10.1065/lca2005.06.215.

Struijs, J., Beusen, A., Van Jaarsveld, H. A. et Huijbregts, M., 2009. Aquatic Eutrophication. Chapter 6 in : Giedkoop, M., Heijungs, R., Huijbregts, MAJ., De Schryver, A., Struijs, J., Van Zelm, R (2009). ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint level. Report I Characterisation factors, first edition.

Van Zelm, R., Huijbregts, M. A. J., Den Hollander, H. A., Van Jaarsveld, H. A., Sauter, F. J., Struijs, J., Van Wijnen, H. J. et Van De Meent, D., 2008. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. In : Atmospheric Environment. 1 janvier 2008. Vol. 42, n° 3, p. 441-453. DOI 10.1016/j.atmosenv.2007.09.072.

Wurtz A., Peuportier B., Application of the life cycle assessment to a building sample for in order to helping in projects evaluation, Climamed Conference, May 2021, Lisbonne (online), Portugal

