RETIME
Inclusive Urban Resilience



INFORMATION PACKAGE

Supporting whole-life decisions in building renovation

Carbon Layers: user guide, background, and case study

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Acronyms and abbreviations

AEC	Architecture, engineering, and construction
B4PICs	Built4People Innovation Clusters
BIM	Building information modelling
CAPEX	Capital expenditure (initial investment)
CEN	European Committee for Standardization
CO_2e	Carbon dioxide equivalent
ECTP	European Construction Technology Platform
EF	Elements/functions (Uniclass table)
EN	European Standard
EPBD	Energy Performance of Buildings Directive
EPD	Environmental product declaration
epJSON	EnergyPlus input file in JSON format
EPW	EnergyPlus weather file
ETICS	External thermal insulation composite system
EU	European Union
GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioning
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle cost
Ma	Materials (Uniclass table)
NPV	Net present value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
Pr	Products (Uniclass table)
SCOP	Seasonal coefficient of performance
SECClasS	Sustainability Enhanced Construction Classification System
SEER	Seasonal energy efficiency ratio
Ss	Systems (Uniclass table)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
U-value	Thermal transmittance ($W/m^2 \cdot K$)

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Glossary

Term	Definition
Whole-life carbon	Greenhouse gas emissions over the entire life cycle of a building or intervention, expressed as GWP in $kgCO_2e$.
GWP	Global warming potential: the climate change impact of emissions, expressed in kilograms of CO_2 equivalent.
Upfront carbon	Emissions associated with material production and construction, occurring before the building is in use.
B4, B6, C, D	Life cycle modules defined in EN 15978 (CEN, 2011): replacement (B4), operational energy use (B6), end of life (C), and benefits and loads beyond the system boundary (D).
Static and dynamic grid factors	A constant electricity emission factor, or one that decreases over time as the electricity grid decarbonises.
Life cycle cost (LCC)	All costs incurred over the study period (investment, energy, maintenance, and replacement), discounted to a net present value.
EPD	Environmental product declaration: third-party verified LCA data for a construction product, in accordance with EN 15804.
IFC	Industry Foundation Classes: the open data model for BIM (ISO 16739-1).
IDS	Information Delivery Specification: a buildingSMART standard that specifies, in a machine-readable form, the information an IFC model must contain.
Second-level space boundaries	IFC surfaces that subdivide each space boundary according to the adjacent element and space; they form the geometric basis of the energy model.
Uniclass 2015 / SECClasS	A construction classification system and its Portuguese adaptation, organised in tables including EF (elements and functions), Ss (systems), Pr (products), and Ma (materials).
epJSON	The JSON-based input format of EnergyPlus.
Ideal loads	A simulation mode in which ideal heating and cooling maintain the setpoints, used to determine energy demand.
Free-floating	A simulation mode without heating or cooling, used to assess the intrinsic thermal behaviour of the building.
Temperature exposure	Degree-hours outside the 20–26 °C range in a free-floating simulation, weighted by the magnitude of the deviation and expressed in °C·zone-h.
Renovation measure	A single intervention on one element function, stored as a set of actions on the existing layers.
Renovation scenario	A whole-building combination of one measure, or retention of the existing construction, per element group.
Baseline	The existing building, assessed with the same rules as every scenario.
NSGA-II	Non-dominated Sorting Genetic Algorithm II: an evolutionary algorithm for multi-objective optimisation that evolves a population of scenarios towards the Pareto front (Deb et al., 2002).
Pareto front	The set of non-dominated scenarios, in which no objective can be improved without the deterioration of another.
Hypervolume	An indicator of the convergence and spread of a set of trade-off solutions; higher values indicate a better approximation of the Pareto front (Zitzler & Thiele, 1999).
K-means	A clustering method that groups similar scenarios, from which one representative per cluster is retained (MacQueen, 1967).
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution: a multi-criteria method that ranks alternatives by their distance to an ideal and negative-ideal solution under user-defined weights (Hwang & Yoon, 1981).
SCOP / SEER	Seasonal coefficient of performance and seasonal energy efficiency ratio of a heat pump in heating and cooling, respectively.
ETICS	External thermal insulation composite system: thermal insulation fixed to the external face of a wall and finished with a render.

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1. Information package overview

This information package describes how Carbon Layers transform a classified Industry Foundation Classes (IFC) model of an existing building into a ranked set of renovation strategies. These strategies are evaluated in terms of whole-life carbon, life cycle cost, energy use, and indoor temperature. The information package combines a user guide, the conceptual background of the method, and a case study with practical exercises, followed by a single list of references.

1.1. Research context

Since the majority of the buildings that will be in use across Europe by 2050 already exist, renovating the existing building stock is essential to achieving the decarbonisation targets set out in the Renovation Wave Strategy and the recast Energy Performance of Buildings Directive (European Commission, 2020; Directive (EU) 2024/1275, 2024). Renovation is also a climate adaptation measure: more frequent heat waves and cold spells expose the occupants of poorly insulated dwellings to indoor temperatures outside the comfort range. Decisions on renovation therefore have to weigh the energy savings of each measure against the embodied carbon of the new materials, the cost over the life cycle, and the resulting indoor thermal conditions.

Building information modelling (BIM) can supply much of the information these assessments require. In practice, however, the link between BIM objects and life cycle data is still established mostly by hand, and few studies address renovation (Parece et al., 2025a). Life cycle assessment is carried out mainly for certification, once the design is complete, rather than to inform design decisions (Parece et al., 2025c), and the integration of BIM and life cycle assessment still faces technical and organisational barriers (Parece et al., 2025b).

This information package results from research carried out at ISTAR-Iscte (Information Science, Technology and Architecture Research Centre), Instituto Universitário de Lisboa (ISCTE-IUL), within the RETIME project. RETIME (Urban Adaptation and Alert Solutions for a TIMEly (re)Action) is a Horizon Europe Innovation Action funded under the call HORIZON-CL5-2023-D4-02 (topic HORIZON-CL5-2023-D4-02-02), grant agreement 101147113 (European Commission, 2024). Coordinated by ISTAR-Iscte, the project runs for 48 months, from 1 May 2024 to 30 April 2028, and involves 18 partners with a total budget of €5,475,761 (Figure 1). It develops four digital solutions shown in Figure 2, which are tested in pilot areas in Portugal, Slovakia, and Estonia (https://retime-project.eu).

RETIME

Project Coordinator

iscte — Conhecimento e Inovação

istar — iscte
Information Sciences, Technologies and Architecture Research Centre

Horizon Europe
Efficient, sustainable and inclusive energy use (HORIZON-CL5-2023-D4-02)

Total Budget: €5,475,761

18 partners

48 months
Start date: 1 May 2024
End date: 30 April 2028

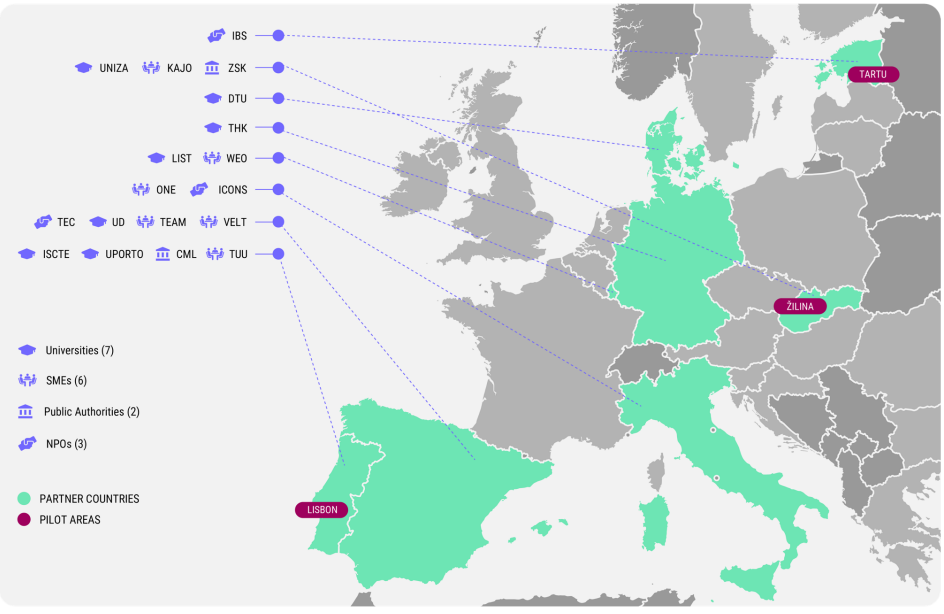


Figure 1. Overview of RETIME: timeline, pilot sites, and consortium.

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The research addresses the use of digital building information to assess the environmental, economic, and thermal performance of existing buildings, and to support renovation choices that reduce whole-life carbon while improving indoor conditions. Within this research, *Carbon Layers* was developed as an open access web application that connects a classified IFC model with energy simulation, life cycle assessment, and life cycle costing, and ranks renovation scenarios according to the priorities of the stakeholders. The building-level assessment complements the digital solutions developed in RETIME, namely the digital building twin and the digital building renovation passport (Figure 2).

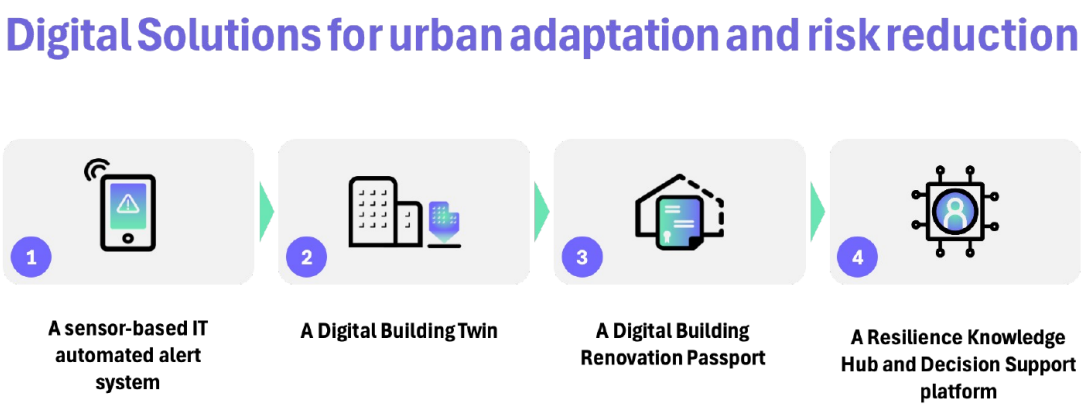


Figure 2. The four digital solutions developed by RETIME for urban adaptation and risk reduction.

1.2. Intended audience

This information package is intended for:

- Architects and engineers who assess renovation options for existing buildings
- Building information modelling (BIM) coordinators who prepare IFC models for energy and carbon assessment
- Students and educators in courses on BIM, life cycle assessment (LCA), and building energy simulation
- Public housing authorities and social housing providers
- Public energy agencies and climate action offices
- European Construction Technology Platform (ECTP)
- Built4People Innovation Clusters (B4PICs)

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1.3. Structure of the information package

Table 1 summarises the structure of this information package.

Table 1. Structure of the information package.

Part	Content	Purpose
1. Information package overview	Research context, structure, and intended audience	To present the research context, the aims, and the intended audience
2. User guide	Purpose and novelty of the application, preparation of the IFC model, the eight-step workflow, the life cycle assessment and life cycle cost settings, and troubleshooting and current limitations	To prepare a model and conduct an assessment
3. Background	Rationale for whole-life decisions in renovation, and standards and policy framework	To clarify terminology and support further study
4. Application to a real-case study	A multi-family residential building in Alvalade, Lisbon, with six exercises, their solutions, and a self-assessment matrix	To apply the reasoning underlying each step
References	Standards, legislation, scientific publications, data sources, and software cited in the text	To situate the work in its research context and to support further study

2. User guide

2.1. Purpose and scope of the application

Carbon Layers is an open access web application for the assessment of building renovation options (Figure 3). Based on an IFC model, it generates a thermal model for EnergyPlus (U.S. Department of Energy, 2025) and runs dynamic simulations of the existing building and of each renovation scenario. Two types of simulation are performed: an ideal loads simulation, which calculates the annual heating and cooling demand required to maintain the setpoints, and a free-floating simulation, without heating or cooling, which calculates the indoor air temperature of each thermal zone. The application does not assess structural behaviour. On this basis, it compares renovation scenarios in terms of energy use, whole-life carbon (LCA), whole-life cost (LCC), and thermal exposure. It can also identify the most favourable combinations of measures through multi-objective optimisation with NSGA-II (Deb et al., 2002) and rank them with the multi-criteria method TOPSIS (Hwang & Yoon, 1981).

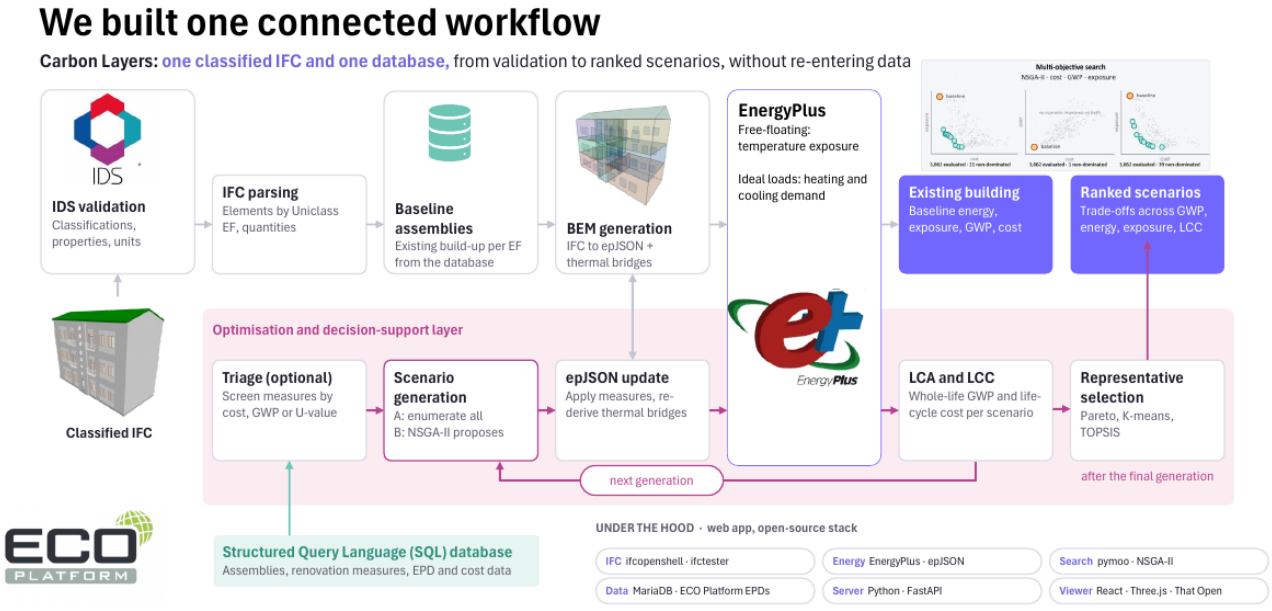


Figure 3. Overview of the workflow, from the classified IFC model to ranked renovation scenarios.

2.2. Novelty of this application

Carbon Layers builds on an earlier tool for embodied carbon assessment based on a construction classification system (Parece et al., 2024). Compared with the BIM-based assessment tools identified in the literature (Parece et al., 2025a), it introduces five features:

- *Automated link between model and data.* Building elements are matched to existing constructions, renovation measures, costs, and life cycle data through their classification codes (Uniclass 2015 and SECClasS), rather than by manual mapping.
- *Renovation measures as actions on existing layers.* Each measure is stored as a set of actions (removal, addition, or retention of layers) rather than as a finished construction, so that one measure can be applied to every compatible existing construction. In the case study, 130 stored measures yield 1,451 options (*Section 4*).
- *Energy model generated from the IFC model.* After the information requirements are verified with IDS, the thermal model is derived from the second-level space boundaries of the IFC model, so that operational energy is simulated dynamically rather than estimated.
- *Comfort assessed together with carbon and cost.* Thermal exposure in free-floating conditions is assessed alongside whole-life carbon and whole-life cost, so that renovation is also evaluated as a climate adaptation measure.
- *Transparent trade-offs.* Multi-objective optimisation identifies the Pareto-optimal scenarios, and TOPSIS ranks them with weights that can be changed without new simulations, which supports the discussion among stakeholders with different priorities.

2.3. Industry Foundation Classes model

Reliable results require an IFC file that meets the following conditions:

- *Building elements are classified with Uniclass codes* (Elements/Functions table, for example EF_25_10_25 for external walls). Classification is the mechanism through which the application links each wall, slab, roof, and window to the construction solutions stored in the database. Unclassified elements are reported as warnings and cannot be assigned a construction.
- *Geometry is closed and consistent* for walls, slabs, roofs, windows, and doors.
- *IfcSpace objects* are present whenever Route A (space-based model generation) is to be used.

Optional shading elements are identified by their codes: balconies (EF_30_20.B), shading walls (EF_25_10_25.B) and perforated screens (EF_25_10_25.S).

Upon upload, the model is checked against an Information Delivery Specification (IDS), and a requirements report is presented. This report is informative and does not interrupt the workflow.

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2.4. Workflow

Each project follows an eight-step sequence (Table 2). A progress bar indicates the current step, and any completed step may be revisited.

Table 2. The eight steps of the workflow.

Step	Content (or Aim)	Description
Step 1	Upload IFC	Loading and analysis of the BIM model
Step 2	Baselines	Selection of the existing construction of each building element type
Step 3	Generate Model	Generation of the EnergyPlus thermal model
Step 4	Simulate Baseline	Simulation of the existing building in EnergyPlus environment
Step 5	Baseline Results	Energy and carbon performance of the existing building
Step 6	Retrofit Options	Screening of renovation options per building element
Step 7	Scenarios	Combination and simulation of renovation scenarios, or optimisation
Step 8	Comparison	Review of payback, carbon, and life cycle indicators across scenarios

Step 1. Upload the Industry Foundation Classes file

1. A project is created in Projects, or an existing project is opened.
2. The .ifc file is dragged into the upload area or selected from the file system.
3. The model is analysed automatically: elements are grouped by Uniclass code and the building is displayed in the 3D viewer. Selecting an element in the viewer displays its IFC properties.

Step 2. Baselines

The IDS and Baseline Selection window presents the IDS report, the number of element groups and elements, and any unclassified elements (Figure 4).

1. For each element group (for example, external walls, roof, ground floor, and windows), the user selects the construction solution that best represents the existing building. The layer composition, U-value, global warming potential (GWP), and cost of the selected solution are displayed.
2. The user selects the Route for thermal model generation. Route B, boundary-based (recommended and default), derives the thermal model from the space boundaries of the building elements. Route A, space-based, derives it from IfcSpace volumes.
3. The user clicks Confirm Selections to save the baseline constructions and the route chosen for each element group; the application then proceeds to step 3.

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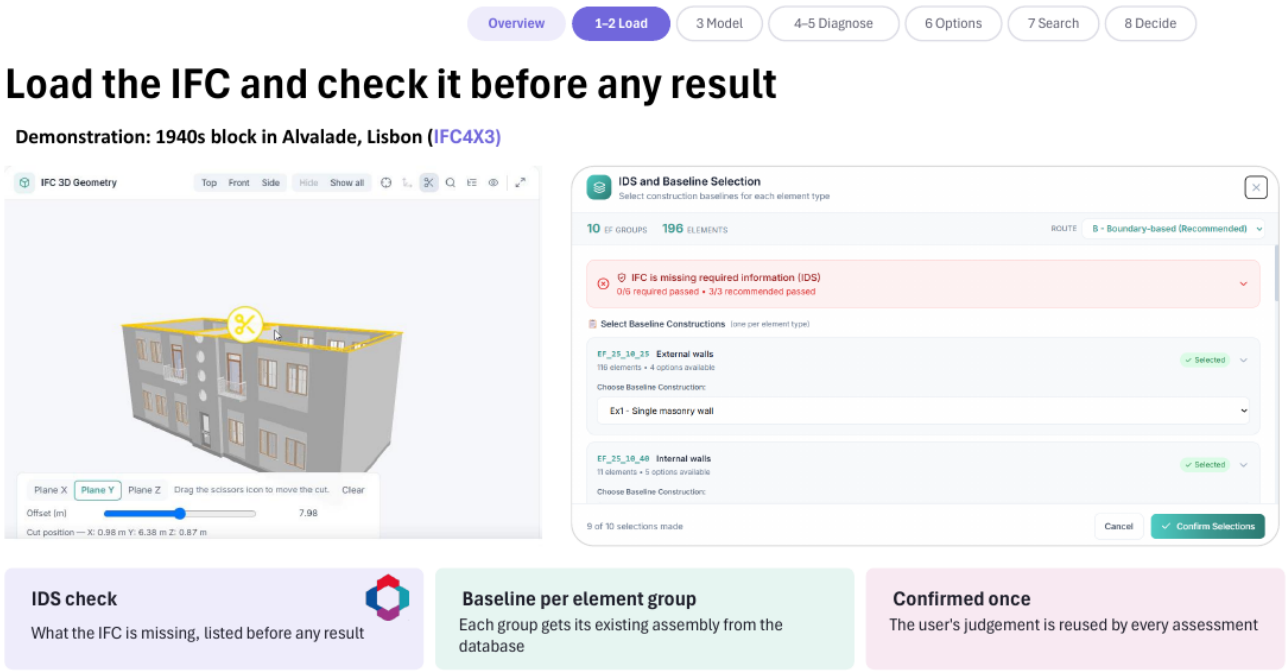


Figure 4. Steps 1 and 2: the IDS report and the baseline construction of each element group.

Step 3. Generate Model

The EnergyPlus model (epJSON) is generated automatically once step 2 is completed. The viewer displays the resulting thermal zones and surfaces, allowing the geometry to be verified (Figure 5).

The model assumptions can be reviewed or modified under Simulation settings before the simulation is run:

- *Simulation Control*: weather file (EPW), timesteps per hour, and run period.
- *Thermostat Settings*: heating and cooling setpoints.
- *Occupancy*, Internal Gains (lighting and equipment), and Schedules (editable profiles).
- *Infiltration* and Ventilation, including natural ventilation and inter-zone air mixing.
- *Envelope & Thermal Bridges*: linear thermal transmittance values.
- *Solar Shading*: external shutters.
- *Ground Temperatures* and Design Days (sizing of heating, ventilation, and air-conditioning systems).

Applying new settings regenerates the model.

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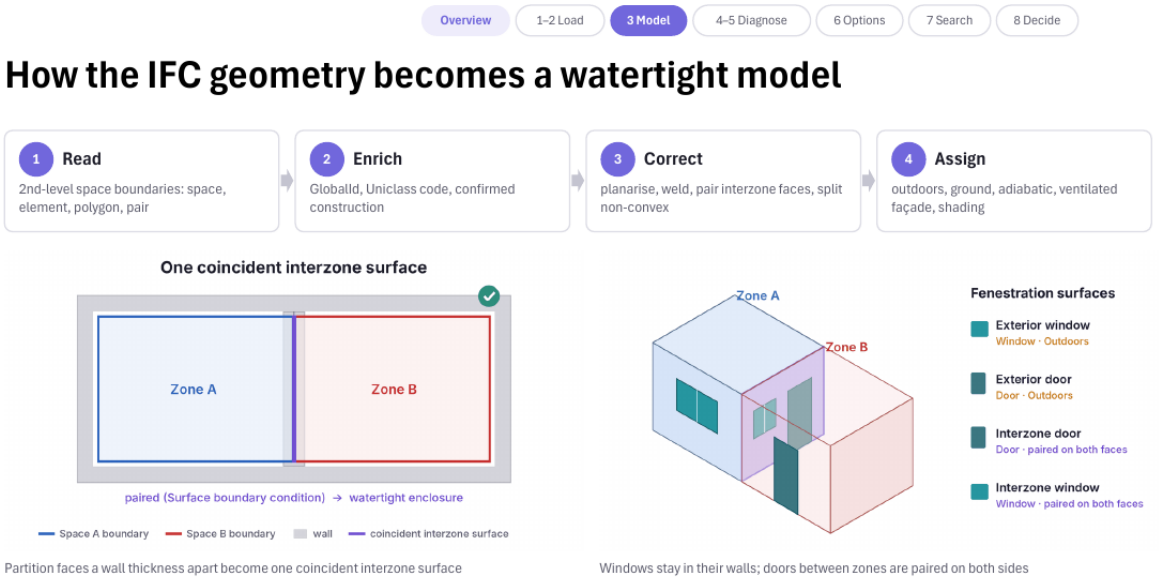


Figure 5. Step 3, Route B: conversion of the space boundaries into a closed thermal model.

Step 4. Simulate Baseline

The simulation of the existing building is launched with Run Simulation, and a progress indicator displays the elapsed time. The duration depends on the size of the model and the number of timesteps, and ranges from less than one minute to several minutes.

Save Baseline to Project stores the model and its results, so that they can be retrieved later without repeating the analysis.

Step 5. Baseline Results

A dashboard presents the performance of the existing building:

- Heating and cooling demand and energy use intensity (kWh/m²·yr).
- Results by thermal zone and by month.
- Operational and embodied carbon.
- Materials and constructions used in the model.

Heating and cooling demand is converted into delivered electricity using the seasonal coefficient of performance (SCOP) and the seasonal energy efficiency ratio (SEER) defined in the life cycle assessment and life cycle cost settings (*Section 2.5*).

Step 6. Retrofit Options

The Retrofit pre-screening screen lists, for each element group, the renovation options available in the database, together with their U-value, cost (€/m²), and embodied carbon (kgCO_2e/m²), compared with the baseline (Figure 6).

- *Show*: all options, or only the five, ten, or twenty best options per element.
- *Rank by*: Pareto ranking with equal weights, Pareto ranking with user-defined weights for U-value, cost, and CO_2e, or a single criterion (U-value, cost, or CO_2e).
- *Ignore shading (.B/.S)*: excludes balconies, shading walls, and screens, which do not form part of the renovatable envelope.
- *Re-run triage*: recalculates all options from the database, which is required after the material data are updated.

The options selected for each element define the search space for step 7.

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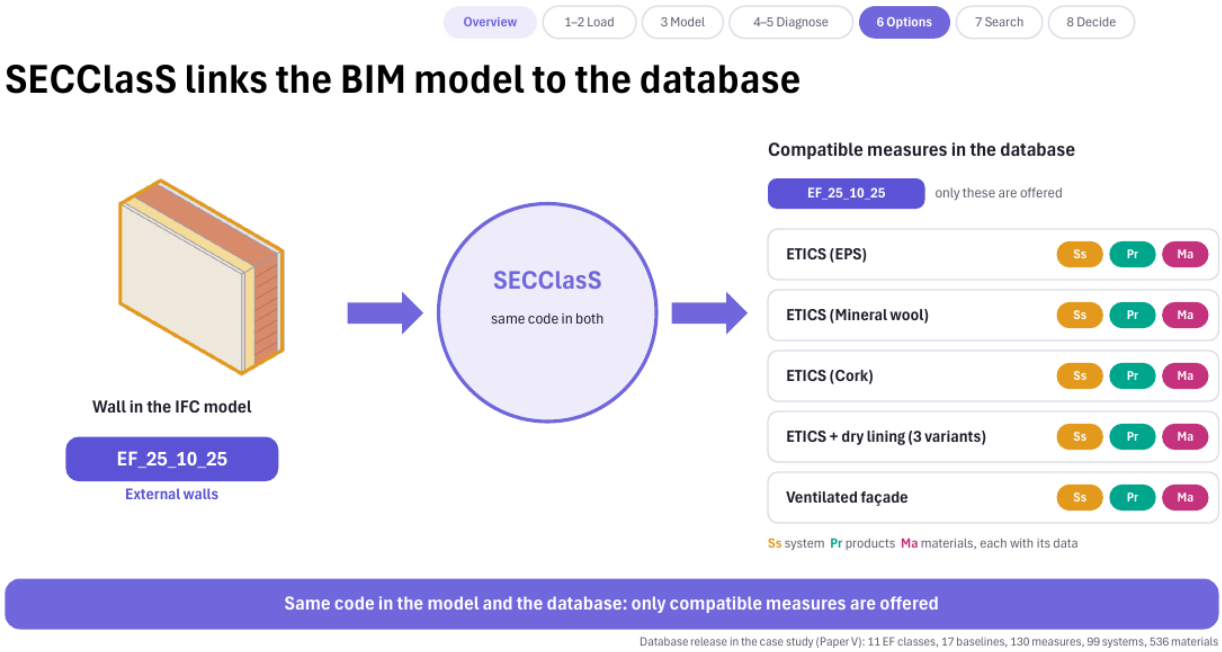


Figure 6. Step 6: the same Uniclass code in the model and in the database ensures that only compatible measures are offered.

Step 7. Scenarios

The selected options are combined, and the resulting renovation scenarios are simulated. The optimisation panel operates in two independent stages.

1. Objectives to optimise, which define the Pareto front. The default objectives are whole-life carbon (LCA), whole-life cost (LCC, €), and thermal exposure (hours outside the setpoints). Additional objectives include initial investment (CAPEX), embodied carbon, operational carbon, and discounted payback. The panel issues a warning when two selected objectives would account for the same quantity twice.

2. TOPSIS ranking weights, which rank the Pareto-optimal solutions to identify the preferred trade-off. The weights do not affect which solutions are found; once a run is complete, they can be adjusted to re-rank the results immediately, without further simulation.

Run parameters:

- *Timesteps/h* (1 to 6, where 4 offers a suitable balance between accuracy and computation time) and Months simulated.
- *Require a measure on every element*: each scenario must include a measure for every element group.
- *Reuse scenarios from the last completed run*: only new or modified combinations are simulated.
- *Delete raw outputs after extraction*: recommended for very large runs to save disk space.
- When the number of combinations is small, all combinations are simulated (enumeration). Otherwise, NSGA-II samples the search space: the user defines Population and Generations, or keeps Auto-tune from combinations active. The Pareto front may optionally be clustered with K-means (Cluster the Pareto front (K-Means)) before ranking.

The panel indicates the total number of combinations and the number to be simulated. The run is launched with Run Optimization, and its progress is displayed.

Results are presented as a ranked table (TOPSIS score, measures, LCC, thermal energy use intensity, thermal exposure, and payback) and as trade-off charts (two-dimensional, three-dimensional, and parallel coordinates) that highlight the baseline, the Pareto-optimal solutions, and the recommended solution. Results can be exported with Export CSV (Excel) or Export CSV (article), and View details opens the full report of any scenario.

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Step 8. Comparison

Once the optimisation has produced results, Continue to Comparison opens a decision-oriented view comprising:

- A recommended choice and its key indicators.
- Charts of trade-offs, carbon over time, economic indicators (cumulative cost, payback, and net present value), energy, cost-optimal analysis, drivers, and robustness.
- A scenario comparison table reporting, for each scenario, the TOPSIS score, investment (CAPEX), whole-life cost (LCC, ISO 15686-5), payback, net present value of energy savings, whole-life carbon, carbon saved, energy, comfort, and construction and demolition waste.

The baseline is always presented as the reference row.

2.5. Life cycle assessment and life cycle cost settings

Life cycle assumptions are held in a single global settings store, which can be edited from the Settings page, the baseline dashboard, the optimisation panel, or the Comparison screen; any change applies throughout the application. Since results are recalculated directly, changing these settings does not require new simulations. The settings are grouped as shown in Table 3.

Table 3. Life cycle assessment and life cycle cost settings.

Group	Parameters
Energy supply	Electricity tariff (€/kWh), heating SCOP, and cooling SEER
Carbon	Grid emission factor ($kgCO_2/kWh$), start year, and study period (years)
Economics	Discount rate, inflation, energy price escalation, maintenance (as a fraction of CAPEX) and its escalation, replacement cost escalation, end-of-life cost and its escalation, and repair of retained elements ($€/m^2 \cdot yr$)
Timing	Construction period (years)
Optimisation	NSGA-II random seed, to ensure reproducible runs

Carbon accounting. Whole-life carbon follows modules A to C of EN 15804+A2 (CEN, 2019), including replacements (B4) over the study period. Module D (benefits and loads beyond the system boundary) is reported separately and excluded from the headline value. Generic life cycle data are taken from ÖKOBAUDAT (Federal Ministry for Housing, Urban Development and Building, 2026), and product-specific environmental product declarations from the ECO Platform (ECO Platform, 2026) can be applied as reversible overlays.

2.6. Projects, database, and settings pages

- *Dashboard:* overview of recent projects and direct upload.
- *Projects:* creation, opening, and deletion of projects. Saved projects retain the IFC model, the baseline selections, the thermal model, and the results.
- *Materials:* consultation of the materials database by category.
- *Database Management:* consultation of construction solutions and renovation options, including their layers, GWP, and costs; search for environmental product declarations (EPDs) on ECO Platform and overlay of their GWP values.
- *Settings:* global life cycle assessment and life cycle cost settings (*Section 2.5*).

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2.7. Troubleshooting and current limitations

Common problems, causes, and potential solutions are shown in Table 4, while Table 5 summarises the current limitations of the application and their implications for the user.

Table 4. Common problems and solutions.

Problem	Probable cause and solution
Numerous “unclassified elements”	The IFC elements lack a Uniclass EF_ classification. The classification should be added in the authoring tool and the model exported again.
Missing or floating surfaces in the model	The IFC geometry should be verified, and Route B is preferred. Route A requires complete IfcSpace objects.
Excessive optimisation time	The number of options per element in step 6, the number of timesteps, or the number of simulated months should be reduced. Large runs may take several hours.
Payback not displayed	The baseline simulation (step 4) must be run before the optimisation, so that the baseline energy use is available.

Table 5. Current limitations of the application.

Limitation	Implication for the user
IFC and data quality	Results depend on the quality of the IFC model and of the data in the materials database. The IDS report verifies data, not the closure of thermal zones; a visual inspection of the model therefore remains necessary.
Simplified systems	Systems are represented by seasonal efficiencies (SCOP, SEER) rather than detailed models; thermal bridges are represented by linear thermal transmittances.
Single impact category	Only GWP is assessed; other impact categories are not yet considered, so burden shifting cannot be detected.
Manually curated data	Constructions, measures, service lives, and costs require expert maintenance, and EPDs are not yet consistently available in machine-readable form.
No calibration	The energy model has not yet been calibrated against measured consumption.

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3. Background

3.1. Why whole-life decisions in renovation

Renovation decisions require a whole-life perspective that weighs the operational savings of a measure against the embodied impacts it introduces, its cost, and its effect on comfort. Embodied carbon is emitted at the outset, and its relative weight increases as buildings become more efficient (World Green Building Council, 2019). Figures 7 to 12 summarise this rationale and the current state of BIM-based assessment tools, as reported in a systematic review of 115 studies published between 2019 and 2024 and indexed in Scopus and Web of Science (Parece et al., 2025a) and in a survey of 62 practitioners (Parece et al., 2025c).

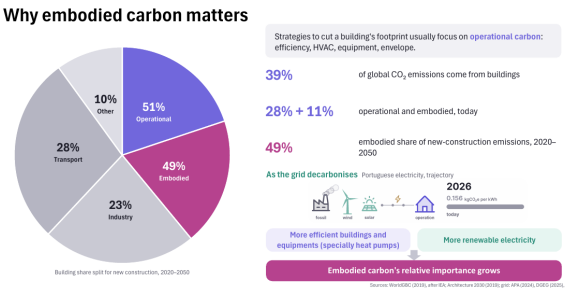


Figure 7. The relative weight of embodied carbon increases as buildings become more efficient and the electricity grid decarbonises.

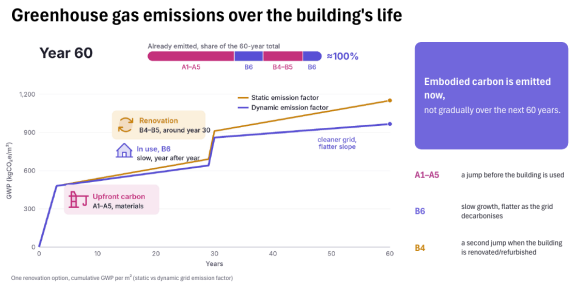


Figure 8. Upfront carbon is emitted at the outset, not distributed over the study period.

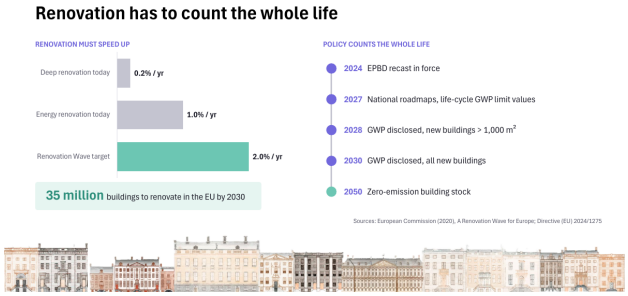


Figure 9. The Renovation Wave and the recast Energy Performance of Buildings Directive.

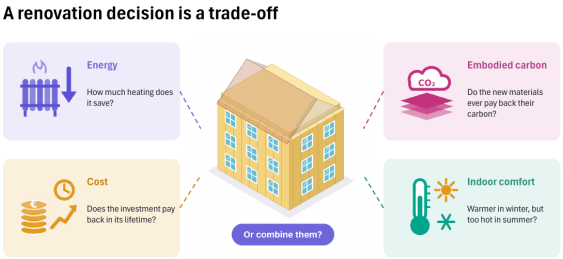


Figure 10. A renovation decision as a trade-off between energy, carbon, cost, and comfort.

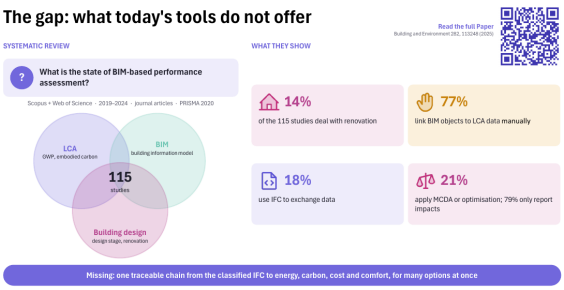


Figure 11. Systematic review of BIM-based performance assessment (115 studies, 2019–2024).

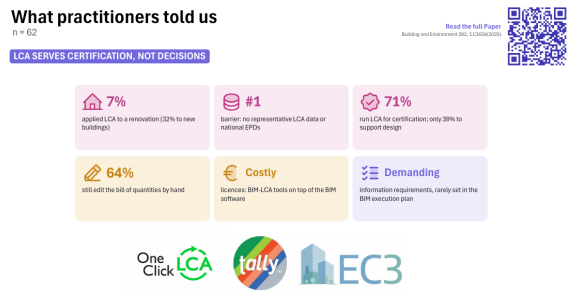


Figure 12. Findings from a survey of 62 practitioners.

3.2. Standards and policy framework

The method and the application draw on the following standards and policy documents:

- *EN 15978* (CEN, 2011): assessment of the environmental performance of buildings (life cycle modules A to D).
- *EN 15804+A2* (CEN, 2019): core rules for environmental product declarations of construction products.
- *ISO 14040 and ISO 14044* (ISO, 2006a, 2006b): principles, framework, and requirements of life cycle assessment.
- *ISO 16739-1* (ISO, 2024): Industry Foundation Classes.
- *Information Delivery Specification 1.0* (buildingSMART International, 2024): machine-readable information requirements for IFC models.
- *Directive (EU) 2024/1275* on the energy performance of buildings (recast), which requires the disclosure of the life cycle global warming potential of new buildings (Directive (EU) 2024/1275, 2024).
- *A Renovation Wave for Europe*, the strategy of the European Commission to at least double the annual energy renovation rate of buildings by 2030 (European Commission, 2020).
- *Uniclass 2015* (NBS, n.d.) and its Portuguese adaptation *SECClasS* (SECClasS, 2021; Salvado et al., 2021): construction classification systems.

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4. Case study

4.1. Selection and description of the building

The case study is a multi-family residential building with load-bearing masonry walls, built in the 1940s in the Alvalade district, 1700 Lisbon, Portugal (38.747° N, 9.136° W). It was modelled in Revit and exported in IFC4X3. Given the low level of detail of the model, in which the existing layers are not described, the existing construction of each element group is obtained from the database.

The building was selected purposively rather than at random, for three reasons. First, it represents a large group of buildings. Alvalade was planned by Faria da Costa between 1940 and 1945 for about 45,000 inhabitants on 230 ha and was built from 1947, on the basis of a small number of standard housing models repeated across its eight residential cells (Câmara Municipal de Lisboa, n.d.; Di Salvatore, 2016). One building therefore stands for many buildings of the same type in the district.

Second, it combines features common to multi-family housing built in Portugal before the first thermal regulation for buildings came into force in 1990 (Decreto-Lei n.º 40/90, 1990): uninsulated masonry walls with stone façades, an unheated stairwell, party walls shared with the adjacent buildings, and an unheated attic. These features define the element groups considered for renovation, namely the external walls, the stairwell walls, the internal walls adjacent to unheated spaces, the windows, and the ceiling below the attic.

Third, the renovation of such buildings involves the trade-offs that the application is designed to address: insulation reduces energy demand and improves indoor conditions, but it adds embodied carbon and cost, and the most favourable solution depends on the priorities of the owners and occupants.

The data below support the exercises in *Section 4.2*, and the solutions are provided in *Section 4.3*. Table 6 summarises the life cycle settings adopted in the case study, Table 7 the main data of the model and of the optimisation, and Table 8 the three preferred strategies.

Table 6. Life cycle settings adopted in the case study.

Setting	Value adopted in the case study
Whole-life carbon	GWP, modules A1–A5, B4, B6, and C; module D reported separately; 50-year study period; only the intervention is accounted for
Life cycle cost	Net present value over 50 years; discount rate of 4%; electricity price of 0.198 €/kWh, escalating at 2% per year
Energy	EnergyPlus 25.2, Lisbon weather data; setpoints of 20 and 26 °C; heat pump with SCOP 3.5 and SEER 4.0; grid emission factor decreasing from 0.156 to 0.010 $kgCO_2e/kWh$ (2026 to 2045)
Indoor temperature	Free-floating simulation; degree-hours outside 20–26 °C, weighted by the magnitude of the deviation

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Table 7. Main data of the model and of the optimisation.

Item	Value
Energy model generated from the IFC	9 thermal zones, 210 surfaces
Baseline final energy use (heat pump supply)	8,893 kWh/yr
Baseline whole-life carbon, 50 years	10.0 tCO_2e
Baseline life cycle cost, 50 years	55.8 k€
Baseline temperature exposure	119,666 °C·zone-h
Renovation measures in the database	130
Options in this building (excluding retention of the existing construction)	External walls 662; stairwell external walls 662; internal walls adjacent to unheated spaces 113; windows 10; ceiling below the attic 4 (1,451 in total)
Search	NSGA-II with 96 scenarios per generation over 32 generations; 3,062 scenarios evaluated in 12 h 18 min; 156 non-dominated solutions

Table 8. Preferred renovation strategies.

Preferred strategy	Investment	Whole-life carbon	Exposure	Measures
R1 (equal weights)	45.2 k€	15.9 tCO_2e	90k	ETICS on the stone façades; interior insulation of the stairwell walls; cellulose insulation in the loft
R2 (priority to carbon or cost)	39.1 k€	15.0 tCO_2e	96k	ETICS on the stone façades; ventilated façade on the stairwell walls; cork insulation in the loft
R3 (priority to comfort)	69.1 k€	23.0 tCO_2e	86k	As R2, with thermal insulating render on the stairwell walls and double glazing with timber frames

Note: exposure in °C·zone-h. The internal walls are retained in all three strategies.

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4.2. Exercises

The six exercises below apply the reasoning underlying each step of the workflow to the case study. Each exercise is worth up to 2 points. The solutions and a self-assessment matrix are provided in *Section 4.3*.

Exercise 1. Information requirements
Which three types of information must the IFC model contain before the energy model can be generated? Which EnergyPlus boundary condition is assigned to a party wall shared with an adjacent building, and on what grounds?
Exercise 2. Size of the decision space
Including the retention of the existing construction, the five element groups offer 663, 663, 114, 11, and 5 options. How many whole-building scenarios are possible? At the computational rate observed in the case study, how long would the evaluation of all scenarios take?
Exercise 3. Measures and options
The database contains 130 measures, whereas the building offers 1,451 options. Explain this difference with reference to the application of ETICS to a double brick wall and to a single brick wall.
Exercise 4. Influence of the energy system
With a heat pump (SCOP 3.5), no scenario achieves a lower cost or lower whole-life carbon than the baseline over 50 years. With direct electric heating (SCOP 1.0), approximately 20% of the scenarios become cheaper and 3.2% reduce carbon. Explain this result.
Exercise 5. Benefits of renovation
Compare strategy R1 with the baseline. Which indicator improves, which deteriorates, and by approximately how much? Given that the number of hours outside the 20–26 °C range decreases by no more than 5.4%, what does this indicate about the nature of the comfort improvement?
Exercise 6. Stakeholder priorities
A housing association prioritises cost, whereas a tenants' association prioritises comfort. Which strategy is preferred in each case, and how should the results be presented to support the discussion?

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4.3. Solutions and self-assessment

This section presents the solutions to the exercises in *Section 4.2* in Table 9. Readers are encouraged to attempt the exercises before consulting them. All values can be checked against the case study data in Tables 6 to 8 and against Figure 13, which shows the ranking of the eight representative strategies with TOPSIS under four sets of priorities.

Table 9. Solutions to the exercises.

No.	Solution
1	Quantities, a classification code for each element, and second-level space boundaries. A party wall is assigned an adiabatic boundary condition, since the adjacent building is assumed to be at a similar temperature and no heat flow is therefore considered.
2	663 × 663 × 114 × 11 × 5 = 2,756,097,630 scenarios. As the search evaluated 3,062 scenarios in 12 h 18 min, approximately 14.5 s per scenario, the evaluation of all scenarios would require approximately 1,260 years on the same hardware, which justifies the use of a genetic algorithm.
3	A measure is stored as a set of actions (removal of the existing render, addition of 80 mm of mineral wool and a new render, and retention of the remaining layers) rather than as a finished wall. The same measure can therefore be applied to a double brick wall, a single brick wall, or any compatible construction, and the application calculates the result in each case. In this way, 130 stored measures yield 1,451 options in this building without any of them being modelled individually.
4	With a SCOP of 3.5, each kWh of heat saved avoids only approximately 0.29 kWh of electricity; the resulting energy and carbon savings do not offset the investment or the embodied carbon of the new materials within 50 years. With direct electric heating, each kWh of heat corresponds to one kWh of electricity, so savings are approximately 3.5 times greater, and some scenarios achieve payback (11.4 years in the case study).
5	Temperature exposure decreases from 119,666 to approximately 90,000 °C·zone-h, a reduction of approximately 25%, whereas whole-life carbon increases from 10.0 to 15.9 tCO_2e, approximately 60%. The limited reduction in hours indicates that the improvement lies in the magnitude of the deviation from the comfort range rather than in its duration: dwellings remain cold for a similar period, but to a lesser extent.
6	Priority to cost: R2. Priority to comfort: R3. Both strategies should be presented on the same chart of cost, carbon, and exposure, with the baseline as reference, so that each stakeholder can identify its own gains and the concessions made by the other.

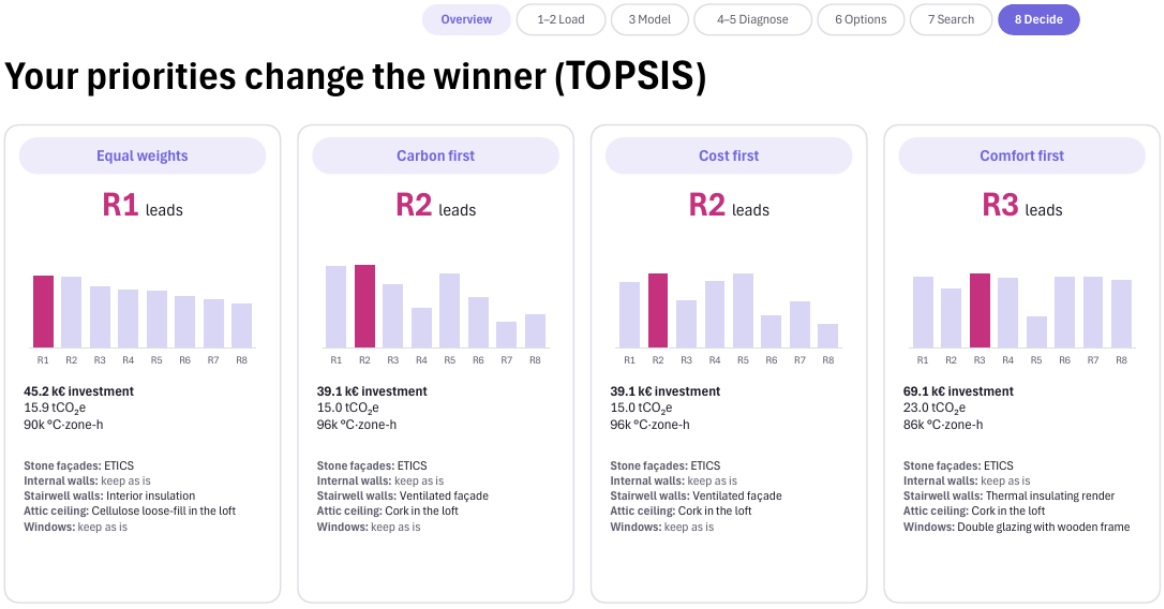


Figure 13. Ranking of the eight representative strategies with TOPSIS under four sets of priorities.

Each solution is scored with 2 points if it is complete and correct, 1 point if it is partially correct, and 0 points otherwise, for a maximum of 12 points. Table 10 relates the total score to a level of proficiency.

Table 10. Self-assessment matrix.

Score	Level	Interpretation
11–12	Expert	Applies the method independently and can explain the results to others.
8–10	Proficient	Understands the workflow and its main trade-offs; minor points should be revised.
5–7	Developing	Understands the main steps; the sections referred to in the solutions should be revisited.
0–4	To be improved	The user guide (*Section 2*) and the background (*Section 3*) should be reviewed before the exercises are repeated.

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