



FuturHist

Report on assessment of insulation systems for the envelope's retrofit including components' integration



Project Overview



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Executive Summary

This deliverable supports passive retrofit of historic masonry in Spain, Poland, Sweden and Scotland by testing internal insulation systems against two KPIs: U-value (energy efficiency) and mould growth risk (MGI, moisture safety). A three-level method combines 1D hygrothermal simulations, indoor climate assessment, and thermal-bridge analysis. Results show that internal wall insulation can substantially lower U-values, but moisture safety depends on climate exposure, wall type, and high-RH material behaviour. Cross-tool checks (Delphin 6.1, WUFI Pro) are mostly consistent while revealing sensitivities. The most critical cases occur with wind-driven rain, minimum thickness, and high indoor moisture loads. Priorities include verifying high-RH material data, favouring capillary-active or suitably vapour-open systems, and applying conservative detailing in exposed orientations.

Simulations of indoor climate indicate that internal insulation improves performance during winter but can increase summer overheating by reducing wall thermal inertia, especially in climates with higher temperature or humidity and future scenarios. Passive measures (shading, night ventilation etc.) are essential measures. Hygroscopic materials help to stabilize indoor relative humidity and can reduce the need for mechanical control, with benefits varying by climate and typology. Thermal-bridge analysis confirms that junctions can erode energy gains and create local moisture risks; targeted, conservation-compatible measures (reveal insulation, capillary-active plasters, airtightness) are needed. Collectively, the findings provide actionable guidance to achieve lower U-values without compromising moisture safety, advancing project objectives on energy, resilience, and heritage protection.

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We acknowledge the use of AcademicAI for proofreading and coding assistance. The authors retain full responsibility for the scientific content, methodology, and findings presented in this work.

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Abbreviations and definitions

c_p	Specific heat capacity; heat required to raise 1 kg of a material by 1 K (J/kg·K).
Energy retrofit	A general concept for all types of renovations where reduced energy consumption is the main goal for the renovation. It is used for the entire renovation process, from planning to evaluation, and is closely related to sustainable renovation. Sustainable renovation of existing buildings is a way of extending the lifespan of a building and improving its living and working conditions, which includes lowering the energy used for those purposes (FuturHist Consortium, 2024).
fRsi	Surface temperature factor; indicator of surface mould/condensation risk (-).
Historic building (HB)	Building of heritage significance; a historic building does not necessarily have to be statutorily designated as cultural heritage.
IWI	Internal wall insulation; insulation applied on the room side of existing walls.
KPI	Key performance indicator.
MGI	Mould Growth Index; indicator of mould risk based on hygrothermal conditions over time.
maxMGI	Maximum Mould Growth Index reached during the simulation period.
RH	ratio of actual water vapour content to saturation at the same temperature (%).
sd	Water-vapour diffusion-equivalent air layer thickness (m); $sd = \mu \times$ thickness.
Typology	A set of buildings with common properties (e.g., age of construction, geometry, thermo-physical properties, and energy performance) (FuturHist Consortium, 2024).
U-value	Thermal transmittance value, i.e., the rate of transfer of heat through a structure.

WDR	Wind-driven rain; combined effect of rain and wind on exterior wetting.
λ	Thermal conductivity; rate of heat flow through a material (W/m·K).
ρ	Density; mass per unit volume of a material (kg/m ³).
μ	Water vapour resistance factor; ratio of a material's vapour diffusion resistance to that of still air (-).
ψ	Linear thermal transmittance of a junction (W/m·K).

1. Introduction

This deliverable supports the project's task on passive retrofit strategies for historic masonry by consolidating typological knowledge and simulation retrofit solutions across Spain, Poland, Sweden, and Scotland. The overarching aim is to balance energy efficiency gains with hygrothermal safety, durability, and heritage compatibility. Historic walls are solid, often capillary-active, and protected by conservation principles that limit invasive interventions; internal insulation is frequently the only viable strategy, but it modifies heat and moisture paths in ways that can elevate risk if materials and details are not judiciously chosen. By bringing together local historical buildings constructions, various retrofit approaches, and climate files representative of present and future conditions, the work establishes a realistic basis for comparing passive solutions that could be deployed at scale in revitalization projects.

Performance is tracked using key indicators defined in D1.6 (FuturHist Consortium, 2025). The U-value quantifies steady-state heat flow through a building element; lower U-values reduce transmission losses, translating into lower heating demand, improved comfort near cold surfaces, and lower emissions when coupled with low-carbon energy systems. Reducing U-value is therefore central to decarbonization pathways but must be achieved without compromising the moisture robustness of heritage fabric. The mould growth risk indicator (MGI) reflects the likelihood that fungi will colonize surfaces or porous materials when temperature and humidity conditions are conducive for sufficient durations. Persistent mould growth degrades materials, negatively affects indoor air quality, and poses health risks; for occupants and owners, this can mean loss of use, increased maintenance, and reputational impacts in sensitive buildings. Ensuring low MGI while lowering U-value frames the core trade-off addressed in this deliverable.

The study uses inputs and insights from previous deliverables that catalogued representative wall typologies for each country and provided material data for various insulation systems. Those baselines are essential to ensure that simulations reflect real constructions, including the presence or absence of external plasters, internal finishes, and ventilation layers that alter moisture exchange.

The analysis is structured in three levels (Chapters 2, 3 and 4) that progressively integrate more physical couplings and spatial complexity. First in Chapter 2, one-dimensional hygrothermal simulations of wall components with internal insulation establish whether proposed layer stacks remain within safe moisture regimes and quantify their thermal transmittance. The focus is on internal wall insulation because it reduces heat flow through the wall, cools the historic masonry, and can reduce drying potential; in combination with indoor moisture loads or wind-driven rain, this can increase the relative humidity at interfaces and enable mould or frost damage if materials are poorly matched. To increase confidence and expose model sensitivities, identical configurations are simulated in two widely used tools, Delphin 6.1 and WUFI Pro. This cross-validation helps isolate differences that arise from material databases (e.g., high-humidity

sorption, capillary conductivity, vapour diffusion resistance) or numerical handling of transient wetting and drying, and it identifies cases where conclusions are robust versus cases where further measurements or conservative design margins are warranted.

The second part (Chapter 3) analyses how established and newly developed sustainable internal insulation systems influence indoor climate under current and future conditions, focusing on summer comfort, overheating risk, relative humidity, and the moisture-buffering capacity of materials. Rising temperatures across Europe, especially in the south, are lowering heating needs during winter but increases summer cooling demand, with implications for energy use, emissions, and urban heat stress. In historic buildings, internal insulation is often the only conservation-compatible retrofit, yet it can reduce the thermal inertia of exterior walls and exacerbate overheating, with performance strongly dependent on climate, building typology, and occupant use of shading and ventilation. Prior studies highlight case sensitivity and limited transferability where constructions (e.g., very thick walls) are atypical. In parallel, maintaining indoor RH near 40–60% is important for comfort and health; mechanical regulation is possible but energy-intensive, whereas hygroscopic, porous materials can passively buffer humidity by adsorbing and releasing moisture. Evidence shows such materials can stabilize RH and reduce air-conditioning energy by about 25–30%, though effectiveness varies by season, typology, and climate. This chapter therefore evaluates overheating and RH dynamics alongside the buffering performance of candidate insulation systems to identify passive configurations that improve comfort with minimal energy and emissions.

Thirdly in Chapter 4, promising assemblies are integrated with junctions and details to assess the impact of thermal bridges. Junctions, e.g., at floor slabs, window reveals, and internal partitions, can dominate local heat flow, depress surface temperatures, and concentrate moisture, even when planar U-values are low. Failure to address these effects can negate energy savings and create localized mould or condensation risks. The deliverable therefore quantifies the linear thermal transmittance of key details, explores practical mitigation options compatible with conservation constraints, and identifies where targeted improvements (e.g., reveal insulation, capillary-active plasters, airtightness measures) are needed to ensure that whole-assembly performance aligns with component-level predictions.

2. Hygrothermal simulations of internal wall insulation

During the task, hygrothermal simulations were used to predict coupled heat and moisture transport in building assemblies, resolving how temperature, relative humidity, and moisture content evolve through layers and at critical interfaces. These simulations support design decisions by quantifying risk of mould growth under realistic boundary conditions. The parametric study extends chosen setup across a structured matrix of variables to map performance sensitivity and identify robust configurations. Key parameters include various boundary conditions and different wall constructions. By varying one or more factors systematically, the comparable outputs were obtained that reveal which combinations are safe, which are marginal, and which require design adjustments (e.g., vapour retarders, thickness changes, commissioning measures). This approach enables consistent, evidence-based recommendations across regions and construction types.

Parametric setups were defined from the typologies catalogued in Deliverable 1.2 (FuturHist Consortium, 2024) and paired with exemplary insulation systems described in Deliverable 2.1 (FuturHist Consortium, 2025). For each typology-system combination, the hygrothermal simulations were performed to assess moisture safety and mould growth risk under representative present and future climates.

Focus on Internal wall insulation (IWI) was prioritized because it presents the highest mould growth risk:

- It reduces heat flow from indoors into the historic wall, lowering the temperature at the insulation-masonry interface. Cooler surfaces increase relative humidity for a given moisture content, lengthening time-of-wetness.
- Outward drying is often limited by driving-rain loads and by the wall's vapour resistance; inward drying is restricted by the new insulation layer and interior finishes. This bidirectional drying constraint might create moisture accumulation at the interface between the historic wall and the insulation.
- Thermal bridges at floor slabs, internal partitions, window reveals, and anchors become colder after IWI, creating local RH spikes that are critical according to mould models.
- Indoor sources (occupancy moisture, intermittent humidification) directly influence RH at the insulated wall's interior boundary, making RH excursions more likely during heating season.

Roofs and ground floors are generally less critical in this context:

- Roofs: Even when insulated internally (e.g., at the ceiling or rafter line), roof assemblies typically experience higher temperatures and strong solar gains, promoting drying. Slopes shed rain quickly, and many roof build-ups include intentional ventilation layers that limit moisture accumulation. Consequently, interface experience less time with RH above mould-critical thresholds compared to IWI on masonry façades exposed to driving rain.
- Ground floors: The main risk comes from ground moisture (rising damp), not from indoor humidity. Where a damp-proof layer/capillary break and basic subfloor ventilation are present, moisture loads are much lower and surfaces stay warmer, so mould risk is typically reduced compared to IWI interfaces.

While roofs and floors are typically less critical than internal wall insulation (IWI) for mould risk, thermal bridges remain a significant concern across all assemblies; their effects (e.g., at junctions) are addressed in detail in Chapter 4.

2.1. Methodology

Primary simulations were carried out in Delphin 6.1 (Bauklimatik Dresden Software GmbH, 2023), using the materials and boundary conditions consistent with D1.2 (FuturHist Consortium, 2024) and D2.1 (FuturHist Consortium, 2025). To increase confidence, a subset of cases (covering the envelope of climates, substrates, and systems) was re-simulated in WUFI Pro Fraunhofer Institute for Building Physics, 2023) with harmonized inputs (identical weather files, interior conditions, initial states). The two tools produced comparable temperature and RH values at critical interfaces; observed differences were documented below.

Delphin is a transient hygrothermal simulation tool for coupled heat and moisture transport in building components. It solves temperature, water vapour diffusion, and capillary liquid transport in 1D and 2D domains, with boundary conditions for wind-driven rain, short- and longwave radiation, convection, and indoor climate coupling. Users can model full layer stacks and 2D junctions (e.g., slab ends, window reveals), define installation moisture, and set spatially varying properties. Material data can be imported from lab measurements or selected from its library. Delphin supports batch runs for parametric studies, outputs detailed time series (T, RH, moisture content, heat and moisture fluxes), and is commonly used for research-grade analyses where custom materials, complex boundary conditions, or 2D details are important. Results can be post-processed for risks such as mould growth, interstitial condensation, and freeze-thaw.

WUFI is a family of tools for transient heat and moisture transport, widely used in practice. WUFI Pro handles 1D assemblies; WUFI 2D expands to two-dimensional details; WUFI Plus couples envelope hygrothermal behaviour with whole-building energy and indoor climate. The software includes extensive climate databases (typical years, measured stations) and material databases,

and models key loads such as wind-driven rain, solar radiation, and interior moisture production. Users can specify initial moisture, construction phases, and vapour control layers, then evaluate outputs (T, RH, water content, fluxes) and apply built-in post-processors for mould growth risk (e.g., isopleth/Viitanen-type indices). WUFI's strengths are its user-friendly workflow, broad libraries, and efficient 1D/2D modelling for design office use; it is often paired with Delphin cross-checks when advanced customization or research-level calibration is required.

Both tools implement the same core physics (heat conduction, vapour diffusion, capillary transport) and similar boundary-condition models, but they differ in interface, libraries, and some numerical details. In many projects, cross-comparison of a subset of cases helps confirm robustness of conclusions.

Materials

2.1.1. All materials were selected from the Delphin Material Library (Bauklimatik Dresden Software GmbH, 2023) to ensure consistent, physically based hygrothermal properties across simulations. Where multiple library entries existed for a given material class, the choice prioritized datasets with well-documented attribution, complete moisture and thermal property curves, and applicability to the national building stock under study.

Brick and stone masonry selections were tailored by country to reflect known regional differences in historic buildings. Because Delphin provides several brick models with varying porosity, strength classes, and moisture transport characteristics, country-specific models were adopted based on published studies using local materials:

- Spain: Brick properties aligned with datasets and findings reported for Spanish masonry (Llorente-Álvarez et al., 2021).
- Poland: Polish brick models were chosen with reference to local investigations and hygrothermal characterizations (Vaněk, 2019; Hofheinz et al., 2025; Misiewicz et al., 2025; Tunkiewicz et al., 2021; Bajno et al., 2024).
- Sweden: Selections drew on Swedish case studies and measurements of local bricks (Johansson et al., 2020).
- Scotland: Because traditional Scottish construction commonly employs stone rather than brick, sandstone and granite datasets from the Delphin library were used to represent masonry substrates (Banfill, 2021).

Eight most common systems from D2.1 were chosen: Autoclaved aerated concrete (AAC), Calcium silicate boards, Cellulose (loose/blown-in/dry application), Clay cork insulation, Mineral wool, Perlite insulation board, Polystyrene/EPS/XPS, and Wood fibre board. The goal was to analyse various systems: vapour open and vapour closed, bio-based and oil-based etc.

A complete list of all materials used in the assemblies, together with key parameters (density ρ , specific heat capacity c_p , thermal conductivity λ , and vapour diffusion resistance factor μ) is provided in Table 1 (for existing walls), Table 2 (for insulation materials) and Table 3 (for other materials).

Table 1. List of materials for existing walls applied in simulations in Delphin.

Name	Material in Delphin	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Brick (Poland)	Old Building Brick Dresden ZK [499]	1734.1	919.2	0.656	24.5
Brick (Spain)	Old Building Brick Dresden ZQ [286]	1948.0	813.2	0.905	98.6
Brick (Sweden)	Old Building Brick Dresden ZC [491]	1904.4	847.4	0.808	22.9
Sandstone	Sandstone India Red [467]	2262.8	874.5	2.870	63.7
Granite	Granite boulder [463]	2452.9	702.2	1.718	53.8
Historical plaster	Lime Plaster (historical) [148]	1800.0	850.0	0.820	12.0
Spruce	Spruce longitudinal (from Saxony) [716]	554.3	2574.5	0.188	222.9
Air gap	Air gap 40 mm (vertical) [17]	1.3	1050.0	0.222	0.3

Table 2. List of insulation materials applied in simulations in Delphin.

Name	Material in Delphin	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Calcium silicate	Climate board (until 2015) [284]	222.3	1303.2	0.057	5.4
Cellulose	Blown-in Cellulose [580]	55.2	2544.4	0.048	2.0
Clay-cork board	Insulation Loam-Cork Board (F) [416]	350.1	1056.4	0.077	28.0
EPS	Polystyrene Foam Board – Expanded [186]	35.0	1500.0	0.040	50.0
Mineral wool	Mineral Wool 035 [731]	67.0	840.0	0.035	1.0
Multipor	Ytong Mineral Foam Multipor 2004 [597]	115.2	1292.3	0.048	4.1
Perlite	Sto-Perlite Indoor insulation board 045 [733]	100.3	1640.1	0.046	8.0
Wood fibre board	Wood Fibre Insulation Board [693]	160.8	1661.9	0.039	3.4

Table 3. List of additional materials applied in simulations in Delphin.

Name	Material in Delphin	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Gypsum board	Rigips gypsum board [427]	732.0	1383.9	0.211	6.8
Mineral plaster	Mineral Interior Plaster [231]	1446.1	873.2	0.609	39.0
Mortar (for calcium silicate)	Remmers iQ-fix [437]	1313.3	862.9	0.497	18.7
Mortar (for clay-cork)	Insulation Loam-Cork Glue mortar (D) [415]	569.2	977.0	0.120	46.1
Mortar (for EPS)	Lime cement mortar [842]	1876.1	757.9	0.803	41.3
Mortar (for Multipor)	Glue Mortar For Mineral Insulation Board Multipor (Xella) [77]	830.0	815.0	0.155	13.0
Mortar (for perlite)	StoDecosil K [843]	1760.3	772.2	0.740	251.4
Mortar (for wood fibre)	Rotkalk Fein [667]	1279.1	827.3	0.315	10.2
OSB	OSB [650]	595.0	1500.0	0.130	165.0
Smart vapour retarder	Proclima Intello [725]	700.3	1000.0	0.230	46877.8

2.1.2. Boundary conditions

2.1.2.1. Initial conditions

The same initial state was applied to all simulations:

- Temperature: 20°C;
- Relative humidity: 80%.

Each simulation ran for 10 years, with comparative analyses performed only on the final year to minimize the influence of initial conditions on the reported results.

2.1.2.2. External climate

Weather files for each country were selected for the city hosting the FuturHist demonstration case: Spain – Córdoba, Poland – Kraków, Sweden – Linköping, and Scotland – Edinburgh. All weather data were sourced from Meteonorm 8 (Meteotest, 2020). Simulations used a present-day climate representative of 2020.

In selected scenarios, a future climate corresponding to RCP 8.5 for 2070 was also applied to assess climate-change impacts (IPCC, 2014). RCPs (Representative Concentration Pathways) are

greenhouse gas concentration trajectories used in climate modelling. RCP 8.5 is the highest forcing pathway commonly used, reaching approximately 8.5 W/m² radiative forcing by 2100 and representing a high-emission, “worst-case” scenario.

Two façade orientations were considered for each climate: a north orientation, and a “worst” orientation characterized by the highest wind-driven rain (WDR) exposure (as indicated by WUFI's WDR indices for the respective climates). The worst orientations applied were:

- east (90°) for Córdoba,
- west (270°) for Kraków and Edinburgh,
- southwest (225°) for Linköping.

External climate and surface exchange parameters followed recommendations from Delphin and WUFI. Two rain exposure options were used to represent different splash/exposure conditions. The values are summarized in Table 4.

Table 4. External boundary condition parameters and rain exposure options.

Parameter	Option 1	Option 2
Effective heat conduction exchange coefficient	25 W/m ² K	
Vapour diffusion mass transfer coefficient	1.19e-07 s/m	
sd-value of painting/surface coating	0 m	
Solar adsorption coefficient	0.7	
Long-wave emissivity	0.9	
Rain exposition	moderate (MR)	High (HR)
Reduction/splash coefficient	0.5	0.7

Figure 1 presents monthly averaged exterior climate variables (temperature, relative humidity, rainfall, and global solar radiation) for Córdoba, Kraków, Linköping, and Edinburgh based on Meteonorm. The four locations span distinct climatic zones and therefore impose different hygrothermal boundary conditions:

- Córdoba (Mediterranean climate) exhibits hot, dry summers with monthly means near 30°C and RH around 40%, virtually no rain from June to September, and very high solar radiation; winters are mild, around 10°C with RH near 80%, a little rainfall, and still higher solar gains than the other sites.
- Kraków (Continental climate) has summers near 20°C with RH around 70%, fairly constant rainfall, and medium solar levels; winters hover around 0°C with RH close to 90%, somewhat less precipitation, and much lower solar radiation.
- Linköping (Northern climate) reaches about 18°C in summer with RH near 60%, experiences persistent but generally lower rainfall than Kraków and higher summer solar radiation; winters are around 0°C with RH near 90%, limited precipitation, and very low solar radiation due to short days.

- Edinburgh (Oceanic climate) shows a narrow annual temperature range with summers around 15°C and winters near 5°C, consistently high RH (80-90%), the highest rainfall of the four cities, and consequently the lowest solar radiation.

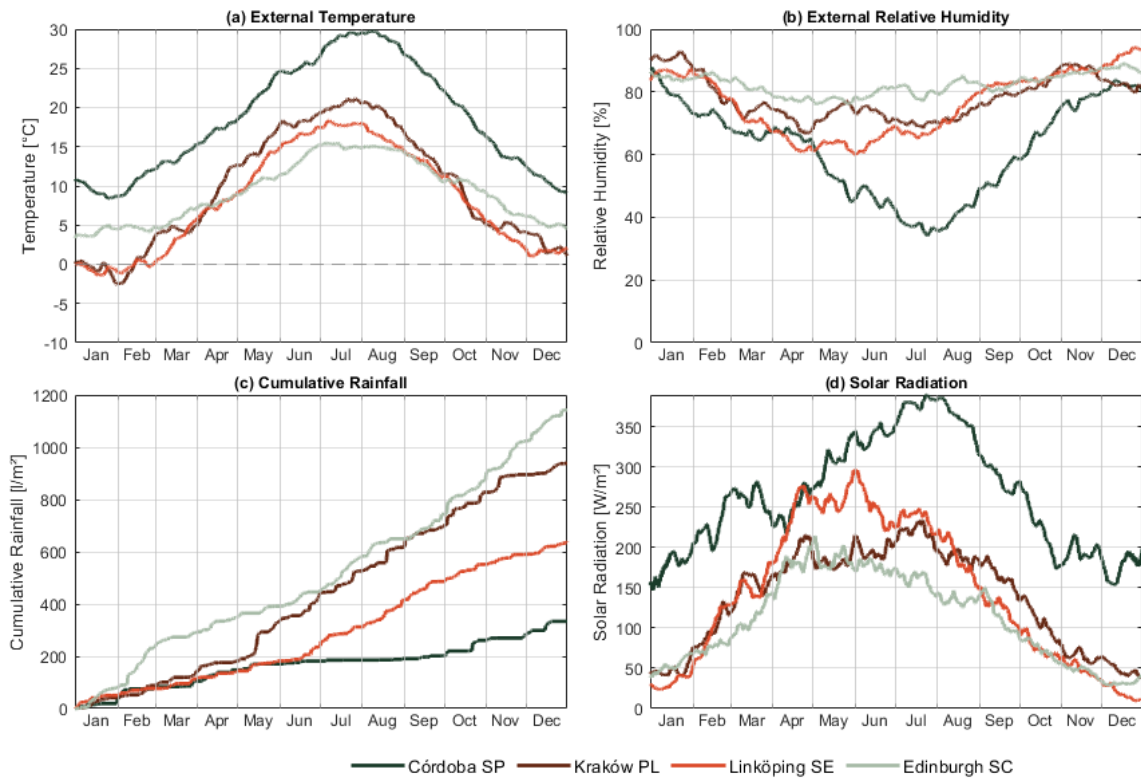


Figure 1. Comparison of external climate (monthly smoothed temperature, relative humidity, cumulative rainfall, and solar radiation) for Córdoba, Kraków, Linköping, and Edinburgh.

Figure 2 compares monthly smoothed outdoor temperatures for the present climate (2020) and the RCP 8.5 future projection for 2070 at the four demo locations. Here, monthly smoothing means reducing a time series' short-term variability by aggregating to monthly resolution – typically via calendar-month means or a 30-day moving average – so that broader trends and seasonal patterns are more clearly visible. All sites warm substantially: Spain (Córdoba) and Poland (Kraków) by about 5°C across the year, and Sweden (Linköping) and Scotland (Edinburgh) by about 3°C. In the future scenario, the monthly averages at all sites remain above 0°C year-round, with systematically elevated temperatures in every month relative to the present.

These shifts imply notable hygrothermal consequences for the envelope: reduced frequency of freezing conditions (lower freeze-thaw stress on masonry and renders), longer and stronger warm-season periods with potentially higher biological activity (mould and algae) on exterior surfaces, altered indoor conditions, and generally higher vapor pressure differentials in summer that can favour outward drying, while also increasing the likelihood of overheating and extended cooling demand.

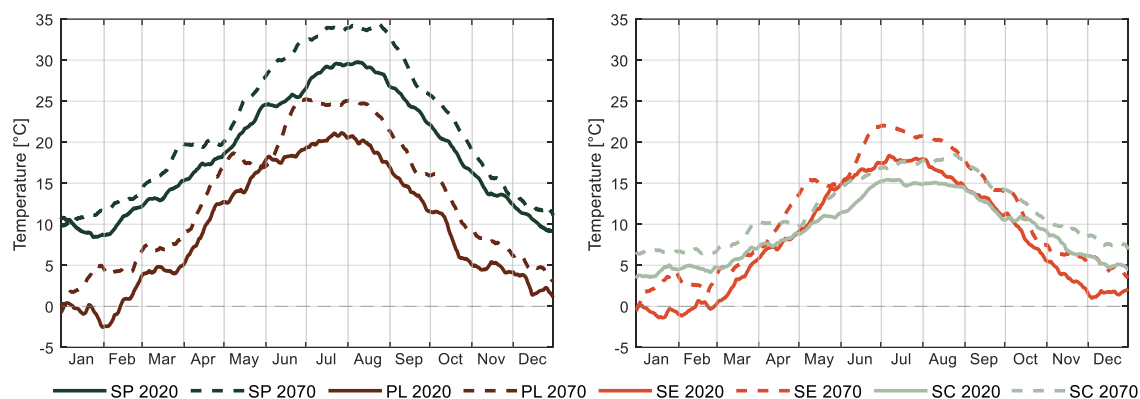


Figure 2. Monthly smoothed outdoor temperature for present climate (2020) and future climate (RCP 8.5, 2070) in Córdoba, Kraków, Linköping, and Edinburgh; dashed lines indicate the 2070 projection.

Figure 3 presents monthly smoothed outdoor relative humidity for the present climate (2020) and the 2070 projection under RCP 8.5. Across all locations there is a slight overall decrease in RH in the future scenario. The most pronounced seasonal changes occur in Kraków, where winter months show reductions up to about 10 percentage points, and in Edinburgh, where late-year values similarly drop by up to roughly 10 percentage points. Córdoba and Linköping exhibit more modest shifts, generally a few percentage points lower than present levels throughout the year.

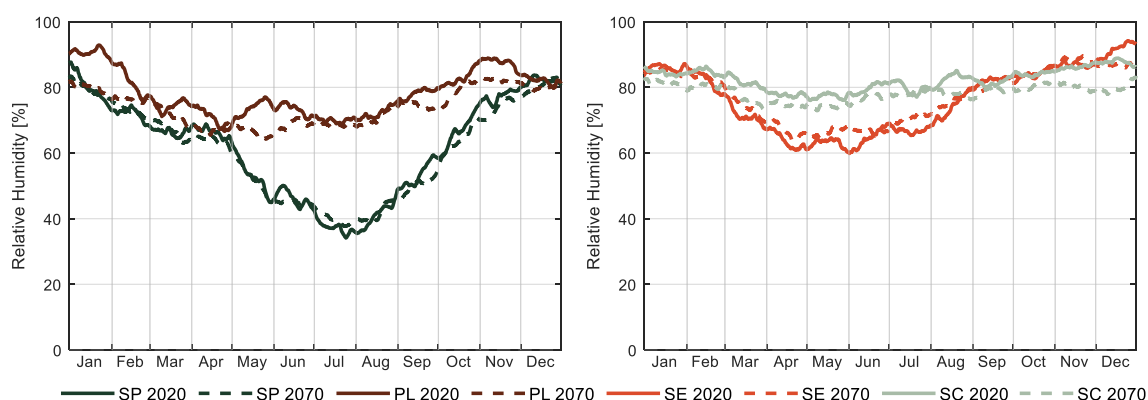


Figure 3. Monthly smoothed outdoor relative humidity for present climate (2020) and future climate (RCP 8.5, 2070) in Córdoba, Kraków, Linköping, and Edinburgh; dashed lines indicate the 2070 projection.

Figure 4 shows cumulative monthly smoothed rainfall for the present climate (2020) and the 2070 RCP 8.5 projection. Annual totals shift markedly and in opposite directions across sites. In Kraków, the future annual total is about 69% of the present value (–31%), while Edinburgh reaches roughly 81% of its present total (–19%). In contrast, Córdoba increases to about 132% of present (+32%), and Linköping to about 121% (+21%).

These changes imply altered wind-driven rain loads on façades, with reduced exterior wetting and potentially improved drying in Kraków and Edinburgh, but increased wetting exposure, and thus higher risks of surface soiling, biological growth, and moisture ingress at vulnerable details, in Córdoba and Linköping. Coupled with the warmer future temperatures, freeze-thaw stresses are expected to diminish, while moisture loads on WDR-exposed façades may intensify, particularly in the Spanish and Swedish contexts.

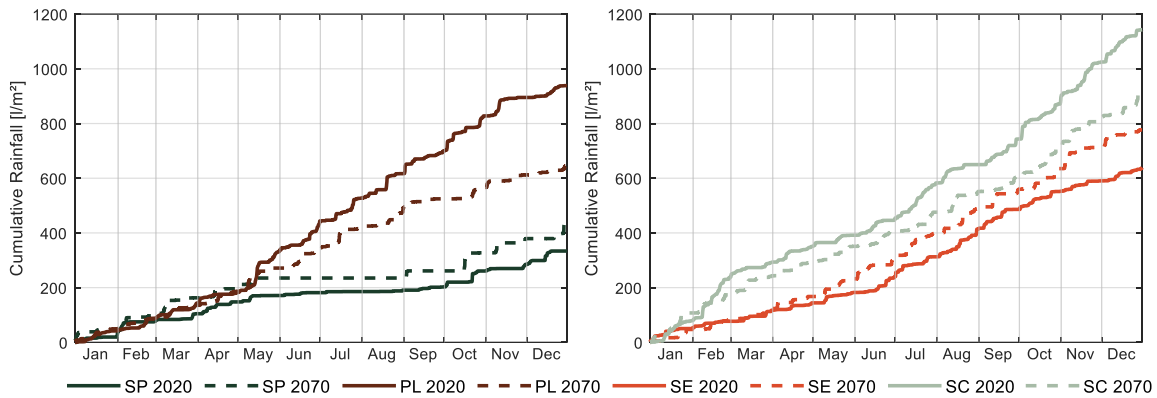


Figure 4. Cumulative rainfall (monthly smoothed progression) for present climate (2020) and future climate (RCP 8.5, 2070); dashed lines indicate the 2070 projection.

Figure 5 compares monthly smoothed global solar radiation for the present climate (2020) and the 2070 RCP 8.5 projection. Spain (Córdoba) and Scotland (Edinburgh) show a noticeable reduction in solar input across much of the year, while Poland (Kraków) and Sweden (Linköping) remain broadly similar to present levels with only minor shifts. Reduced insolation in Córdoba and Edinburgh implies lower exterior surface heating and diminished solar-driven drying potential, as well as slightly reduced passive solar gains indoors; by contrast, the near-neutral change in Kraków and Linköping suggests that solar-related drying and gains will remain comparable to today.

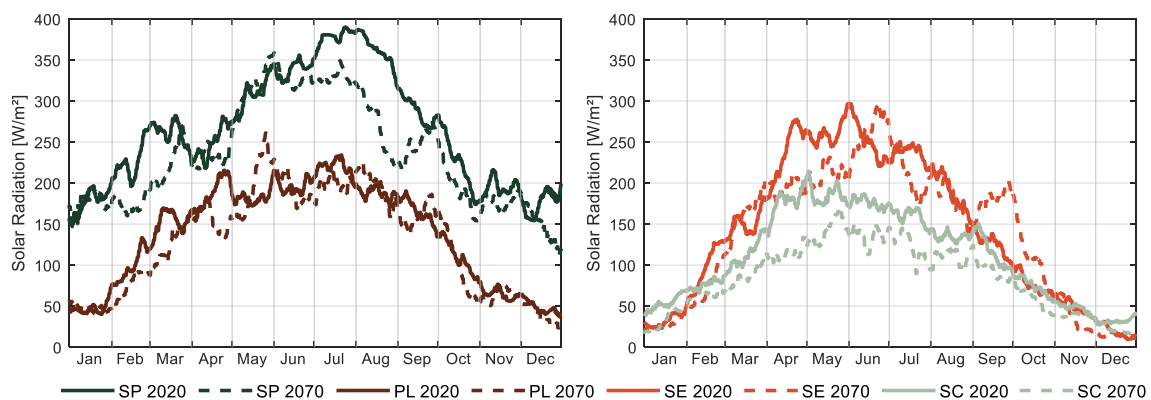


Figure 5. Monthly smoothed global solar radiation for present climate (2020) and future climate (RCP 8.5, 2070); dashed lines indicate the 2070 projection.

2.1.2.3. Indoor climate

The indoor climate was modelled using the WTA 6.2 approach (WTA, 2014), which couples interior conditions to the outdoor climate via seasonal functions. Indoor temperature follows a bounded annual profile, varying between 20°C and 25°C as a function of outdoor temperature (cold vs. warm season). Indoor relative humidity (RH) is likewise linked to outdoor temperature and is constrained within load-class-specific bands to reflect different moisture productions and ventilation behaviour.

Two bounding scenarios were defined for sensitivity analyses: a low moisture load (LML, “best case”) with RH between 25-55%, and a high moisture load (HML, “worst case”) with RH between 40-70%. Where no comparison of internal conditions was required, a normal moisture load (NML) with RH between 30-60% was applied. Heat and vapour surface transfer coefficients follow the recommended default values from Delphin and WUFI (Table 5).

Table 5. Internal climate model parameters (WTA 6.2) and surface transfer coefficients.

Parameter	LML	NML	HML
Internal temperature	20-25°C		
Internal relative humidity	25-55%	30-60%	40-70%
Surface heat transfer coefficient (convective + radiative)	7.7 W/m ² K		
Surface vapor diffusion coefficient	5.6e-08 s/m		

Figure 6 shows monthly smoothed indoor relative humidity on the left axis for the three WTA 6.2 moisture-load classes (LML, NML, HML) and indoor temperature on the right axis, which depends only on the outdoor temperature and is therefore identical across moisture-load cases. In Córdoba, the highest outdoor temperatures translate via the WTA coupling into generally higher indoor RH levels across all load classes than other sites. Indoor temperature remains at the upper bound of 25°C for roughly four months (June-September), while the minimum setpoint is scarcely reached, so both RH and temperature seldom approach their lower limits. In Kraków, indoor RH spans approximately 33-54% under LML and 48-69% under HML, with NML in between; the maximum indoor temperature of 25°C is not attained in any month, and the minimum of 20°C persists from November through March. Linköping behaves very similarly to Kraków, with seasonally constrained temperatures around the lower bound in winter and comparable RH envelopes across the three load classes. Edinburgh shows narrower RH bands than Kraków and Linköping, ranging about 38-50% (LML) to 53-65% (HML), while indoor temperatures remain comparatively mild. The highest monthly mean stays below 23°C, and the minimum setpoint of 20°C prevails from November through April.

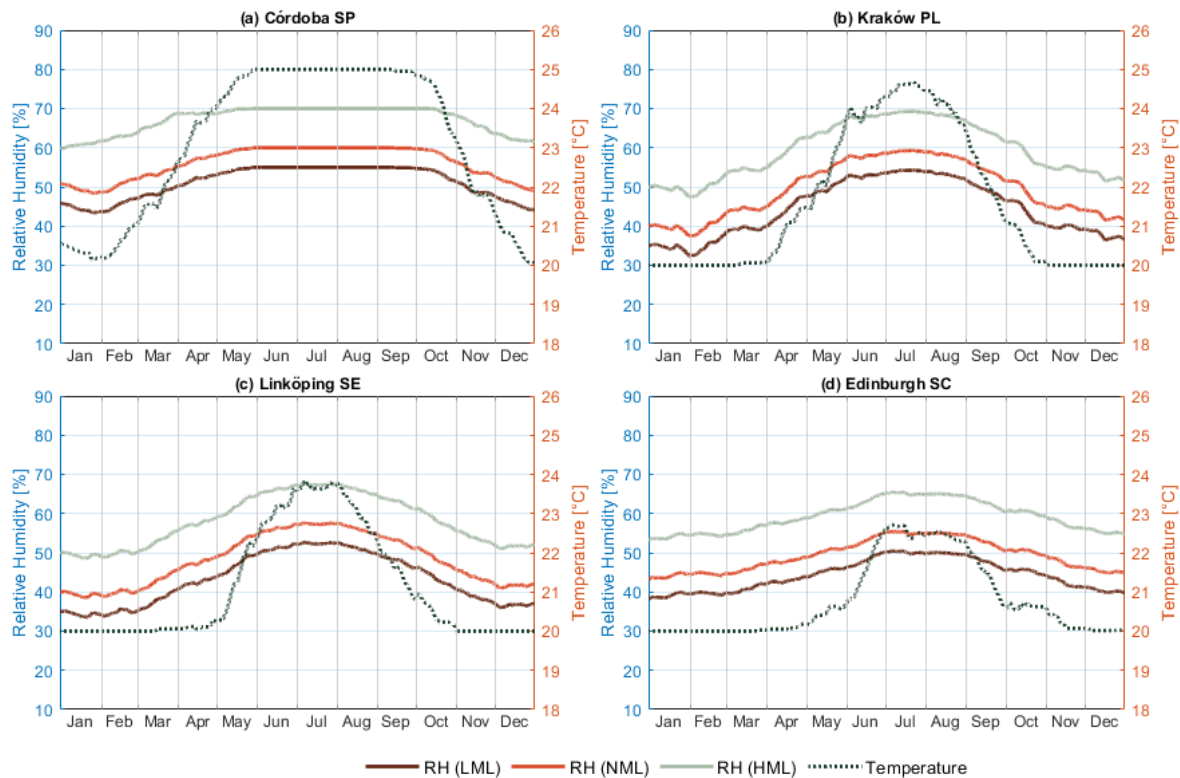


Figure 6. Comparison of internal climate (monthly smoothed temperature and relative humidity) for Córdoba, Kraków, Linköping, and Edinburgh.

2.1.3. Evaluation method

To evaluate the potential for mould growth, the VTT mould growth index (MGI) was applied at the identified critical interface (Viitanen et al., 2015). The index is well suited for comparing simulations because it responds to the full-time history rather than only extremes: under typical European conditions it rises during the colder, more humid months and recedes in summer when air is warmer, capturing the yearly changes.

The MGI ranges from 0 to 6, where 0 denotes no growth and 6 indicates heavy, widespread growth. It is computed from the local temperature and relative humidity together with material-specific growth parameters that reflect sensitivity and the decline term. Material classes used here are: sensitive (cellulose, wood fibre) and medium-resistant (autoclaved aerated concrete, calcium silicate, perlite, clay-cork, EPS, mineral wool). In this study, the commonly used assumption was applied that mould growth does not appreciably decline with time for any of the materials considered.

Following Viitanen et al. (2015), a traffic-light interpretation is applied. For interior surfaces, $MGI < 1$ is within 'green light' (mould-safe), 1-3 is within 'yellow light' (needs attention), and > 3 is within 'red light' (significant risk). For in-wall locations, the green threshold is $MGI < 2$, yellow is 2-3, and red is > 3 .

The VTT index is one of several possible approaches and has limitations. It was calibrated primarily for wood (pine sapwood) and extended to other materials via sensitivity groupings; uncertainty at low growth levels is on the order of ± 0.5 MGI (Ojanen et al., 2010). Furthermore, the model does not include the inhibitory effect of high alkalinity in fresh mineral systems, nor time-dependent changes, such as carbonation, ageing, and dust deposition, that reduce pH and may increase susceptibility over service life (Jensen et al., 2021). Accordingly, results should be viewed with caution and, where feasible, supported by additional indicators and material-specific evidence.

2.2. Simulations in Delphin

For each wall and insulation system, simulations were run across a full factorial of boundary and design variables: two insulation thicknesses, two façade orientations (north and site-specific worst WDR), two climates (present and future), two wind-driven rain exposures (moderate, high), and two internal moisture loads (low, high). Overall, more than 3000 scenarios were simulated and analysed.

Results focus on moisture safety at the identified critical interface, especially mould growth index (MGI) under the different climates and exposures.

2.2.1. System construction

2.2.1.1. Existing walls

Existing wall assemblies were defined based on the typology descriptions in D1.2 (FuturHist Consortium, 2024).

2.2.1.1.1. Spain

Historic Spanish walls are predominantly brick masonry, typically plastered on both interior and exterior faces. Because construction differences among the identified typologies are minor, three representative wall models were defined using the same material layers but varying total wall thicknesses to capture the observed range in practice. The layer build-ups and thickness variants are summarized in Table 6.

Table 6. Existing wall constructions in Spain.

Name	SP1	SP2	SP3
Historical plaster	20 mm	20 mm	20 mm
Brick (Spain)	500 mm	700 mm	250 mm
Historical plaster	20 mm	20 mm	20 mm
Total thickness	540 mm	740 mm	290 mm
U-value	1.30 W/m ² K	1.01 W/m ² K	2.02 W/m ² K

2.2.1.1.2. Poland

Historic wall assemblies are broadly similar across typologies, with solid brick masonry and interior plaster as the common baseline. The primary variation concerns the exterior finish: some buildings retain a historic lime-based plaster, while others have exposed brick without an external plaster layer. Accordingly, two representative variants were defined using the same core materials and thicknesses, differing only in the presence or absence of the exterior plaster. The detailed layer configurations are summarized in Table 7.

Table 7. Existing wall constructions in Poland.

Name	PL1	PL2
Historical plaster		20 mm
Brick (Poland)	500 mm	500 mm
Historical plaster	20 mm	20 mm
Total thickness	520 mm	540 mm
U-value	1.05 W/m ² K	1.02 W/m ² K

2.2.1.1.3. Sweden

Swedish historic wall typologies exhibit notable variation in wall thickness, which was reflected in the model set by defining multiple thickness variants with otherwise consistent layer build-ups. In addition, many buildings, particularly those with thinner masonry, already feature internal insulation, most commonly wood-fibre boards of about 5 cm. This existing layer was included as a baseline variant where applicable, as it substantially lowers the wall's U-value, even without any new retrofit measures. The detailed layer configurations and thickness options are summarized in Table 8.

Table 8. Existing wall constructions in Sweden.

Name	SE1	SE2	SE3	SE4
Historical plaster	20 mm	20 mm	20 mm	20 mm
Brick (Sweden)	500 mm	700 mm	250 mm	250 mm
Wood fibre board				50 mm
Historical plaster	20 mm	20 mm	20 mm	20 mm
Total thickness	540 mm	740 mm	290 mm	340 mm
U-value	1.19 W/m ² K	0.92 W/m ² K	1.89 W/m ² K	0.55 W/m ² K

2.2.1.1.4. Scotland

Scottish historic walls are predominantly stone masonry rather than brick. The baseline assemblies were defined with a constant masonry thickness typical of solid walls, using sandstone as the primary substrate, with variants that either include or omit a historic external lime plaster. On the interior, a common finish is timber lath-and-plaster mounted on battens with an air gap behind and limited convection; this cavity provides rudimentary insulation and can noticeably reduce the wall's U-value even without additional retrofit layers. To reflect regions where harder igneous stone is prevalent, a granite masonry variant without external plaster was also included. The layer configurations and assumed thicknesses are summarized in Table 9.

Table 9. Existing wall constructions in Scotland.

Name	SC1	SC2	SC3	SC4	SC5
Historical plater	20 mm		20 mm		
Sandstone	600 mm	600 mm	600 mm	600 mm	
Granite					600 mm
Air gap			40 mm	40 mm	
Spruce			20 mm	20 mm	
Historical plaster	20 mm	20 mm			20 mm
Total thickness	640 mm	620 mm	680 mm	660 mm	620 mm
U-value	2.34 W/m ² K	2.48 W/m ² K	1.40 W/m ² K	1.45 W/m ² K	1.83 W/m ² K

2.2.1.2. Insulation systems

Internal insulation configurations were defined based on the Internal Wall Insulation (IWI) options catalogued in D2.1 (FuturHist Consortium, 2025), using the same system labels as in D2.1 for traceability. Each IWI system was applied to all wall typologies defined in Section 2.2.1.1, with two insulation thickness variants per system (a “minimum” and a “maximum” representative value). These thicknesses do not represent absolute market extrema but reflect the most common ranges identified in D2.1.

To enable consistent cross-system comparison focused on insulation material and vapour control behaviour, secondary layer thicknesses (adhesive/mortar beds and interior finishing plasters) were harmonized to 1 cm across all systems. All other hygrothermal properties were taken from the Delphin material library entries corresponding to each system's components.

2.2.1.2.1. IWI-4: Autoclaved aerated concrete

Autoclaved aerated concrete (AAC) insulation boards are mineral vapour-open, and hygroscopic. Typical properties for AAC used as internal insulation include low thermal conductivity, moderate vapour diffusion resistance (μ -value often in the range 3-5), and pronounced moisture storage and hygroscopic properties. The accompanying mineral mortars (adhesive/base and finishing coats) are likewise vapour-open, enabling inward drying, and support moisture buffering of the interior finish. The system is non-combustible and dimensionally stable, with negligible risk of interstitial blistering or delamination due to its cohesive, fully mineral composition.

Installation typically involves substrate preparation (removal of loose finishes; levelling as required), application of a continuous mineral adhesive/base coat (full-surface buttering; nominal 10 mm), placement of AAC boards in staggered bond with tight joints, optional mechanical fixings where required by substrate or national guidance, and an interior mineral base/finishing coat (nominal 10 mm). Where specified, an alkali-resistant glass-fibre mesh is embedded in the base coat. The layer build-up, thickness options, and calculated R-values for this system are summarized in Table 10.

The most critical surface for mould growth risk assessment is the interface between the new mineral mortar (adhesive/base coat) and the AAC insulation board. Surface temperature and relative humidity at this plane were monitored in simulations for compliance with mould-growth criteria.

Table 10. Construction of wall insulation system with autoclaved aerated concrete (AAC).

Name	AAC-min	AAC-max
Mortar (for Multipor)	10 mm	10 mm
Multipor	50 mm	100 mm
Mortar (for Multipor)	10 mm	10 mm
Total thickness	70 mm	120 mm
R-value	1.32 m ² K/W	2.51 m ² K/W

2.2.1.2.2. IWI-5: Calcium silicate boards

Calcium silicate (CS) internal insulation is a vapour-open, capillary-active, mineral system. Its open pore structure enables rapid capillary redistribution and buffering of moisture, promoting inward drying and mitigating surface humidity peaks. The material is non-combustible and highly alkaline, which can be beneficial against mould growth when combined with suitable mineral plasters. To preserve its capillary-active function, no vapour-retarding layers are introduced within the system.

Installation typically involves substrate preparation (removal of non-adherent finishes; levelling as required), priming or pre-wetting of very absorbent substrates per manufacturer guidance, application of a continuous mineral adhesive/base coat (nominal 10 mm) with full-surface contact, placement of CS boards in staggered bond with tight joints, and finishing with a mineral plaster (nominal 10 mm). Where specified, a reinforcing mesh is embedded in the base/finish system. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 11.

The primary plane assessed for mould risk is the interface between the new mineral mortar (adhesive/base coat) and the calcium silicate board, where surface temperature and relative humidity were monitored in simulations.

Table 11. Construction of wall insulation system with calcium silicate (CS).

Name	CS-min	CS-max
Mortar (for calcium silicate)	10 mm	10 mm
Calcium silicate	30 mm	60 mm
Mineral plaster	10 mm	10 mm
Total thickness	50 mm	80 mm
R-value	0.56 m ² K/W	1.09 m ² K/W

2.2.1.2.3. IWI-7: Cellulose (loose/blown-in/dry application)

Blown-in cellulose (CEL) is a vapour-open, hygroscopic, and moderately capillary-active insulation. In this system, a smart vapour retarder (variable-permeance membrane) is placed on the warm side of the insulation. Its vapour resistance increases under dry, cold conditions (heating season) to limit inward vapour drives into the insulation, and decreases under warm, humid conditions to enable inward drying toward the interior. An OSB sheathing provides a robust substrate and contributes moderate vapour resistance and airtightness when taped; the interior gypsum board is vapour-open and serves as the finish layer.

Installation typically involves fixing vertical studs or a service frame to the interior face of the existing wall, installing the smart vapour retarder on the room side of the frame with sealed overlaps and airtight connections to adjoining elements, applying OSB sheathing (joints taped) as the blowing face, dense-packing cellulose to the specified thickness and density, and finishing with a gypsum board lining. Particular attention is required at all membrane penetrations and perimeter junctions to ensure airtightness and continuity of the variable-perm layer. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 12.

The interface of primary interest for mould growth assessment is the interior surface of the existing wall at the contact with the new cellulose insulation, where temperature and relative humidity were monitored in the simulations.

Table 12. Construction of wall insulation system with cellulose (CEL).

Name	CEL-min	CEL-max
Blown-in Cellulose	80 mm	120 mm
OSB	10 mm	10 mm
Smart vapour retarder	-	-
Gypsum board	13 mm	13 mm
Total thickness	103 mm	143 mm
R-value	1.81 m ² K/W	2.64 m ² K/W

2.2.1.2.4. IWI-10: Clay cork insulation

Clay-cork boards (CCB) are a natural composite combining cork granulate with a clay binder. The system is vapour-open and capillary-active due to the clay matrix, while cork contributes low thermal conductivity and hygroscopic moisture buffering. The accompanying mineral mortars are likewise vapour-open, preserving inward drying and allowing redistribution of transient moisture without introducing vapour-retarding layers.

Installation typically includes substrate preparation and levelling, application of a continuous mineral adhesive/base coat (nominal 10 mm) with full-surface contact, placement of clay-cork boards in staggered bond with tight joints, and application of a mineral finishing coat (nominal 10 mm). Where specified, a reinforcing mesh is embedded in the base/finish coat. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 13.

The primary plane assessed for mould risk is the interface between the new mineral mortar (adhesive/base coat) and the clay-cork board, where temperature and relative humidity were monitored in the simulations.

Table 13. Construction of wall insulation system with clay-cork board (CCB).

Name	CCB-min	CCB-max
Mortar (for clay-cork)	10 mm	10 mm
Clay-cork board	40 mm	60 mm
Mortar (for clay-cork)	10 mm	10 mm
Total thickness	60 mm	80 mm
R-value	0.69 m ² K/W	0.95 m ² K/W

2.2.1.2.5. IWI-16: Mineral wool

Mineral wool (MW) batts are vapour-open, non-hygroscopic, and effectively non-capillary (fibre structure is typically hydrophobic), providing high air-filled porosity and good thermal performance while allowing water vapour to pass. To manage seasonal vapour drives, the system incorporates a smart vapour retarder (variable-permeance membrane) on the warm side: its vapour resistance increases under dry, cold conditions to limit moisture ingress from indoors, and decreases under warm, humid conditions to promote inward drying toward the room. The interior lining (e.g., gypsum board) is vapour-open and provides mechanical protection; where an intermediate sheathing is used, joints and perimeters are taped to ensure airtightness.

Installation typically involves fixing a timber or metal stud frame to the interior face of the existing wall, fitting mineral wool batts to a uniform, snug density without gaps, installing the smart vapour retarder on the room side of the insulation with sealed overlaps and airtight connections to adjacent elements, and completing with the interior lining. Particular care is taken around services and junctions to maintain continuous airtightness of the membrane layer. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 14.

The interface of primary interest for mould risk assessment is the interior surface of the existing wall at the contact with the new mineral wool insulation, where temperature and relative humidity were monitored in the simulations.

Table 14. Construction of wall insulation system with mineral wool (MW).

Name	MW-min	MW-max
Mineral wool	50 mm	100 mm
Smart vapour retarder	-	-
Gypsum board	13 mm	13 mm
Total thickness	63 mm	113 mm
R-value	1.49 m ² K/W	2.92 m ² K/W

2.2.1.2.6. IWI-17: Perlite insulation board

Perlite boards (PER) are a mineral, vapour-open, and capillary-active internal insulation made from expanded volcanic glass, typically bonded with a mineral binder. The open, microcellular pore structure provides low thermal conductivity alongside good vapour permeability and moisture redistribution, supporting inward drying. The system is non-combustible and compatible with mineral mortars and plasters, avoiding the need for vapour-retarding layers within the build-up.

Installation involves standard mineral IWI practice: substrate preparation and levelling as required; application of a continuous mineral adhesive/base coat (nominal 10 mm) for full-surface contact; placement of perlite boards in staggered bond with tight joints; and application of a mineral finishing coat (nominal 10 mm), typically with an embedded reinforcing mesh where specified. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 15.

The primary plane assessed for mould risk is the interface between the new mineral mortar (adhesive/base coat) and the perlite board, where surface temperature and relative humidity were monitored in the simulations.

Table 15. Construction of wall insulation system with perlite (PER).

Name	PER-min	PER-max
Mortar (for perlite)	10 mm	10 mm
Perlite	50 mm	120 mm
Mortar (for perlite)	10 mm	10 mm
Total thickness	70 mm	140 mm
R-value	1.11 m ² K/W	2.64 m ² K/W

2.2.1.2.7. IWI-19: Polystyrene/EPS/XPS

Expanded polystyrene (EPS) and extruded polystyrene (XPS) are closed-cell, hydrophobic insulations. They are not capillary-active and have relatively high vapour diffusion resistance (XPS > EPS), meaning they act as vapour-retarding layers within the assembly. XPS typically offers lower water absorption and higher compressive strength than EPS; both provide low thermal conductivity but limited moisture buffering and inward-drying potential. Given their combustibility, an appropriate non-combustible lining (e.g., gypsum board) is required to meet fire safety provisions.

Installation generally follows mineral IWI practice adapted for polystyrene boards: prepare and level the substrate; apply a continuous mineral adhesive/base coat (nominal 10 mm) for full-surface contact to prevent convective bypass; place EPS/XPS boards in staggered bond with tight joints; add mechanical fixings if required by substrate or regulations; embed an alkali-resistant glass-fibre mesh in the base coat where specified; and finish with a mineral plaster (nominal 10 mm). Perimeter and junction detailing must ensure airtightness and avoid moisture

traps, as inward drying through the boards is limited. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 16.

The interface most relevant for mould growth assessment is between the new mineral mortar (adhesive/base coat) and the polystyrene insulation board. Temperature and relative humidity at this plane were monitored in the simulations.

Table 16. Construction of wall insulation system with polystyrene (EPS).

Name	EPS-min	EPS-max
Mortar (for EPS)	10 mm	10 mm
EPS	50 mm	100 mm
Mortar (for EPS)	10 mm	10 mm
Total thickness	70 mm	120 mm
R-value	1.28 m ² K/W	2.53 m ² K/W

2.2.1.2.8. IWI-30: Wood fibre board

Wood fibre boards (WF) are vapour-open, hygroscopic, and capillary-active. Their porous fibre network provides strong moisture buffering (adsorption/desorption) and lateral capillary redistribution, supporting inward drying while dampening indoor relative humidity peaks. Thermal conductivities are low and comparable to other bio-based boards; the system is typically paired with mineral or clay/lime plasters to preserve vapour openness. No dedicated vapour retarder is used; airtightness is provided by the continuous interior plaster layer and careful detailing.

Installation generally follows mineral IWI practice adapted to bio-based boards: prepare and level the substrate; apply a compatible full-surface adhesive/base coat (e.g., lime, hydraulic lime, clay, or manufacturer-specified mineral adhesive; nominal 10 mm); place wood fibre boards in staggered bond with tight, well-supported joints; add mechanical fixings where required by guidance or substrate; and finish with a mineral or clay/lime plaster (nominal 10 mm), typically with an embedded alkali-resistant glass-fibre mesh. Junctions and penetrations are detailed for airtightness continuity via the plaster layer. The layer build-up, thickness options, and calculated thermal resistances are summarized in Table 17.

The interface assessed for mould risk is the plane between the new mineral/plaster adhesive coat and the wood fibre board, where temperature and relative humidity were monitored in the simulations.

Table 17. Construction of wall insulation system with wood fibre (WF).

Name	WF-min	WF-max
Mortar (for wood fibre)	10 mm	10 mm
Wood fibre board	40 mm	80 mm
Mortar (for wood fibre)	10 mm	10 mm
Total thickness	60 mm	100 mm
R-value	1.09 m ² K/W	2.11 m ² K/W

Results & discussion

For each wall, simulation results are summarized as heatmaps. Each heatmap arranges:

2.2.2.

- rows by boundary-condition combinations (internal moisture load, façade orientation, rain exposure, and climate: present vs future);
- columns by insulation systems (material) and thickness level (min, max; see Section 2.2.1.2 for nominal thicknesses).

The cell value is the maximum Mould Growth Index (maxMGI) at the critical location over the simulated period; the cell colour follows a 'traffic-light' scale to aid interpretation:

- **'green light'** = mould-safe (maxMGI < 2),
- **'yellow light'** = requires further investigation (maxMGI 2-3),
- **'red light'** = critical (maxMGI > 3).

Because several scenarios lie close to these boundaries, it's important to note that the VTT model carries an uncertainty of approximately ± 0.5 MGI at low growth levels. Apparent class changes near 1.0, 2.0, or 3.0 should therefore be treated cautiously unless validated by additional indicators or sensitivity checks.

Throughout the analysis, scenarios are referenced with a compact code:

[Wall]/[Insulation]-[Thickness]/[Climate]/[Orientation]/[Rain]/[MoistureLoad].

- Walls: *SP1, SP2, SP3, PL1, PL2, SE1, SE2, SE3, SE4, SC1, SC2, SC3, SC4, SC5*;
- Insulation: *AAC, CS, PER, WF, CCB, EPS, CEL, MW*;
- Thickness: *min, max*;
- Climate: *Present, Future*;
- Orientation: *North, WDR* (site-specific worst for wind-driven rain);
- Rain: *MR* = moderate rain, *HR* = high rain;
- Internal moisture load: *LowML, HighML*.

Example: a thin EPS layer on the unplastered Polish wall in the present climate, worst WDR orientation, high rain, and low internal moisture load is written as *PL1/EPS-min/Present/WDR/HR/LowML*.

2.2.2.1. Córdoba, Spain

Setup

Three otherwise identical walls were analysed that differ only in masonry thickness: *SP1* (50 cm, Figure 7), *SP2* (70 cm, Figure 8), and *SP3* (25 cm, Figure 9), with all other inputs held constant. Figures present detailed outputs; examples referenced below are marked in the figures. Patterns are consistent across the three walls.

Impact of masonry thickness

Increasing masonry thickness systematically lowers maxMGI at the IWI interface by buffering temperature and moisture fluctuations. Performance follows *SP2* (best) > *SP1* > *SP3* (most vulnerable). For *SP1* and *SP2*, almost all scenarios remain in the 'green light' range (with a few reaching 'yellow light'), while *SP3* shows isolated 'red light' cases under combined stressors.

Impact of insulation system

Risk concentrates in wood fibre (*WF*), the only system reaching 'yellow light' and, for *SP3*, 'red light'. Thick *WF* (*WF-max*) under *HighML* is the principal trigger. For example, *SP2/WF-max/Present/North/MR/HighML* yields maxMGI ≈ 2.1 versus *WF-min* ≈ 1.1 ; same scenario in *SP3* reaches maxMGI ≈ 3.1 versus ≈ 2.6 .

Cellulose (*CEL*) is moderately higher than mineral systems but remains within 'green light' (typically ≈ 1.0 – 2.0). All other systems (*AAC*, *CS*, *PER*, *CCB*, *EPS*, *MW*) are consistently within 'green light' (≈ 0.0 – 0.5) with no critical scenarios.

Impact of internal moisture load

Internal moisture load governs the outcomes. Under *LowML*, all configurations – including *WF* and thin masonry in *SP3* – remain within 'green light'. Under *HighML*, risk increases markedly for *WF*, especially for *WF-max* and *SP3*; for instance, *SP3/WF-max/Present/North/HR/HighML* is ≈ 3.1 vs ≈ 0.1 with *LowML*.

Impact of wind-driven rain (WDR)

In Córdoba, raising *WDR* from moderate (*MR*) to high (*HR*) does not produce systematic changes in the 'light' classification. It slightly elevates *WF* responses under *HighML* but seldom shifts the overall risk category.

Impact of wall orientation

Orientation exerts a stronger influence than rain level alone. Although the *WDR* façade (90°) is most exposed to rain, the *North* façade is generally more critical due to reduced solar gains and limited drying. 'Yellow/red light' outcomes cluster on *North*-facing *WF* under *HighML*, while *WDR* cases are typically somewhat less severe. Only *SP3* with *WF-max* and *HighML* occasionally reaches 'yellow light' on the *WDR* façade.

Impact of future climate (RCP 8.5, 2070)

Overall mould risk declines as higher temperatures shorten periods favourable to mould growth, offsetting slightly higher rainfall and reduced solar radiation. The most critical present-day cases improve; for example, *SP3/WF-max/Future/North/HR/HighML* drops below the 'red light' threshold ($\text{maxMGI} < 3.0$; *Present* ≈ 3.1). For *SP1* and *SP2*, all scenarios remain at or below ≈ 2.0 across orientations. Differences between *Present* and *Future* conditions are most pronounced for *WF-max* under *HighML*; other systems remain stably within 'green light'.

Key takeaways

- Most assemblies in Córdoba are within 'green light'; greater masonry thickness enhances robustness ($\text{SP2} > \text{SP1} > \text{SP3}$).
- Elevated risk arises from thin masonry (*SP3*) combined with *WF-max* and *HighML*, particularly on *North* façades.
- Future warming reduces the few elevated-risk cases, reinforcing predominantly 'green light' outcomes.

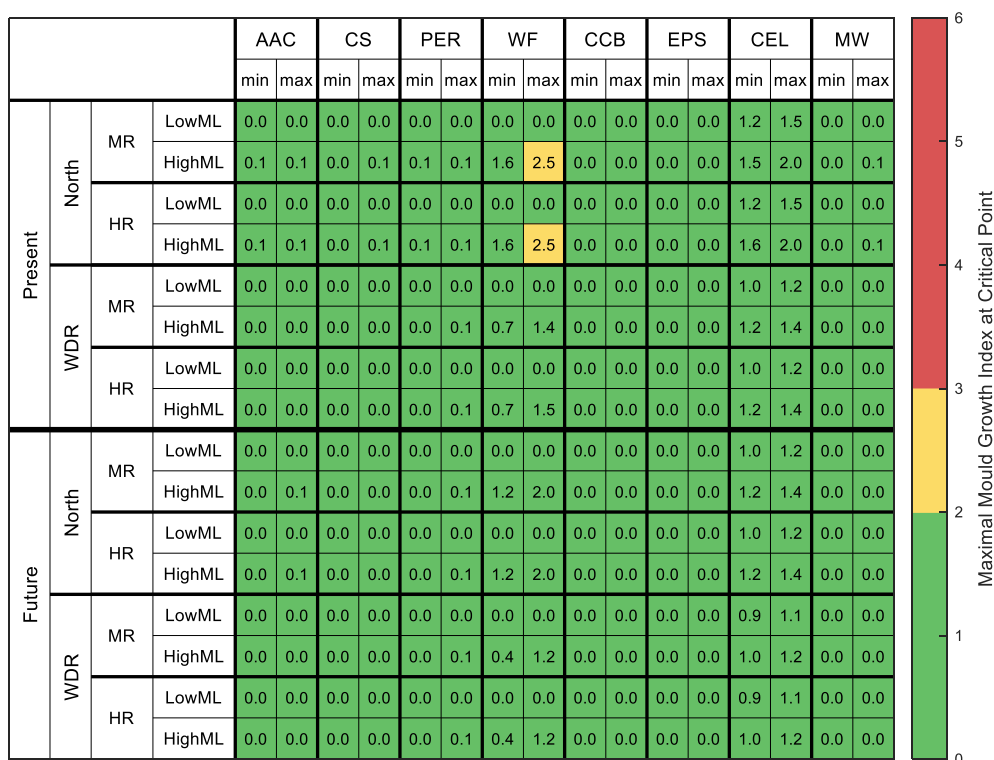


Figure 7. Maximal Mould Growth Index (maxMGI) in each scenario with wall SP1.

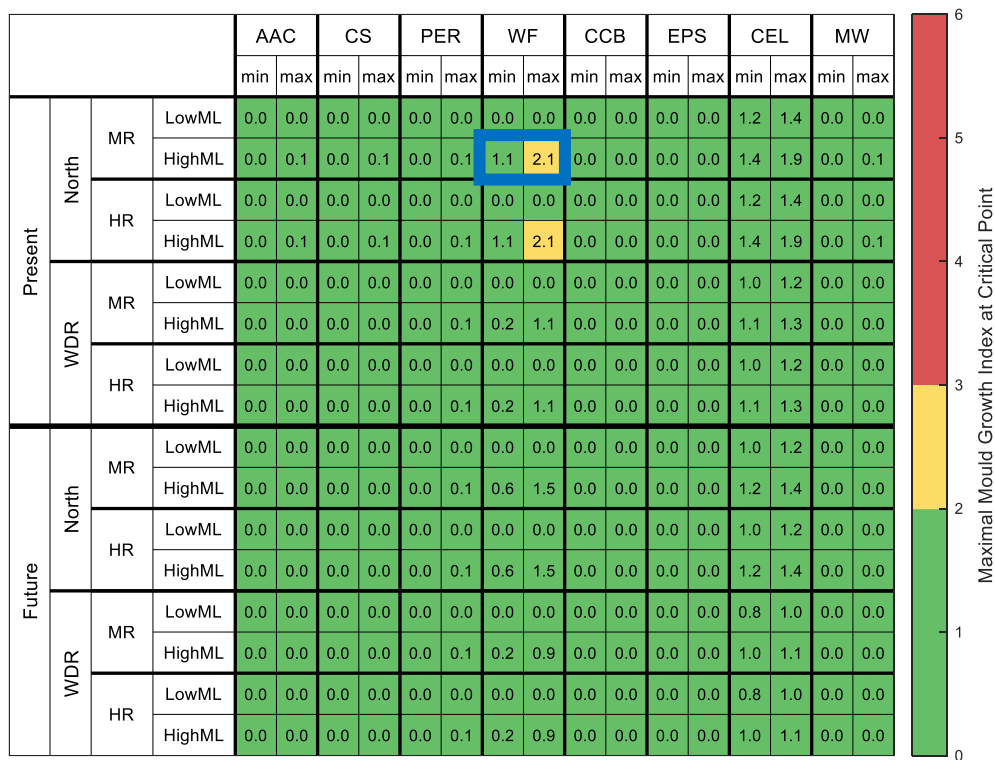


Figure 8. Maximal Mould Growth Index (maxMGI) in each scenario with wall SP2.

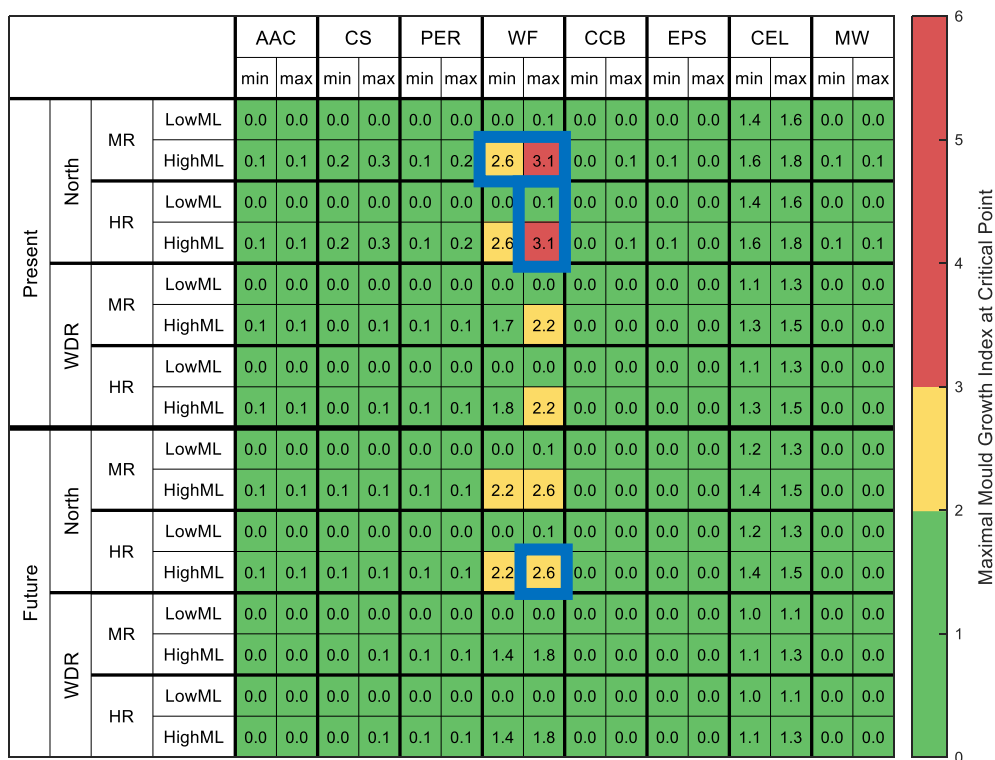


Figure 9. Maximal Mould Growth Index (maxMGI) in each scenario with wall SP3.

2.2.2.2. Kraków, Poland

Setup

Two wall configurations were analysed: *PL1* without external plaster (Figure 10) and *PL2* with an external plaster layer (Figure 11). All other inputs are identical; examples cited below are marked in the figures.

Impact of external plaster

Adding external plaster (*PL2*) consistently reduces wind-driven rain ingress and lowers maxMGI at the IWI interface. Overall trends across materials remain similar, but *PL2* generally performs better than *PL1*.

Impact of insulation system

- Autoclaved aerated concrete (AAC): Most robust. Remains well within 'green light' even under adverse conditions; thickness has negligible influence.
e.g., *PL1/AAC-max/Present/North/HR/HighML* ≈ 0.4 vs *AAC-min* ≈ 0.1
- Calcium silicate (CS): Generally, 'green light'; thick layers under high rain (*HR*) and *HighML* can reach 'yellow light'.
e.g., *PL1/CS-max/Present/North/HR/HighML* ≈ 2.3 vs *CS-min* ≈ 0.5
- Perlite (*PER*): Similar to CS but with higher MGIs; thick layers can approach the threshold
e.g., *PL1/PER-max/Present/North/HR/LowML* ≈ 2.9 vs *PER-min* ≈ 0.3
- Wood fibre (*WF*): Strongly dependent on thickness and internal moisture load. Under *LowML* many cases are within 'green light', but with *HighML* and *WF-max*, critical outcomes are frequent, especially for *PL1*. Future climate improves results but *WF-max/HighML* cases often remain within 'yellow light'.
e.g., *PL2/WF-max/Present/WDR/HR/HighML* ≈ 3.2 vs *WF-min* ≈ 2.0
- Clay cork insulation (*CCB*): Consistently 'green light'; values rise under adverse conditions but remain below thresholds.
e.g., *PL1/CCB-max/Present/North/HR/HighML* ≈ 1.9 ; *CCB-min* ≈ 1.4
- EPS: Different mechanism due to high vapour resistance – restricted drying can drive risk even at *LowML* when rain is high. 'Yellow/red light' occurs in *PL1* under *HR* regardless of thickness.
e.g., *PL1/EPS-min/Present/WDR/HR/HighML* ≈ 3.1 vs *EPS-max* ≈ 3.2
- Cellulose with SVR (*CEL*): Most critical overall. For *PL1*, no scenario is within 'green light' and MGIs can reach up to 4.8. For *PL2*, favourable conditions (*LowML*, moderate rain *MR*) can be within 'green light', but small increases in internal moisture load or rain quickly shift to 'yellow light' or 'red light'.
e.g., *PL2/CEL-max/Present/WDR/HR/LowML* ≈ 3.1 vs *CEL-min* ≈ 2.2

- Mineral wool with SVR (MW): Intermediate. In *PL1* many cases are within 'yellow/red light'; only *LowML* with moderate rain (*MR*) tends to be within 'green light'.
e.g., *PL2/MW-max/Present/North/HR/LowML* ≈ 2.4 vs *MW-min* ≈ 0.9

Impact of internal moisture load

Switching from *LowML* to *HighML* significantly increases risk, moving several systems (*WF*, *PER*, *EPS*, *CEL*, *MW*) from 'green light' to 'red light' under unfavourable rain. *LowML* does not guarantee safety without rain protection: in *PL1*, *CEL* can remain within 'red light' even at *LowML*, while in *PL2* high rain (*HR*) can still push some systems to 'yellow light' or 'red light'. *AAC*, *CCB*, and *CS-min* remain consistently within 'green light'.

Impact of wind-driven rain (WDR)

Rain impact is much stronger for *PL1* than *PL2* because the external plaster limits ingress. In *PL2*, many configurations (*AAC*, *CCB*, and often *WF*) maintain their risk class when shifting from *MR* to *HR*. In *PL1*, systems such as *EPS*, *MW*, and *CEL* show clear deterioration with increased rain. Under the *Future* climate, with lower total rainfall, the *MR-HR* distinction becomes less consequential.

Impact of wall orientation

Orientation effects are modest but non-negligible. Although the west façade (270°) is *WDR*-worst, the *North* façade often proves more critical due to limited solar drying. For example, *PL1/EPS-min/Present/WDR/HR/LowML* ≈ 0.4 , whereas the same on the *North* façade reaches ≈ 2.2 . In *PL2*, orientation-driven class changes are less frequent but can occur for *CS*, *PER*, *WF*, *EPS*, *CEL*, and *MW*.

Impact of future climate (RCP 8.5, 2070)

Higher temperatures ($\approx +5^{\circ}\text{C}$) and reduced annual rainfall ($\sim 69\%$ of present) substantially lower MGIs. Many present 'yellow/red light' cases shift to 'green light'. Persistent 'yellow/red light' outcomes mainly involve *WF-max* under *HighML*. The largest improvements occur for high-risk present systems (*CEL*, *EPS*, *PER*, *WF*, *MW*); for instance, *PL2/CEL-max/Present/North/HR/HighML* ≈ 4.6 drops to ≈ 1.6 in the *Future*.

Key takeaways

- External plaster (*PL2*) markedly improves robustness by limiting rain ingress; material rankings otherwise remain similar.
- Internal moisture load is the primary driver; *HighML* combined with rain exposure elevates risk, especially for *WF*, *EPS*, *CEL*, and *MW*.
- *AAC* and *CCB* are consistently within 'green light'; *CS-min* generally remains within 'green-light', while *PER* and *CS-max* can reach 'yellow light' under *HR/HighML*.
- Orientation has a secondary but noticeable effect; *North* façades are often more critical than *WDR* due to reduced solar drying.

- Future climate strongly reduces risk in Kraków; many currently critical combinations become within 'green light', with residual concerns focused on *WF-max* under *HighML*.

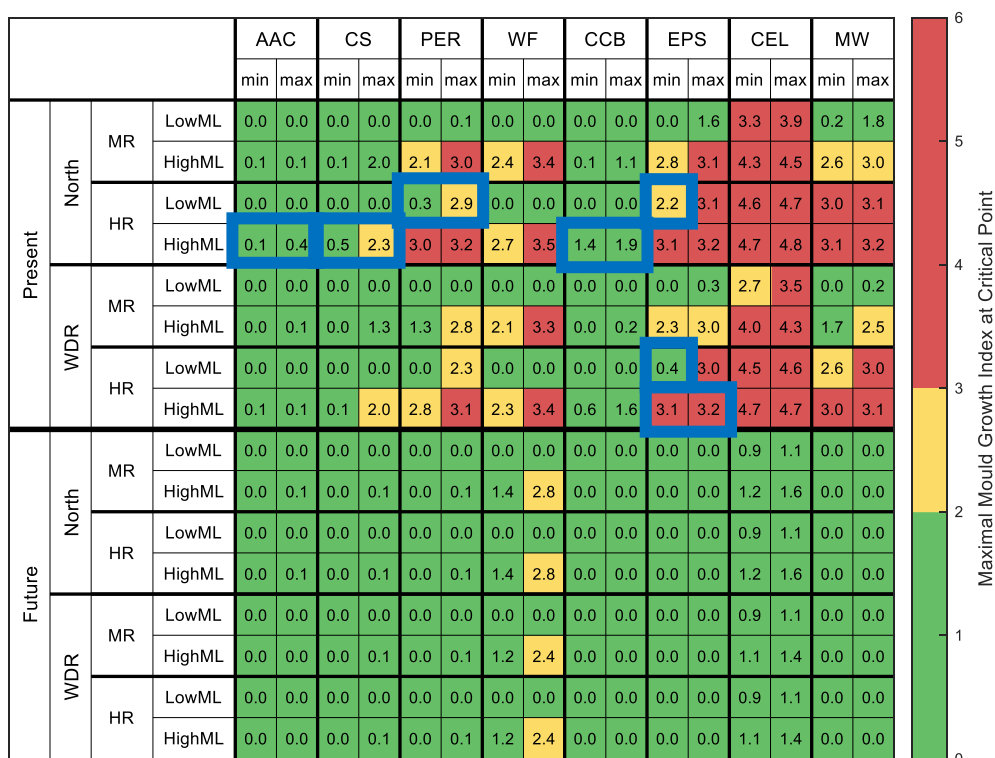


Figure 10. Maximal Mould Growth Index (maxMGI) in each scenario with wall PL1.

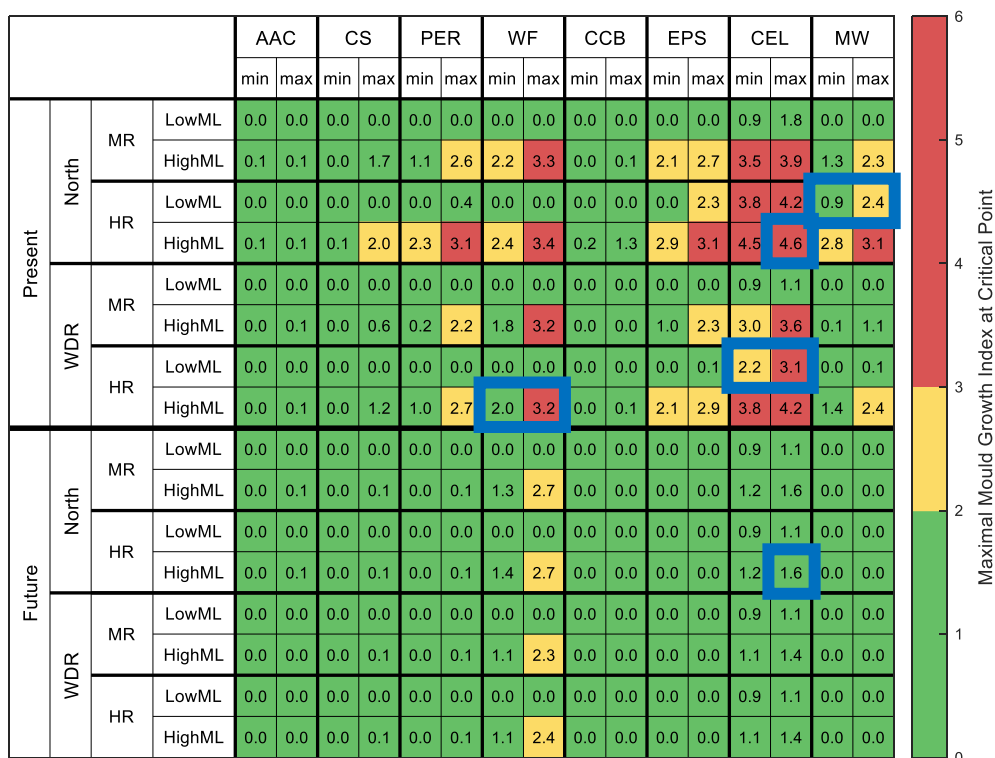


Figure 11. Maximal Mould Growth Index (maxMGI) in each scenario with wall PL2.

2.2.2.3. Linköping, Sweden

Setup

Three walls differing only in masonry thickness were analysed: *SE1* (50 cm, Figure 12), *SE2* (70 cm, Figure 13), and *SE3* (25 cm, Figure 14). A fourth configuration, *SE4*, represents a thin wall with an already existing 5 cm internal wood-fibre layer and is reported separately due to its different construction (Figure 15). Examples referenced below are marked in the figures.

Impact of masonry thickness (*SE1* – *SE3*)

Thicker masonry systematically reduces mould risk by increasing thermal and moisture buffering, lowering peak relative humidity and shortening critical periods at the IWI interface. Performance ranks *SE2* (best) > *SE1* > *SE3* (most vulnerable), mirroring the Spanish results.

Impact of insulation system (*SE1* – *SE3*)

- Autoclaved aerated concrete (AAC) remains consistently within 'green light'.
- Calcium silicate (CS) is predominantly within 'green light' but can reach 'yellow light' under *HighML*, particularly for *CS-max*.
e.g., *SE1/CS-max/Present/North/MR/HighML* $\approx$ 2.1 vs *CS-min* $\approx$ 0.1
- Perlite (*PER*) follows a similar trend to CS with slightly higher MGIs; 'yellow light' occurs only under *HighML*, with thickness-dependent changes in *SE1*–*SE2*.
e.g., *SE1/PER-max/Present/North/MR/HighML* $\approx$ 2.7 vs *PER-min* $\approx$ 1.4
- Wood fibre (*WF*) is the most sensitive system: thick layers under *HighML* are almost always within 'red light'. In *SE1* – *SE2*, increasing *WF* thickness under *HighML* shifts outcomes from 'green/yellow light' to 'red light', while in *SE3* even *WF-min* under *HighML* is already critical.
e.g., *SE2/WF-max/Present/North/MR/HighML* $\approx$ 3.3 vs *WF-min* $\approx$ 1.9
- Clay cork insulation (*CCB*) remains within 'green light' across scenarios.
- EPS is mostly within 'green light'; 'yellow light' appears on *North* façades under *HighML*, with minimal thickness influence.
- Cellulose (*CEL*) reaches 'yellow light' under *HighML* and can get to 'red light' on *North* façades for *CEL-max*.
e.g., *SE1/CEL-max/Present/North/HR/HighML* $\approx$ 3.6 vs *CEL-min* $\approx$ 2.9
- Mineral wool (*MW*) is generally within 'green light' but can reach 'yellow light' under *HighML* on *North* façades, with thickness-driven shifts in these cases.
e.g., *SE3/MW-max/Present/North/MR/HighML* $\approx$ 2.1 vs *MW-min* $\approx$ 0.4

Impact of internal moisture load

Under *LowML*, nearly all *SE1–SE3* scenarios remain within 'green light' (with minor *CEL* exceptions). Under *HighML*, MGIs rise sharply, especially for *WF* and *CEL*, producing transitions from 'green light' to 'red light' under otherwise identical conditions. The effect is strongest for *SE3* due to limited buffering (e.g., *SE2/WF-max/Present/North/HR: HighML* ≈ 3.3 vs *LowML* ≈ 0.0). In *SE4*, nearly all cases are within 'green light', reducing the load from *HighML* to *LowML* consistently shifts results back to 'green light'.

Impact of wind-driven rain (WDR)

Rain effects are generally limited and often within model uncertainty for *SE1–SE3*, but borderline shifts can occur, especially for *CEL* and *MW* in *SE3* (e.g., *SE3/CEL-min/Present/North/HR/HighML* ≈ 3.4 vs *MR* ≈ 2.6). In *SE4*, reducing rain from high (*HR*) to moderate (*MR*) typically produces 'green light' outcomes, with only a few *WF-max* cases remaining within 'yellow light'. More pronounced rain sensitivity appears in selected *Future* scenarios (e.g., *SE3/MW-max/Future/North/HR/HighML* ≈ 2.5 vs *MR* ≈ 0.2).

Impact of wall orientation

Orientation effects are moderate. Although the *WDR*-most exposed façade in Linköping is southwest (225°), *North* is typically slightly more critical due to reduced solar drying. Differences between *North* and *WDR* are most visible under *HighML* for *CS*, *PER*, *EPS*, *CEL*, and *MW* (e.g., *SE1/EPS-max/Present/WDR/MR/HighML* ≈ 1.4 vs north ≈ 2.6). For *WF* under *HighML* in *SE1–SE3*, both orientations are often already within 'red light', so traffic light does not change between wall orientations. In *SE4*, *North* cases more readily reach 'yellow light' than the *WDR* façade.

Impact of pre-existing internal wood fibre (*SE4*)

The existing 5 cm *WF* layer elevates the temperature at the new insulation's critical interface, generally lowering MGIs compared with an otherwise similar thin wall without this layer. Most *SE4* scenarios fall within the 'green light'. This assessment focuses on the new insulation interface and does not address potential mould growth within the pre-existing, moisture-sensitive *WF* layer itself. 'Yellow light' outcomes are confined to a few combinations:

- *PER-max* under severe boundary conditions;
- selected *WF-max* cases under *HighML*;
- and some *CEL* cases on the north façade with high rain and *HighML*.

e.g., *SE4/PER-max/Present/North/HR/HighML* ≈ 2.1 vs *PER-min* ≈ 0.0

These are also the cases where boundary-condition changes (moisture load, rain, orientation, climate) can meaningfully shift the class. Orientation remains influential in *SE4*: *North* is typically more critical, while the *WDR* façade benefits from greater drying (e.g., *SE4/WF-max/Present/North/HR/HighML* ≈ 3.0 vs ≈ 2.0 on the *WDR* façade under otherwise identical conditions).

Impact of future climate (RCP 8.5, 2070)

Warming generally reduces MGIs for many systems (*CS*, *PER*, *WF*, *EPS*, *MW*) in *SE1–SE3* and shifts most *SE4* scenarios to 'green light'. However, for highly sensitive materials the benefit can be offset by moisture availability; selected *CEL* cases become more critical, especially on thin walls and *North* façades (e.g., *SE3/CEL-max/Future/North/HR/LowML* ≈ 2.8 vs ≈ 1.7 at *Present*). In *SE4*, the main exceptions that may remain within 'yellow light' are the most critical *WF-max* cases on the *North* façade under *HighML*; isolated *CEL* cases can also worsen (e.g., *SE4/CEL-min/Future/North/HR/HighML* ≈ 2.1 vs ≈ 1.0 at *Present*). Thus, warming alone does not guarantee lower risk in cold, moisture-prone contexts.

Key takeaways

- Wall thickness matters in *SE1–SE3* ($SE2 > SE1 > SE3$); *SE4*'s pre-existing *WF* layer raises interface temperatures and generally lowers MGIs.
- *WF* under *HighML* is the principal vulnerability; *CEL* shows elevated sensitivity on *North* façades and thinner walls.
- *AAC* and *CCB* are consistently within 'green light'; *CS* and *PER* are mostly within 'green light' with 'yellow light' under *HighML*; *EPS* and *MW* are generally within 'green light' but can reach 'yellow light' on *North* façades at *HighML*.
- Rain and orientation effects are moderate but can tip borderline cases, particularly for *CEL* and *MW* in *SE3*; in *SE4*, *North* façades and *High rain/HighML* drive the few 'yellow/red light' outcomes.
- Future climate often reduces risk, yet select *CEL* and *WF* configurations remain or become out of 'green light', underscoring the need for case-specific assessment.

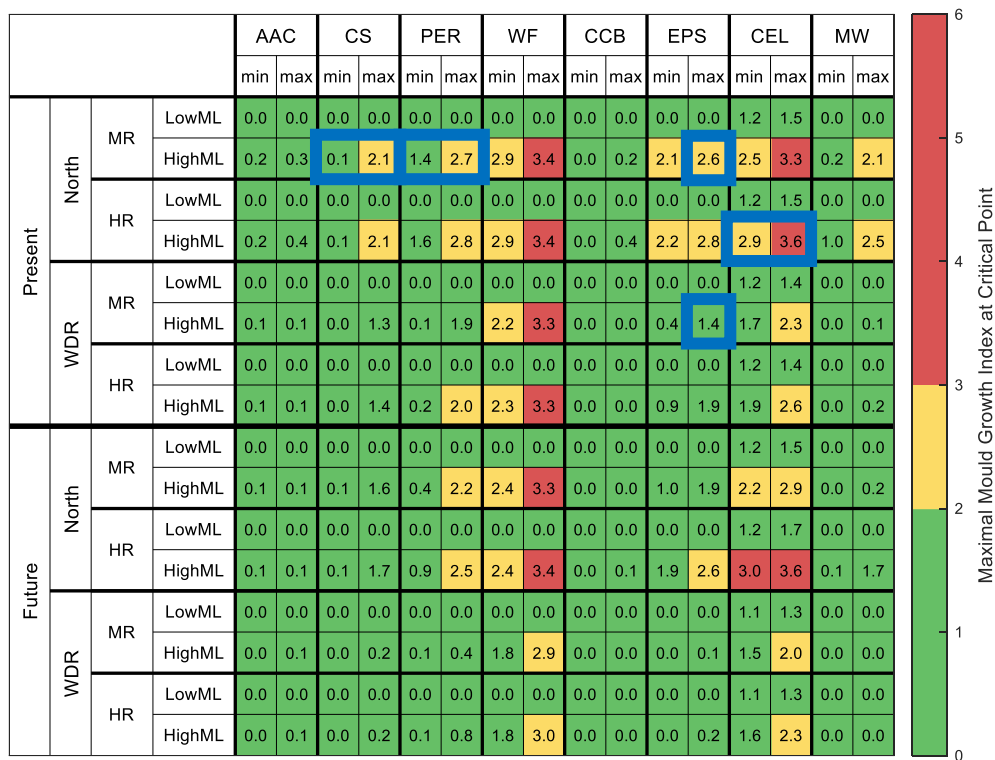


Figure 12. Maximal Mould Growth Index (maxMGI) in each scenario with wall SE1.

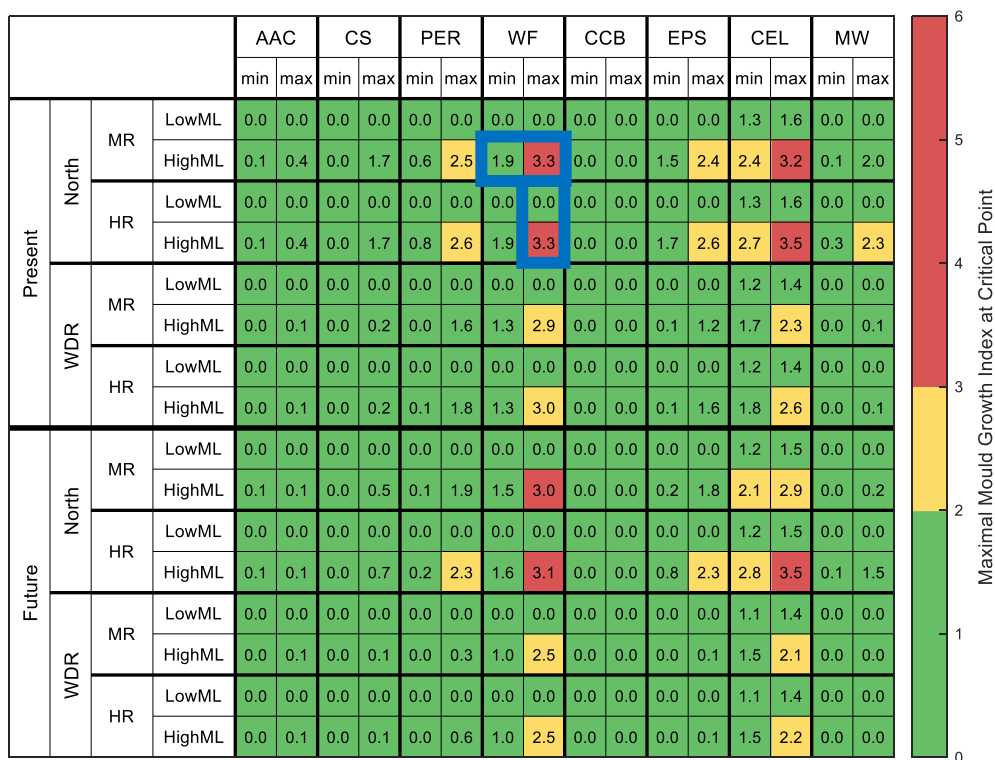


Figure 13. Maximal Mould Growth Index (maxMGI) in each scenario with wall SE2.

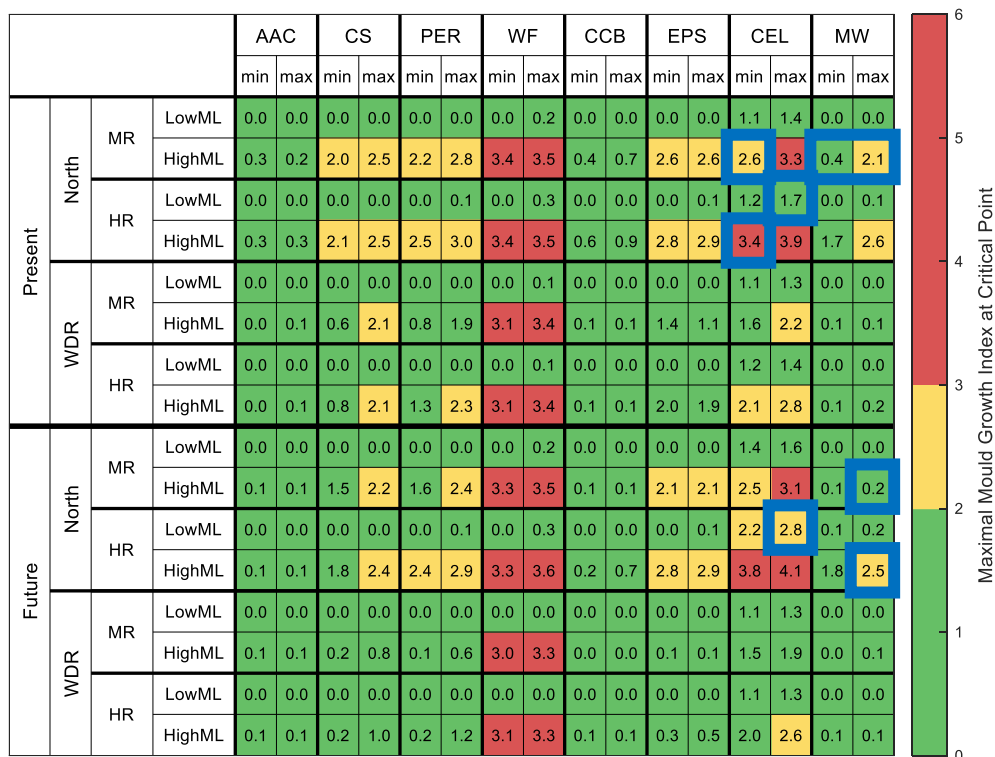


Figure 14. Maximal Mould Growth Index (maxMGI) in each scenario with wall SE3.

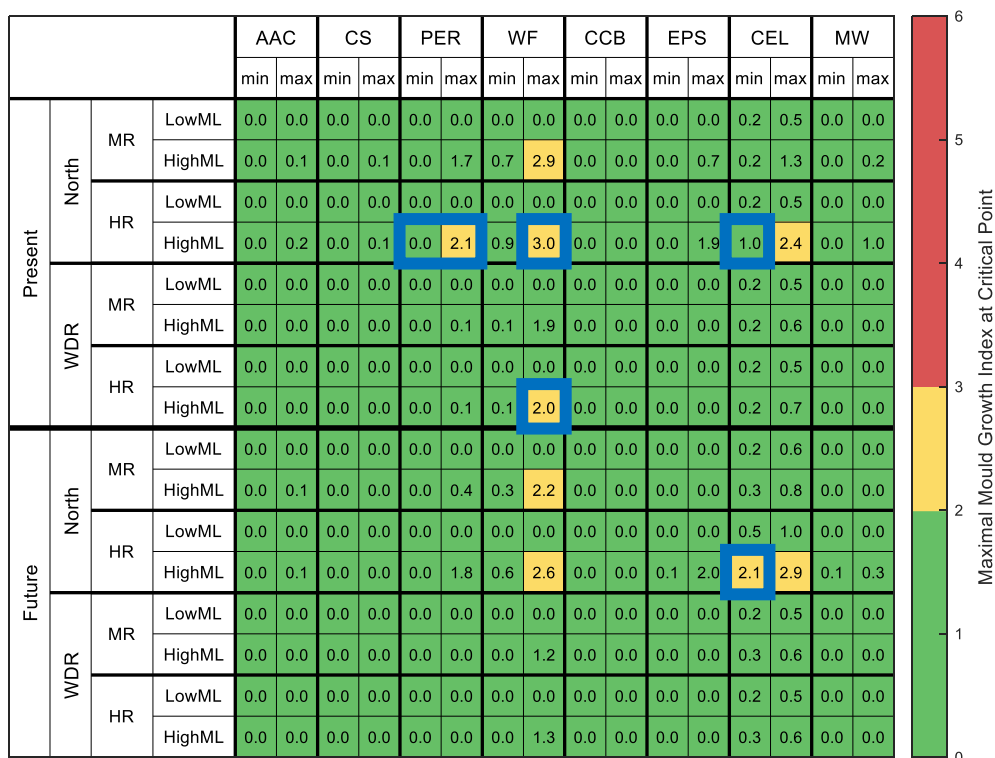


Figure 15. Maximal Mould Growth Index (maxMGI) in each scenario with wall SE4.

2.2.2.4. Edinburgh, Scotland

Setup

Five wall configurations were analysed: SC1 (Figure 16) - SC2 (Figure 17), sandstone with historical internal plaster: SC1 with external plaster, SC2 without; SC3 (Figure 18) - SC4 (Figure 19), sandstone with lath-and-plaster interior: SC3 with external plaster, SC4 without; and SC5 (Figure 20), granite without external plaster.

Impact of external plaster and interior build-up

External plaster consistently reduces rain ingress and lowers MGIs across sandstone walls (SC1 vs SC2; SC3 vs SC4). Lath-and-plaster interiors (SC3-SC4) add an air gap that enhances drying, yielding lower MGIs than historical internal plaster (SC1-SC2). Granite without plaster (SC5) is the most exposed and most critical configuration.

Impact of insulation system

- Autoclaved aerated concrete (AAC): Consistently within 'green light' across boundary conditions.
e.g., SC2/AAC-max/Present/WDR/HR/HighML ≈ 1.4 vs LowML ≈ 0.0
- Calcium silicate (CS): Predominantly within 'green light', reaching 'yellow light' under HighML, especially for CS-max and without external plaster.
e.g., SC3/CS-max/Present/North/HR/HighML ≈ 2.2 vs CS min ≈ 1.1
- Perlite (PER): More sensitive, within 'yellow light' under HighML and occasionally 'red light' on WDR; Scotland shows a clear thickness effect even at LowML due to high rain.
e.g., SC1/PER-max/Present/WDR/MR/LowML ≈ 2.1 vs PER-min ≈ 0.7
- Wood fibre (WF): 'Green light' at LowML; shift to 'yellow/red light' under HighML. Once HighML applies, thickness adds limited further risk.
- Clay cork insulation (CCB): Mostly 'green light'; 'yellow light' occurs under combined HighML and High rain on WDR.
- EPS: 'Yellow light' on North façades under HighML and frequently 'yellow/red light' on WDR; thickness effects are minor and within uncertainty.
e.g., SC1/EPS-max/Present/North/HR/HighML ≈ 2.9 vs EPS-min ≈ 3.0
- Cellulose (CEL): Among the most critical – consistently 'red light' on WDR at Present and 'yellow/red light' on North under HighML.
- Mineral wool (MW): Similar to CEL but with slightly lower MGIs.

Impact of internal moisture load

Internal moisture load governs outcomes. On North façades, LowML cases are generally within 'green light', while on WDR many LowML cases are already outside of 'green light' (notably PER,

EPS, CEL, MW). Increasing to *HighML* drives large MGI jumps and colour changes across systems, e.g., *SC1/WF-max/Present/North/MR/HighML* ≈ 3.5 vs ≈ 0.2 under *LowML*.

Impact of wind-driven rain (WDR)

Shifting from *MR* to *HR* usually has limited impact, but under *WDR* it can flip colours in sensitive systems, e.g., *SC3/EPS-max/Present/WDR/HR/LowML* ≈ 2.9 vs *MR* ≈ 1.8 .

Impact of wall orientation

Orientation is decisive and differs from Spain and Poland: the *WDR* façade (west, 270°) is more critical than *North* because extreme rain loads outweigh solar drying. Large colour differences are common, e.g., *SC1/CEL-min/Present/WDR/MR/LowML* ≈ 4.2 vs *North* ≈ 1.2 .

Impact of granite wall (SC5)

In *SC5*, *WDR* $\gg$ *North* across all systems; thickness effects are visible even at *LowML* (e.g., *SC5/CS-max/Present/WDR/MR/LowML* ≈ 2.8 vs *CS-min* ≈ 0.3).

Impact of future climate (RCP 8.5, 2070)

Higher temperatures and reduced rainfall generally lower MGIs across wall types, with the largest gains in present-day *WDR/LowML* cases (e.g., *SC2/MW-max/Future/WDR/HR/LowML* ≈ 0.6 vs ≈ 3.2 at *Present*). Most notable improvements occur for *PER*, *EPS*, *MW*, and *CEL-min*. Remaining 'red light' cases are mainly tied to *HighML*, highly sensitive materials (*WF-max*, *CEL-max*), and highly exposed assemblies, particularly *SC5*, where roughly half of scenarios remain critical.

Key takeaways

- *WDR* is the dominant external driver; the *WDR* façade is more critical than *North*. External plaster and lath-and-plaster interiors significantly reduce risk.
- *AAC* and *CCB* are generally within 'green light'; *CS* and *PER* are mostly within 'green light' but show thickness sensitivity under *HighML* and on *WDR*.
- *EPS*, *CEL*, and *MW* frequently become above 'green light' on *WDR*; *CEL* is the most critical.
- Internal moisture load is another driver: *HighML* pushes many systems to 'yellow/red light'; *LowML* may still be unsafe on *WDR*, especially in *SC5*.
- Future climate substantially reduces risk in Scotland, yet *HighML* and highly exposed configurations, most notably *SC5*, can remain out of 'green light'.

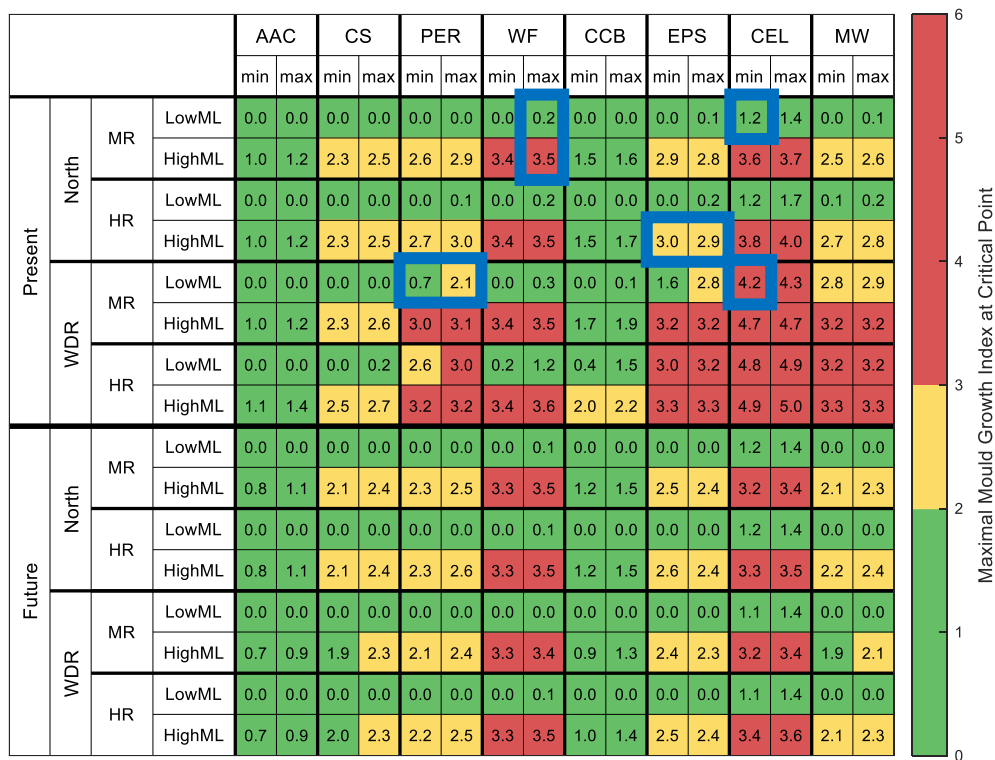


Figure 16. Maximal Mould Growth Index (maxMGI) in each scenario with wall SC1.

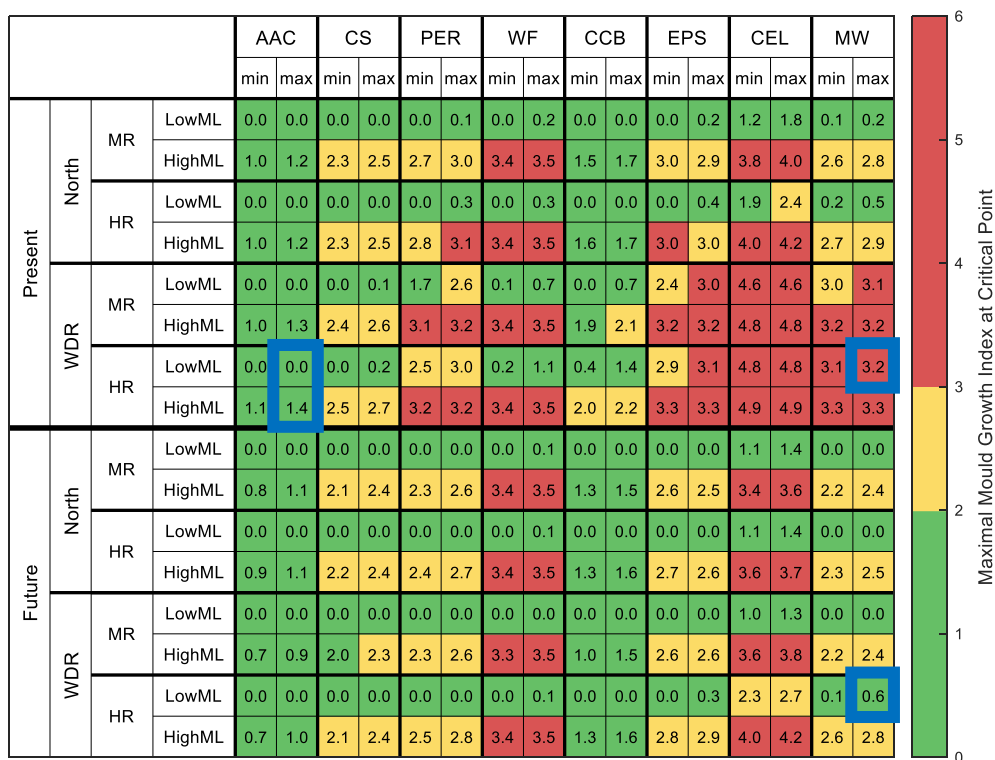


Figure 17. Maximal Mould Growth Index (maxMGI) in each scenario with wall SC2.

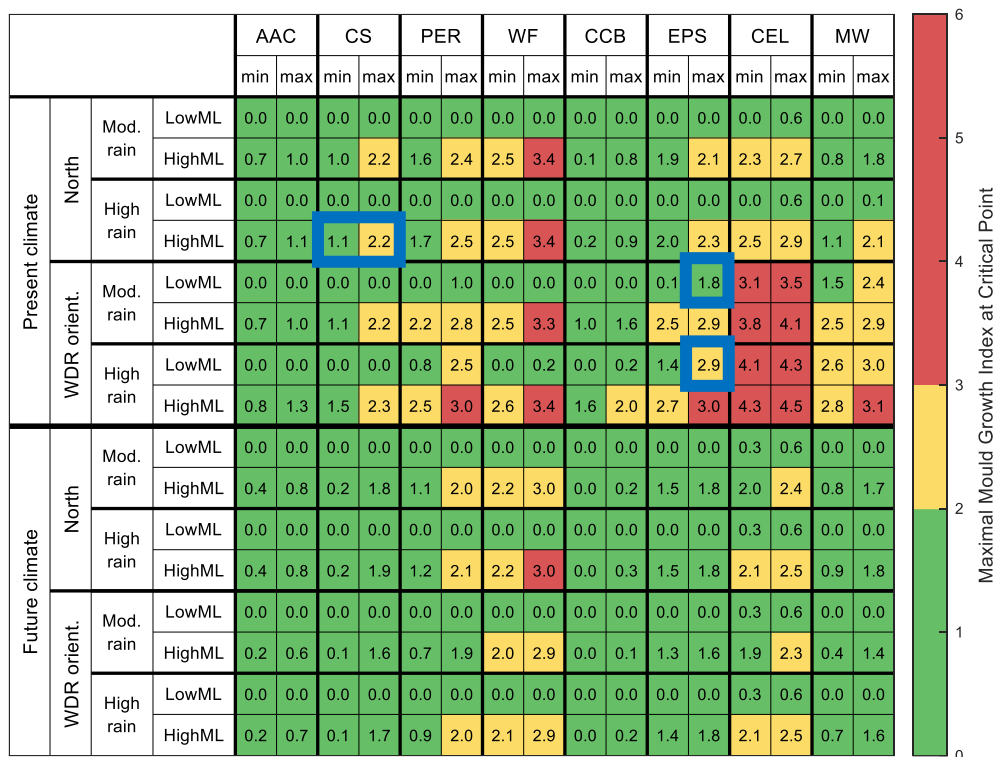


Figure 18. Maximal Mould Growth Index (maxMGI) in each scenario with wall SC3.

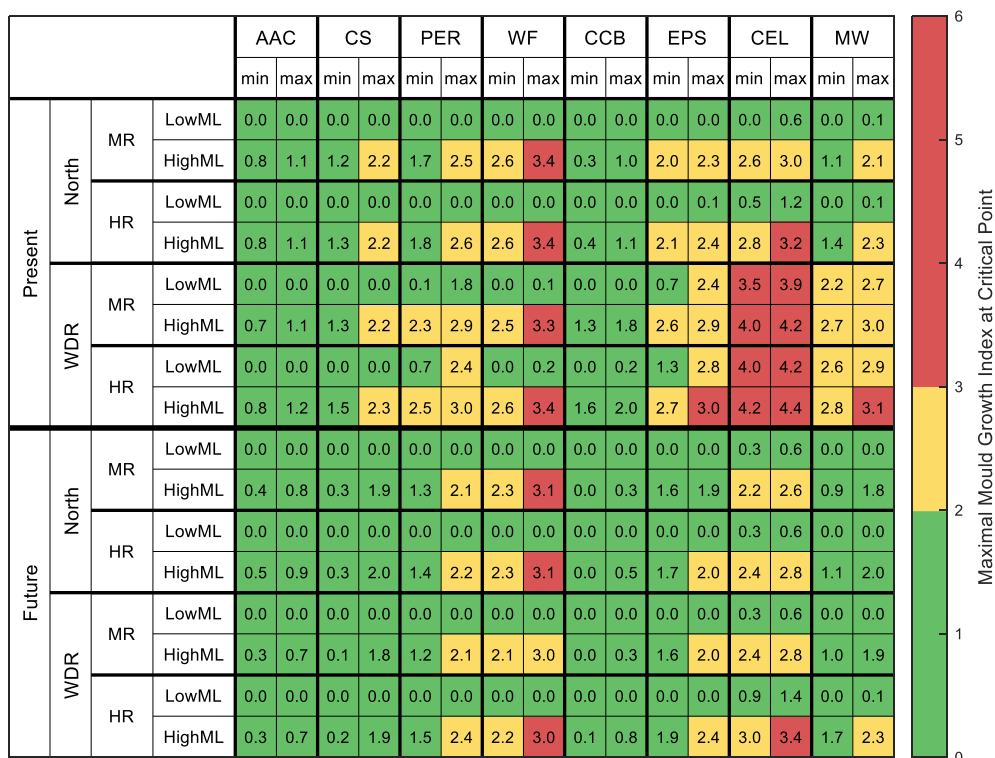


Figure 19. Maximal Mould Growth Index (maxMGI) in each scenario with wall SC4.

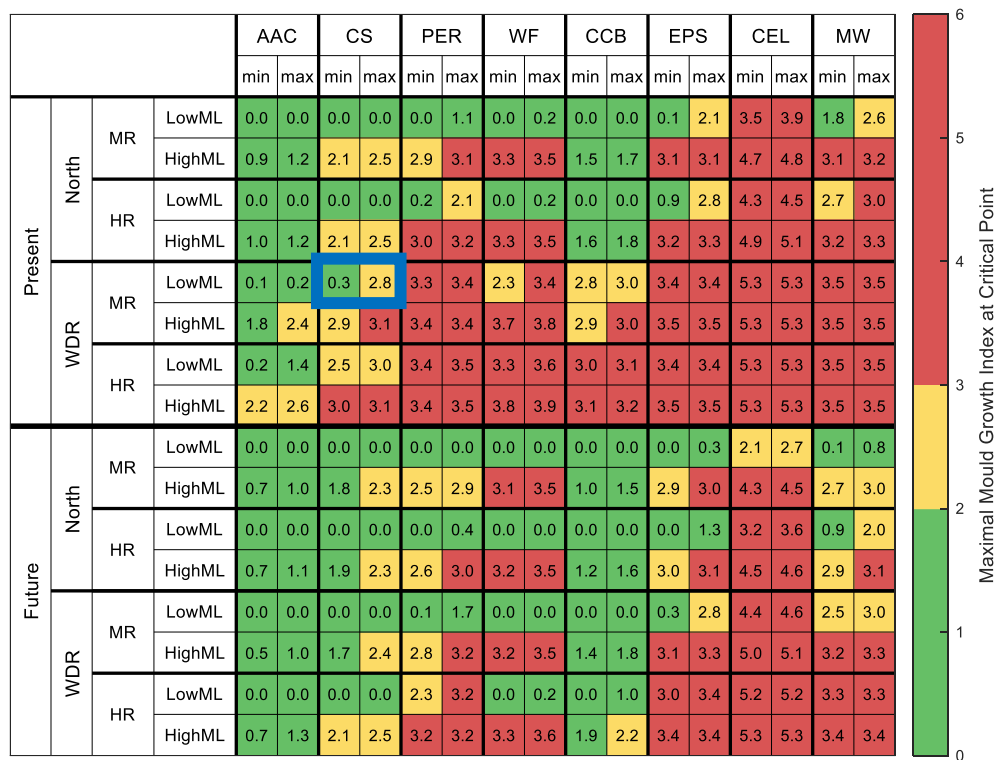


Figure 20. Maximal Mould Growth Index (maxMGI) in each scenario with wall SC5.

2.2.3. Summary

The summary of the results presented in Section 2.2.2 is shown in the table below.

Table 18. Cross-country comparison.

Aspect	Spain (Córdoba)	Poland (Kraków)	Sweden (Linköping)	Scotland (Edinburgh)
Overall risk level	Low (mostly 'green light')	Moderate to high	Moderate	High (most critical)
Wall thickness effect	thicker = safer	<i>Not applicable</i>	thicker = safer	<i>Not applicable</i>
Rain protection (ext. plaster)	<i>Not applicable</i>	Strong effect (safer with)	<i>Not applicable</i>	Very strong effect
Robust systems	AAC, CS, PER, CCB, EPS, MW	AAC, CCB	AAC, CCB	Mostly AAC (but not always safe)
Critical systems	WF only	CEL, EPS, WF, PER, MW	WF, CEL	CEL, WF, EPS, PER, MW
Internal moisture load (ML)	Dominant driver	Dominant driver	Dominant driver	Dominant driver
Rain exposure (MR → HR)	Minor effect	Strong (esp. if no plaster)	Minor	Strong (especially WDR)
Critical orientation	North	North	North (slightly)	WDR (west)
Future climate effect	Slight improvement	Strong improvement	Mixed (mostly ↓, some ↑)	Partial improvement

2.3. Simulations in WUFI

While the core physics of coupled heat and moisture transport are shared across hygrothermal tools, each platform differs in model formulations, material libraries, boundary-condition implementations, and numerical solvers. To test the robustness of our conclusions and identify any tool-dependent sensitivities, a representative subset of scenarios was repeated in WUFI and compared both inputs and outcomes, focusing on the resulting mould growth index (MGI).

The primary aim was to assess whether WUFI reproduces the ranking of risk across typologies and systems and to identify any configurations where tool choice would reverse a design recommendation. Exact numerical coincidence is neither expected nor required: differences in default surface transfer coefficients, rain deposition models, discretization, and library material functions can lead to small offsets in peak relative humidity, time-of-wetness, or the timing of drying events.

The comparison covered the same wall typologies and variants used previously: *SP1*, *SP2*, *PL1*, *PL2*, *SE1*, *SC1*, *SC2*, *SC3*, and *SC5*. The climate was the present-day reference climate (*Present*). Two orientations (*North* and the wind-driven-rain (*WDR*) exposure) and two indoor moisture load cases (*LowML* and *HighML*) were simulated. Rain exposure followed the medium-rain (*MR*) and

high-rain (*HR*) categories, respectively. The insulation systems replicated the prior set: *AAC*, *CS*, *PER*, *WF*, *EPS*, *CEL*, and *MW*, at minimum and maximum thickness options to represent the span of practical designs.

Model in WUFI

Our objective was methodological uniformity with the Delphin simulations. First, layer stacks in WUFI were assembled by selecting materials from its library that most closely matched those used in Delphin. Manual edits to material files were avoided. Boundary conditions were kept identical: the same weather files, including wind-driven rain, wind speed, and solar radiation, and the same indoor temperature and humidity scenarios were used. Exposure parameters (orientation, wind-driven rain category, and indoor moisture loads) were set to mirror the Delphin configurations. Initial conditions matched the Delphin start date and included the same initial temperature and relative humidity. Numerical settings were left at WUFI defaults; output intervals and simulation periods were aligned with the Delphin post-processing windows. MGI was evaluated using the same mathematical model as the one for the Delphin outputs, ensuring that observed differences stem primarily from solver and material-function implementations rather than from post-processing choices.

2.3.1.1. Various materials between Delphin and WUFI

Material selection in WUFI was guided by the principle of using the closest library entry by name and intended use (for example, "Calcium silicate board," "EPS," "Wood fibre insulation," "Autoclaved aerated concrete"). Where multiple candidates existed, the entry was preferred whose core hygrothermal properties most closely matched the Delphin dataset: bulk density ρ , specific heat capacity c_p , thermal conductivity λ , and vapour diffusion resistance μ . Manual edits to WUFI material files were avoided.

Finally, mould sensitivity classifications were kept consistent across tools. Wood-based and cellulose-based materials were assigned to the same VTT/Viitanen sensitivity class in WUFI as in the Delphin post-processing, ensuring that mould growth index comparisons reflect physics and boundary conditions rather than differences in default sensitivity assumptions.

To make differences transparent, the key library-property deviations in WUFI relative to the Delphin reference as percentage differences at representative states were quantified. These summaries accompany the results so that any observed performance gap can be related back to material-function differences rather than solver effects.

2.3.1.1.1. Existing wall masonry

For the Spanish brick typology, the Delphin library entry "Old Building Brick Dresden ZQ [286]" was compared with WUFI's "Old Building Brick Dresden ZQ" (Table 19). The datasets are nearly identical in porosity, moisture storage, liquid transport, and thermal conductivity, but they differ markedly in vapour diffusion resistance: WUFI's μ is about 70% lower than Delphin's. This makes

the brick substantially more vapour-open in WUFI, generally enhancing drying and suppressing interstitial RH peaks at the IWI interface. As a result, otherwise identical setups tend to produce lower mould growth indices in WUFI than in Delphin, with the largest effects in marginal configurations (for example, wood-fibre insulation under HighML on the North orientation). The magnitude of the difference depends on neighbouring layers, particularly if a vapour-tight product like EPS constrains one drying path, and on the specific boundary conditions. Where this discrepancy affects risk classification, a targeted sensitivity check that harmonizes μ between tools (or documents μ -adjusted reruns) is recommended.

Table 19. Comparison of material properties between Delphin and WUFI for Brick (Spain).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Old Building Brick Dresden ZQ [286]	1948.0	813.2	0.905	98.6
WUFI	Old Building Brick Dresden ZQ	1972	800	0.904	30
Difference		+1%	-2%	0%	-70%

For the Polish brick typology, Delphin's "Old Building Brick Dresden ZK [499]" was compared with WUFI's "Old Building Brick Dresden ZK" (Table 20). The datasets align closely in density, specific heat, and vapour diffusion factor (differences within 0–2%), while thermal conductivity is about 6% higher in WUFI. This slightly reduces the masonry's thermal resistance in WUFI, which can lower interface temperatures during the heating season and modestly increase mould growth index relative to Delphin. The effect is expected to be moderate and most noticeable in marginal cases where small temperature shifts influence time-of-wetness near the IWI interface.

Table 20. Comparison of material properties between Delphin and WUFI for Brick (Poland).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Old Building Brick Dresden ZK [499]	1734.1	919.2	0.656	24.5
WUFI	Old Building Brick Dresden ZK	1737	916	0.695	25
Difference		0%	0%	6%	2%

For the Swedish brick typology, Delphin's "Old Building Brick Dresden ZC [491]" was compared with WUFI's "Old Building Brick Dresden ZC" (Table 21). The main difference is thermal conductivity: WUFI is about 12% higher (0.908 vs 0.808 W/mK). Density is slightly higher in WUFI (+4%), specific heat is slightly lower (-1%), and the vapour diffusion factor is effectively identical. The higher λ in WUFI means the brick conducts heat more readily, which can reduce interface temperatures during the heating season and raise relative humidity at the IWI interface. Consequently, modestly higher MGI in WUFI was expected for cold, moisture-loaded scenarios, with the effect remaining moderate overall.

Table 21. Comparison of material properties between Delphin and WUFI for Brick (Sweden).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Old Building Brick Dresden ZC [491]	1904.4	847.4	0.808	22.9
WUFI	Old Building Brick Dresden ZC	1985	836	0.908	23
Difference		4%	-1%	12%	0%

For the sandstone case, Delphin's "Sandstone India Red [467]" was compared with WUFI's "Sandstone India Red" (Table 22). The datasets are effectively identical: density, specific heat, and vapour diffusion factor match after rounding, and thermal conductivity in WUFI is only about 3% lower. With such minor differences, any meaningful divergence in results was not expected; MGI should be essentially the same in both tools for otherwise identical setups.

Table 22. Comparison of material properties between Delphin and WUFI for Sandstone.

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Sandstone India Red [467]	2262.8	874.5	2.870	63.7
WUFI	Sandstone India Red	2263	875	2.791	64
Difference		0%	0%	-3%	0%

For the granite case, Delphin's "Granite boulder [463]" was compared with WUFI's "Granite" (Table 23). The datasets are effectively identical: density, specific heat, and vapour diffusion factor match after rounding, and thermal conductivity in WUFI is only about 3% lower. The lower λ reduces heat loss and increases temperatures in the IWI interface slightly. Similar to the Sandstone case, any meaningful divergence in results for the granite case was not expected; MGI should be essentially the same in both tools for otherwise identical setups.

Table 23. Comparison of material properties between Delphin and WUFI for Granite.

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Granite boulder [463]	2452.9	702.2	1.718	53.8
WUFI	Granite	2453	702	1.66	54
Difference		0%	0%	-3%	0%

2.3.1.1.2. Insulation materials

For the AAC internal insulation, Delphin's "Ytong Mineral Foam Multipor 2004 [597]" was compared with WUFI's "Ytong Multipor" (Table 24). The libraries diverge primarily in specific heat (-34%) and thermal conductivity (-17%), while the density and vapour diffusion resistance factor values are similar or identical. In combination, these changes yield a somewhat lower volumetric heat capacity (ρc_p) and a higher thermal resistance of the AAC layer in WUFI. The lower λ reduces heat loss and tends to keep the IWI interface colder during the heating season. Conversely, the lower c_p reduces thermal inertia and may allow larger short-term temperature swings. The net effect depends on climate and moisture load; under heating-season, high-moisture scenarios,

the λ effect typically dominates, so slightly higher MGI in WUFI was expected for otherwise identical setups.

Table 24. Comparison of material properties between Delphin and WUFI for Autoclaved aerated concrete (AAC).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Ytong Mineral Foam Multipor 2004 [597]	115.2	1292.3	0.048	4.1
WUFI	Ytong Multipor	115	850	0.040	4.1
Difference		0%	-34%	-17%	0%

For the calcium silicate insulation, Delphin's "Climate board (until 2015) [284]" was compared with WUFI's "Calcium silicate, AI" (Table 25). The core parameters match, and no discrepancies were identified. Accordingly, no meaningful differences in simulated outcomes was expected: MGI should be essentially identical across tools for otherwise identical setups. If minor deviations appear, they are likely attributable to numerical settings or subtle differences in sorption/capillary curves; these effects are expected to be negligible for the risk assessments presented.

Table 25. Comparison of material properties between Delphin and WUFI for Calcium silicate (CS).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Climate board (until 2015) [284]	222.3	1303.2	0.057	5.4
WUFI	Calcium silicate, AI	222	1303	0.057	5.4
Difference		0%	0%	0%	0%

For the perlite insulation, Delphin's "Sto-Perlite Indoor Insulation Board 045 [733]" was compared with WUFI's "Sto Perlite Interior Insulation Board 045" (Table 26). The main differences are a lower thermal conductivity in WUFI (-9%) and a much lower specific heat (-48%). The reduced λ in WUFI improves insulation performance, tending to reduce temperatures in the IWI interface and increase RH peaks, which increases MGI. Conversely, the lower c_p reduces thermal inertia and may allow larger short-term temperature swings. The net effect depends on climate and moisture load; under heating-season, high-moisture scenarios, the λ effect typically dominates, so slightly higher MGI in WUFI was expected for otherwise identical setups.

Table 26. Comparison of material properties between Delphin and WUFI for Perlite (PER).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Sto-Perlite Indoor insulation board 045 [733]	100.3	1640.1	0.046	8.0
WUFI	Sto Perlite Interior Insulation Board 045	100	850	0.042	8
Difference		0%	-48%	-9%	0%

For the wood fibre insulation, Delphin's "Wood Fibre Insulation Board [693]" was expected with WUFI's "Wood Fibre Insulation Board 1" (Table 27). Differences are small: WUFI shows a slightly lower thermal conductivity (-2%), a modestly higher density (+4%), a lower specific heat (-16%), and a marginally lower vapour diffusion factor (-3%). These shifts suggest a minor increase in insulation effectiveness and a slight increase in RH peaks at the IWI interface in WUFI, tending toward a higher MGI. The reduced c_p could allow slightly larger short-term temperature fluctuations, but given the small magnitudes, the overall impact on MGI should be minor and likely within model uncertainty.

Table 27. Comparison of material properties between Delphin and WUFI for Wood fibre (WF).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Wood Fibre Insulation Board [693]	160.8	1661.9	0.039	3.4
WUFI	Wood Fibre Insulation Board 1	168	1400	0.0381	3.3
Difference		4%	-16%	-2%	-3%

For the EPS case, Delphin's "Polystyrene Foam Board – Expanded [186]" was compared with WUFI's "EPS (heat cond.: 0.04 W/mK – density: 30kg/m³)" (Table 28). The WUFI entry differs markedly: density is lower (-14%), while specific heat is similar, thermal conductivity, and the vapour diffusion factor are identical. The lower ρ , will result in a modestly lower net thermal inertia (ρc_p) in WUFI, which may permit slightly larger short-term temperature swings and nudge MGI upward.

Table 28. Comparison of material properties between Delphin and WUFI for Expanded polystyrene (EPS).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Polystyrene Foam Board – Expanded [186]	35.0	1500.0	0.040	50.0
WUFI	EPS (heat cond.: 0.04 W/mK - density: 30kg/m ³)	30	1500	0.04	50
Difference		-14%	0%	0%	0%

For the cellulose insulation, Delphin's "Blown-in Cellulose [580]" was compared with WUFI's "Cellulose insulation" (Table 29). The principal difference is thermal conductivity, which is 26% lower in WUFI. This improves insulation performance, resulting in lower temperatures in the IWI interface and increasing RH peaks, and therefore tends to higher the mould growth index relative to Delphin. With vapour diffusion factor unchanged, moisture transport differences should be minimal unless the libraries' sorption or capillary curves diverge; absent such differences, modestly lower MGI in WUFI was expected for otherwise identical setups.

Table 29. Comparison of material properties between Delphin and WUFI for Cellulose (CEL).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Blown-in Cellulose [580]	55.2	2544.4	0.048	2.0
WUFI	Cellulose insulation	55	2544	0.0357	2
Difference		0%	0%	-26%	0%

Delphin's "Mineral Wool 035 [731]" was compared with WUFI's "ISOVER ULTIMATE Kontur FSP - 032" (Table 30). The WUFI entry has a markedly lower density (-40%), a higher specific heat (+23%), and a lower thermal conductivity (-11%). The reduced λ improves insulation in WUFI, tending to keep the IWI interface colder and increases RH peaks, which increases MGI. At the same time, the net thermal inertia (ρc_p) is lower in WUFI because the drop in density outweighs the c_p increase, which may permit slightly larger short-term temperature swings and nudge MGI upward. Overall, differences are expected to be small, with the improved insulation typically dominating and resulting in a higher MGI in WUFI for otherwise identical setups.

Table 30. Comparison of material properties between Delphin and WUFI for Mineral wool (MW).

Software	Material in Library	ρ [kg/m ³]	c_p [J/kgK]	λ [W/mK]	μ [-]
Delphin	Mineral Wool 035 [731]	67.0	840.0	0.035	1.0
WUFI	ISOVER ULTIMATE Kontur FSP -032	40	1030	0.031	1.0
Difference		-40%	23%	-11%	0%

2.3.1.2. Various boundary conditions between Delphin and WUFI

For the surface transfer coefficients for exterior and interior surfaces, equivalent values were used in WUFI Pro. The surface heat transfer coefficients were set to 25 and 7.7 W/m²K for the exterior and interior surfaces respectively. Meanwhile, the surface vapour transfer coefficients were generated automatically from the convective heat transfer coefficients, resulting in $1.295 \cdot 10^{-7}$ and $2.45 \cdot 10^{-7}$ s/m for the exterior and interior surfaces respectively (Künzel, 1995; Dang, Janssen and Roels, 2023).

In WUFI the wind-driven rain load is calculated using equation below (Dang et al., 2024):

$$R_{WDR} = (R_1 + R_2 \cdot U_{10} \cdot \cos\theta) \cdot R_{hor}$$

While for Delphin, the wind-driven rain load is calculated using the ISO 15927-3 method (ISO, 2009), in equation below:

$$R_{WDR} = \left(\frac{2}{9} \cdot C_R \cdot C_T \cdot O \cdot W \right) \cdot U_{10} \cdot R_{hor}^{0.88} \cdot \cos\theta$$

Where, R_{WDR} is the calculated wind-driven rain amount [L/(m²·h)], R_{hor} [L/(m²·h)] is the horizontal rain intensity, while R_1 [-] and R_2 [s/m] are location factors related to the building height. For a

vertical structure, the default value for R_1 is 0, while R_2 ranges from 0.05 to 0.2 s/m according to the building height and position on the wall section. U_{10} [m/s] is the wind flow measured at a standard meteorological height of 10 m, and θ [°] is the angle between the wind direction and the normal direction to the façade. C_R [-] is the terrain roughness coefficient which accounts variability of mean wind velocity due to terrain roughness and height above ground, and thus depends on the vertical height z [m], terrain factor K_R [-], roughness length z_0 [m], and the minimum height z_{min} [m]. C_T [-] is the topography coefficient ranging from 1 to 1.6 which accounts for increase in mean wind speed over isolated hills and escarpments. O [-] is the obstacle factor which considers the horizontal distance between the wall and nearest obstacle with equivalent or higher height and ranges from 0.2 to 1.0, and W [-] is a wall factor ranging from 0.2 to 0.5 specifying the distribution of rain deposition at different positions of five low-rise building types and one high-rise building type, as depends on type of wall, overhangs, etc.

The wind-driven rain was calculated in Excel for both methods, to determine differences and to adjust the location factors in WUFI to obtain equivalent wind-driven rain load on a vertical wall surface. The calculations were carried out using wall factor W (the rain exposure coefficient in Delphin) of 0.5 and 0.7 in the ISO 15927-3 method, which resulted in location factor R_2 values of 0.03778 and 0.05289 respectively.

2.3.2. Results & discussion

The purpose of this comparison is not to obtain identical outcomes but to highlight scenarios where Delphin and WUFI diverge in their 'traffic light' risk assignments. Figures are organized analogously to the Section 2.2.2 but use a new colour scheme to emphasize cross-tool differences.

Traffic light classes are as before: 'green light' = safe; 'yellow light' = requires further investigation; 'red light' = critical.

Each cell in the figures lists the maximum mould growth index (maxMGI) for a scenario, with the top number from Delphin and the bottom number from WUFI. Scenarios not rerun in WUFI are marked with a grey X.

Colour meaning (cross-tool difference): pink tones indicate Delphin higher than WUFI; blue tones indicate WUFI higher than Delphin; white indicates no practical difference (same class).

Legend codes compare classifications:

- **D>>>W**: Delphin much higher than WUFI (red light in Delphin versus green light in WUFI).
- **D>>W**: Delphin higher by one class (red to yellow, or yellow to green).
- **D>W**: Delphin higher by one class, but the maxMGI gap is within the VTT model uncertainty (± 0.5).

- **EQ**: equal class in both tools.
- **D<W**: Delphin lower by one class, but the maxMGI gap is within uncertainty.
- **D<<W**: Delphin lower by one class (green to yellow, or yellow to red).
- **D<<<W**: Delphin much lower (green in Delphin versus red in WUFI).

“Within uncertainty” means the difference between Delphin and WUFI maxMGI is less than 1.0; treat such differences with caution.

2.3.2.1. Córdoba, Spain

Scope

- Climate: only *Present*
- Walls: SP1 (540 mm), SP2 (740 mm)
- Insulation systems: AAC, CS, PER, WF, EPS, CEL, MW

The results of comparison are shown in Figure 21 (*SP1*) and Figure 22 (*SP2*).

Observed differences between tools

- Overall consistency: Results are largely consistent across tools. SP2 shows no discrepancies at all. Classifications are equal (EG) for every material and moisture load tested.
- *SP1* exceptions: Differences appear only for *SP1* and only for wood fibre (WF) under *HighML*. These cases were the sole Spanish configurations in Delphin that reached ‘yellow light’; all other *SP1* cases were within ‘green light’ in Delphin and equal to WUFI (EG).
- Magnitude of gaps: For the *SP1*/WF/*HighML* scenarios, WUFI yields slightly higher maxMGI than Delphin, but the increase remains within the VTT model uncertainty (± 0.5), corresponding to $D < W$. All remaining *SP1* cases are EG.

Potential reasons of differences

- Not specified beyond the observation that WUFI is slightly higher than Delphin for WF under *HighML* in *SP1*, and that all differences remain within the ± 0.5 uncertainty band.

Key takeaways

- Spanish results are highly consistent across tools. *SP2* is fully equal (EG) across all systems and loads.
- Minor, within-uncertainty increases occur only for WF under *HighML* in *SP1* ($D < W$); everything else is EG.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.1	X	X	0.0 0.0	0.0 0.0	1.2 1.0	1.5 1.1	0.0 0.0	0.0 0.0	D>>>W
		HighML	0.1 0.2	0.1 0.3	0.0 0.0	0.1 0.1	0.1 0.2	0.1 0.2	1.6 2.1	2.5 3.1	X	X	0.0 0.0	0.0 0.0	1.5 1.3	2.0 1.5	0.0 0.0	0.1 0.0	D>>W
	HR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.1	X	X	0.0 0.0	0.0 0.0	1.2 1.0	1.5 1.1	0.0 0.0	0.0 0.0	D>W
		HighML	0.1 0.2	0.1 0.3	0.0 0.0	0.1 0.1	0.1 0.2	0.1 0.2	1.6 2.2	2.5 3.1	X	X	0.0 0.0	0.0 0.0	1.6 1.3	2.0 1.5	0.0 0.0	0.1 0.0	EQ
WDR	MR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.0 0.9	1.2 1.0	0.0 0.0	0.0 0.0	D<W
		HighML	0.0 0.1	0.0 0.1	0.0 0.0	0.0 0.1	0.0 0.1	0.1 0.1	0.7 1.3	1.4 2.4	X	X	0.0 0.0	0.0 0.0	1.2 1.2	1.4 1.4	0.0 0.0	0.0 0.0	D<<W
	HR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.0 0.9	1.2 1.0	0.0 0.0	0.0 0.0	D<<<W
		HighML	0.0 0.1	0.0 0.1	0.0 0.0	0.0 0.1	0.0 0.1	0.1 0.1	0.7 1.3	1.5 2.5	X	X	0.0 0.0	0.0 0.0	1.2 1.2	1.4 1.5	0.0 0.0	0.0 0.0	D<<<W

Figure 21. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SP1.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.2 1.0	1.4 1.2	0.0 0.0	0.0 0.0	D>>>W
		HighML	0.0 0.1	0.1 0.2	0.0 0.0	0.1 0.1	0.0 0.1	0.1 0.2	1.1 1.4	2.1 2.6	X	X	0.0 0.0	0.0 0.0	1.4 1.5	1.9 1.7	0.0 0.0	0.1 0.0	D>W
	HR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.2 1.0	1.4 1.3	0.0 0.0	0.0 0.0	EQ
		HighML	0.0 0.1	0.1 0.2	0.0 0.0	0.1 0.1	0.0 0.1	0.1 0.2	1.1 1.4	2.1 2.6	X	X	0.0 0.0	0.0 0.0	1.4 1.5	1.9 1.7	0.0 0.0	0.1 0.0	D>W
WDR	MR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.0 0.8	1.2 1.1	0.0 0.0	0.0 0.0	D<W
		HighML	0.0 0.1	0.0 0.1	0.0 0.0	0.0 0.0	0.0 0.1	0.1 0.1	0.2 0.5	1.1 1.9	X	X	0.0 0.0	0.0 0.0	1.1 1.3	1.3 1.5	0.0 0.0	0.0 0.0	D<<W
	HR	LowML	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	1.0 0.8	1.2 1.1	0.0 0.0	0.0 0.0	D<<<W
		HighML	0.0 0.1	0.0 0.1	0.0 0.0	0.0 0.0	0.0 0.1	0.1 0.1	0.2 0.6	1.1 1.9	X	X	0.0 0.0	0.0 0.0	1.1 1.3	1.3 1.6	0.0 0.0	0.0 0.0	D<<<W

Figure 22. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SP2.

2.3.2.2. Kraków, Poland

Scope

- Climate: only *Present*;
- Walls: PL1 (without external plaster), PL2 (with external plaster);
- Insulation systems: AAC, WF, EPS, MW.

The results of comparison are shown in Figure 23(PL1) and Figure 24 (PL2).

Observed differences between tools

- Overall agreement: Classifications are largely consistent, with the biggest divergences under *HighML* and for *North/WDR* exposures.
- AAC: Mostly equal and within 'green light' in both tools. Gaps appear under *HighML* (especially *AAC-max, North*), sometimes exceeding the VTT uncertainty.
e.g., *PL1/AAC-max/North/MR/HighML*: Delphin ≈ 0.1 vs WUFI ≈ 2.2
($D < W$ and outside the uncertainty band)
- WF: Largely equal at *LowML*. Under *HighML* with *WF-min*, WUFI is consistently more critical; the gap narrows when *WF-max* is used. With thicker WF (*WF-max*), Delphin increases and the gap often reduces to equal/near-equal (EG) or $D < W$.
e.g., *PL2/WF-min/WDR/MR/HighML*: Delphin ≈ 1.8 vs WUFI ≈ 3.0 ($D \lll W$)
- EPS: Many discrepancies. WUFI stays ≈ 0.0 , while Delphin spans up to 'red light'. Gaps between software are smaller for PL2 but remain visible.
As a next step, research should validate these simulation results against monitored indoor climate data from representative case-study buildings, including seasonal measurements of temperature, relative humidity, ventilation behaviour, and occupant use of shading or night cooling. The planned implementation of selected measures in the Spanish and Polish FuturHist demonstrators, together with the ongoing longitudinal monitoring campaign, will enable comparison between simulated performance and empirical evidence.
- MW: Similar to EPS. Delphin spans within 'green/yellow/red light'; WUFI remains near 0.0 .
e.g., *PL1/MW-max/North/HR/LowML*: Delphin ≈ 3.1 vs WUFI ≈ 0.0 ($D \ggg W$)

Potential reasons of differences

- Material data at high RH: For AAC and WF, WUFI likely uses stronger high-RH sorption and/or higher liquid transport, elevating interface RH under *HighML* and yielding higher MGIs ($D < W$). For WF, this effect is most apparent with thinner layers (*WF-min*), where interface temperatures are lower and moisture functions dominate; thicker WF warms the interface and narrows the gap.
- Vapour-resistant/retarded systems: For EPS and MW, WUFI's assumptions (e.g., hydrophobic/low-capillarity behaviour and slightly lower thermal conductivity) limit moisture accumulation and warm the interface, keeping MGIs near zero, while Delphin predicts higher RH build-up at the interface ($D \ggg W$).
- Proximity to the mould threshold: In cases where RH hovers near the VTT threshold, small RH differences between tools translate into large MGI/classification shifts (especially visible for EPS and MW).

- Rain exposure and wall protection: Divergences are largest for *North/WDR* and *HighML*. The unrendered wall (PL1) is more sensitive to rain-data/transport differences. Even in PL2 (with external plaster), *WF-min* under *HighML* can show $D \ll W$ due to material functions outweighing the reduced wetting.

Key takeaways

- Agreement is good overall, but *HighML* amplifies cross-tool differences.
- AAC and WF: WUFI tends to predict higher MGIs under *HighML* ($D < W$), plausibly due to stronger high-RH sorption/capillary transport in its material data.
- EPS and MW: WUFI remains near zero ('green light'), while Delphin often predicts 'yellow/red light' ($D \gg W$), likely reflecting different assumptions on capillarity/hydrophobicity and thermal conductivity.
- Results near the VTT threshold are especially sensitive; small RH shifts can cause large MGI/class changes.
- For interpretation and design, treat *HighML* and highly exposed orientations as needing cross-tool checks and sensitivity analysis, with particular attention to EPS/MW (Delphin-critical) and WF/AAC (WUFI-critical) discrepancies.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.0	x	x	x	x	0.0 0.0	0.0 0.0	x	x	0.0 0.0	1.6 0.0	x	x	0.2 0.0	1.8 0.0	D>>>W
		HighML	0.1 1.6	0.1 2.2	x	x	x	x	2.4 3.6	3.4 3.8	x	x	2.8 0.1	3.1 0.1	x	x	2.6 0.0	3.0 0.0	D>W
	HR	LowML	0.0 0.0	0.0 0.0	x	x	x	x	0.0 0.0	0.0 0.0	x	x	2.2 0.0	3.1 0.0	x	x	3.0 0.0	3.1 0.0	EQ
		HighML	0.1 1.7	0.4 2.3	x	x	x	x	2.7 3.6	3.5 3.8	x	x	3.1 0.1	3.2 0.1	x	x	3.1 0.0	3.2 0.0	D<W
WDR	MR	LowML	0.0 0.0	0.0 0.0	x	x	x	x	0.0 0.0	0.0 0.0	x	x	0.0 0.0	0.3 0.0	x	x	0.0 0.0	0.2 0.0	D<<W
		HighML	0.0 0.8	0.1 1.8	x	x	x	x	2.1 3.2	3.3 3.7	x	x	2.3 0.0	3.0 0.0	x	x	1.7 0.0	2.5 0.0	D<<<W
	HR	LowML	0.0 0.0	0.0 0.0	x	x	x	x	0.0 0.0	0.0 0.0	x	x	0.4 0.0	3.0 0.0	x	x	2.6 0.0	3.0 0.0	D<<<W
		HighML	0.1 0.8	0.1 1.9	x	x	x	x	2.3 3.3	3.4 3.8	x	x	3.1 0.1	3.2 0.1	x	x	3.0 0.0	3.1 0.0	D<<<W

Figure 23. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall PL1.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	D>>>W
		HighML	0.1 1.4	0.1 2.2	X	X	X	X	2.2 3.5	3.3 3.8	X	X	2.1 0.0	2.7 0.0	X	X	1.3 0.0	2.3 0.0	D>>W
	HR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	2.3 0.0	X	X	0.9 0.0	2.4 0.0	D>W
		HighML	0.1 1.5	0.1 2.2	X	X	X	X	2.4 3.5	3.4 3.8	X	X	2.9 0.0	3.1 0.0	X	X	2.8 0.0	3.1 0.0	EQ
WDR	MR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	D<W
		HighML	0.0 0.6	0.1 1.7	X	X	X	X	1.8 3.0	3.2 3.7	X	X	1.0 0.0	2.3 0.0	X	X	0.1 0.0	1.1 0.0	D<<W
	HR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.1 0.0	X	X	0.0 0.0	0.1 0.0	D<<<W
		HighML	0.0 0.7	0.1 1.8	X	X	X	X	2.0 3.1	3.2 3.7	X	X	2.1 0.0	2.9 0.0	X	X	1.4 0.0	2.4 0.0	D<<<W

Figure 24. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall PL2.

2.3.2.3. Linköping, Sweden

Scope

- Climate: only *Present*;
- Walls: SE1;
- Insulation systems: AAC, WF, EPS, MW.

The results of comparison are shown in Figure 25.

Observed differences between tools

- AAC: Differences emerge only under *HighML*. In these cases, Delphin remains close to 0.0, while WUFI rises to roughly 2–3.
e.g., SE1/AAC-max/North/MR/HighML: Delphin ≈ 0.3 vs WUFI ≈ 2.9 (D << W)
- WF: Discrepancies are confined to the thin insulation (WF-min) under *HighML*. On the North façade, the gaps remain within ±0.5 MGI, so both tools are broadly aligned and WUFI is only slightly higher (D < W). Under WDR, the gaps are slightly beyond ±0.5 and push WUFI into a higher risk class. When the thick layer (WF-max) is used, both tools move into the 'red light' and effectively agree (EG).
e.g., SE1/WF-min/WDR/HR/HighML: Delphin ≈ 2.3 vs WUFI ≈ 3.7 (D << W)
- EPS: The two tools agree when either the North façade is considered or LowML applies. Under the combination of WDR and HighML, however, WUFI becomes more critical and can flip the classification.
e.g., SE1/EPS-max/WDR/HR/HighML: Delphin ≈ 1.9 vs WUFI ≈ 3.0 (D << W)

- *MW*: The pattern is similar to *EPS*, though class flips are less frequent. Here, small RH differences near the VTT threshold appear amplified in WUFI's outputs under *WDR* and *HighML*.

e.g., *SE1/MW-max/WDR/HR/HighML*: Delphin ≈ 0.2 vs WUFI ≈ 3.0 ($D \ll W$)

Potential reasons of differences

- *AAC*: Under *HighML*, WUFI's AAC data likely reflect stronger high-RH sorption and/or liquid transport. This increases high-RH storage and raises the interface response, and because μ -value is similar across tools, the net effect is a higher MGI in WUFI compared with Delphin.
- *WF*: For *WF-min* at *HighML*, WUFI's stronger high-RH sorption/capillarity, together with thin insulation and Sweden's higher *WDR* exposure, increases wetting sensitivity and elevates MGI in WUFI. With *WF-max*, both tools get to 'red light', so the observed gap effectively disappears.
- *EPS* and *MW*: Under *WDR* combined with *HighML*, small differences in RH near the VTT mould threshold are amplified by WUFI's parameter set (including slightly lower λ -value). This reduces drying potential relative to Delphin and nudges WUFI into 'red light', while Delphin remains within 'green light' in the same configurations.

Key takeaways

- Agreement between the tools is good for the *North* façade and under *LowML*; the most significant divergences occur when *WDR* and *HighML* act together.
- WUFI tends to predict higher MGIs for AAC under *HighML* and for *WF-min*, *EPS*, and *MW* under *WDR* with *HighML* ($D \ll W$), and in several cases this leads to class flips relative to Delphin.
- With thick wood fibre (*WF-max*), both tools align in the 'red light', indicating effective agreement in the most moisture-sensitive *WF* scenarios.
- Configurations operating near the VTT mould threshold are particularly sensitive to small RH differences, so results in this range should be interpreted with caution.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.9	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	D>>>W
		HighML	0.2 2.6	0.3 2.9	X	X	X	X	2.9 3.8	3.4 3.9	X	X	2.1 2.4	2.6 2.8	X	X	0.2 0.8	2.1 2.2	D>>W
	HR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.0	0.0 1.0	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.1	D>W
		HighML	0.2 2.6	0.4 2.9	X	X	X	X	2.9 3.8	3.4 3.9	X	X	2.2 2.6	2.8 3.0	X	X	1.0 1.9	2.5 2.8	EQ
WDR	MR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.2	X	X	0.0 0.0	0.0 0.0	X	X	0.0 0.0	0.0 0.0	D<W
		HighML	0.1 2.2	0.1 2.6	X	X	X	X	2.2 3.7	3.3 3.9	X	X	0.4 1.7	1.4 2.3	X	X	0.0 0.1	0.1 1.7	D<<W
	HR	LowML	0.0 0.0	0.0 0.0	X	X	X	X	0.0 0.0	0.0 0.3	X	X	0.0 0.0	0.0 0.1	X	X	0.0 0.1	0.0 1.0	D<<<W
		HighML	0.1 2.3	0.1 2.7	X	X	X	X	2.3 3.7	3.3 3.9	X	X	0.9 2.6	1.9 3.0	X	X	0.0 2.7	0.2 3.0	D<<<W

Figure 25. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SE1.

2.3.2.4. Edinburgh, Scotland

Scope

- Climate: only *Present*;
- Walls: SC1 (sandstone with external and internal plaster), SC2 (sandstone with internal plaster only), SC3 (sandstone with external plaster and lath-and-plaster inside), SC5 (granite with internal plaster only);
- Insulation systems: AAC, WF, EPS, MW (selected scenarios).

The results of comparison are shown in Figure 26 (SC1), Figure 27 (SC2), Figure 28 (SC3) and Figure 29 (SC5).

Observed differences between tools (walls SC1 and SC2)

- AAC: Differences appear only under *HighML*, with Delphin lower and typically one class better than WUFI. This aligns with WUFI's AAC sorption and liquid transport functions generating higher high-RH storage and interface RH, leading to higher MGI despite similar μ -value.
e.g., SC1/AAC-max/WDR/MR/HighML Delphin $\approx$ 1.2 vs WUFI $\approx$ 2.8 (D << W)
- WF: No class differences were observed across the tested scenarios; classifications are equal (EG).
- EPS: On the *North* façade, WUFI tends to be slightly higher but remains in the same class or within ± 0.5 (EG or D < W). Under *WDR*, Delphin becomes higher, especially at *LowML*,

and WUFI often stays within 'green light'. Under *HighML*, gaps shrink toward the uncertainty margin.

e.g., *SC1/EPS-max/WDR/MR/LowML*: Delphin ≈ 2.8 vs WUFI ≈ 0.1 ($D \gg W$)

e.g., *SC1/EPS-max/WDR/MR/HighML*: Delphin ≈ 3.2 vs WUFI ≈ 2.6 ($D > W$)

- *MW*: Mirrors *EPS* under *WDR*. At *LowML* with *WDR*, Delphin often indicates 'yellow' or 'red light', while WUFI remains within 'green light' ($D \gg W$). At *HighML* with *WDR*, the tools may differ in colour assignment but gaps are mostly within ± 0.5 ($D > W$).

e.g., *SC1/MW-max/WDR/MR/LowML*: Delphin ≈ 2.9 vs WUFI ≈ 0.1

e.g., *SC1/MW-max/WDR/MR/HighML*: Delphin ≈ 3.2 vs WUFI ≈ 2.2

Observed differences between tools (wall SC3)

- Overall: More critical than *SC1/SC2*, with most cross-tool differences concentrated on the *WDR* orientation.
- *AAC*: WUFI is almost always higher, and even a *LowML* case flips colour assignment.
e.g., *SC3/AAC-max/WDR/MR/HighML*: Delphin ≈ 1.0 vs WUFI ≈ 2.5 ($D \ll W$)
- *WF*: No colour differences or gaps outside ± 0.5 , indicating EG or $D < W$.
- *EPS*: Equal for *North* or *LowML*; *WDR + HighML* makes Delphin higher. *EPS-min* sometimes flips colours but typically remains within ± 0.5 .
e.g., *SC3/EPS-max/WDR/MR/HighML*: Delphin ≈ 2.9 vs WUFI ≈ 1.8 ($D \gg W$)
- *MW*: Mirrors *EPS* with larger gaps on *WDR*.
e.g., *SC3/MW-max/WDR/MR/HighML*: Delphin ≈ 2.9 vs WUFI ≈ 0.9 ($D \gg W$)

Observed differences between tools (wall SC5)

- Overall: Most critical wall in Delphin. Cross-tool differences are limited to a handful of *LowML/HighML* edge cases.
- *AAC*: Differences appear only for *MR* with *HighML* at minimum thickness.
e.g., *SC5/AAC-min/North/MR/HighML*: Delphin ≈ 0.9 vs WUFI ≈ 2.7 ($D \ll W$)
- *WF*: Mostly EG. Single *LowML* outlier at minimum thickness under *WDR*.
e.g., *SC5/WF-min/WDR/MR/LowML*: Delphin ≈ 2.3 vs WUFI ≈ 0.0 ($D \gg W$)
- *EPS* and *MW*: Very similar behaviour. Large differences arise in the single *LowML* scenario at *WDR* with minimum thickness, with Delphin higher.
e.g., *SC5/EPS-min/WDR/MR/LowML*: Delphin ≈ 3.4 vs WUFI ≈ 0.0 ($D \gg W$; *MW* analogous)

Potential reasons of differences

- *AAC*: WUFI's *AAC* sorption/liquid transport curves produce higher high-RH storage and interface RH, pushing MGIs higher than Delphin under *HighML*, even where μ -value is similar.

- *EPS* and *MW*: Under *WDR* and especially at *LowML* Delphin often exceeds WUFI because WUFI treats *MW* as hydrophobic/low-capillarity and applies slightly lower λ -value, which reduces moisture build-up and warms the interface. Many *WDR/LowML* cases sit near the VTT threshold, so small RH shifts trigger large MGI changes and class flips ($D \gg W$ or $D \ggg W$).

Key takeaways

- For *AAC*, WUFI tends to be more critical under *HighML* across *SC1-SC3* and shows class flips even at *LowML* in *SC3* ($D \ll W$), reflecting higher high-RH storage and interface RH in its material functions.
- For *EPS* and *MW*, Delphin is generally more critical under *WDR*, particularly at *LowML*, while WUFI often remains within 'green light' ($D > W$ to $D \ggg W$). At *HighML*, differences narrow but colour flips can still occur, typically within ± 0.5 MGI.
- For *WF*, the tools align well in Scotland across *SC1-SC3* and *SC5*, yielding equal classifications or differences within the uncertainty band.
- *SC3* is more critical than *SC1/SC2*, with discrepancies concentrated on the *WDR* façade; *SC5* is the most critical overall, though cross-tool gaps are limited to specific edge cases.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.1	0.2 1.1	X	X	0.0 0.0	0.1 0.1	X	X	0.0 0.1	0.1 0.2	D>>>W D>>W D>W EQ D<W D<<W D<<<W
		HighML	1.0 2.8	1.2 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	2.9 3.0	2.8 2.9	X	X	2.5 2.2	2.6 2.5	
	HR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.1	0.2 1.2	X	X	0.0 0.0	0.2 0.4	X	X	0.1 0.3	0.2 0.6	
		HighML	1.0 2.8	1.2 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.0 3.1	2.9 3.0	X	X	2.7 2.5	2.8 2.7	
WDR	MR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.0	0.3 0.6	X	X	1.6 0.0	2.8 0.1	X	X	2.8 0.0	2.9 0.1	D<W D<<W D<<<W
		HighML	1.0 2.7	1.2 2.8	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.2 2.8	3.2 2.6	X	X	3.2 2.0	3.2 2.2	
	HR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.2 0.1	1.2 0.9	X	X	3.0 0.0	3.2 0.3	X	X	3.2 0.4	3.2 0.6	
		HighML	1.1 2.7	1.4 2.9	X	X	X	X	3.4 3.9	3.6 3.9	X	X	3.3 3.0	3.3 2.9	X	X	3.3 2.5	3.3 2.7	

Figure 26. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SC1.

D2.8 / Report on assessment of insulation systems for the envelope's retrofit including components' integration

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.2	0.2 1.3	X	X	0.0 0.0	0.2 0.3	X	X	0.1 0.3	0.2 0.5	D>>>W
		HighML	1.0 2.8	1.2 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.0 3.1	2.9 3.0	X	X	2.6 2.5	2.8 2.7	D>>W
	HR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.0 0.2	0.3 1.3	X	X	0.0 0.1	0.4 0.6	X	X	0.2 0.6	0.5 0.9	D>W
		HighML	1.0 2.8	1.2 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.0 3.1	3.0 3.1	X	X	2.7 2.7	2.9 2.9	EQ
WDR	MR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.1 0.1	0.7 0.9	X	X	2.4 0.0	3.0 0.2	X	X	3.0 0.2	3.1 0.4	D<W
		HighML	1.0 2.8	1.3 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.2 2.9	3.2 2.9	X	X	3.2 2.4	3.2 2.6	D<<W
	HR	LowML	0.0 0.0	0.0 0.1	X	X	X	X	0.2 0.1	1.1 1.1	X	X	2.9 0.0	3.1 0.7	X	X	3.1 0.9	3.2 1.3	D<<<W
		HighML	1.1 2.8	1.4 2.9	X	X	X	X	3.4 3.9	3.5 3.9	X	X	3.3 3.1	3.3 3.1	X	X	3.3 2.8	3.3 3.0	D<<<W

Figure 27. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SC2.

Legend: maxMGI DELPHIN maxMGI WUFI			AAC		CS		PER		WF		CCB		EPS		CEL		MW		
			min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	
North	MR	LowML	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	D>>>W
		HighML	0.7 2.2	X	X	X	X	X	2.5 3.3	X	X	X	1.9 1.9	X	X	X	0.8 0.3	X	D>W
	HR	LowML	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	EQ
		HighML	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	EQ
WDR	MR	LowML	0.0 0.0	X	X	X	X	X	0.0 0.0	X	X	X	0.1 0.0	X	X	X	1.5 0.0	X	D<W
		HighML	0.7 2.1	1.0 2.5	X	X	X	X	2.5 3.1	3.3 3.8	X	X	2.5 1.5	2.9 1.8	X	X	2.5 0.2	2.9 0.9	D<<W
	HR	LowML	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	D<<<W
		HighML	0.8 2.1	X	X	X	X	X	2.6 3.2	X	X	X	2.7 1.9	X	X	X	2.8 0.7	X	D<<<W

Figure 28. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SC3.

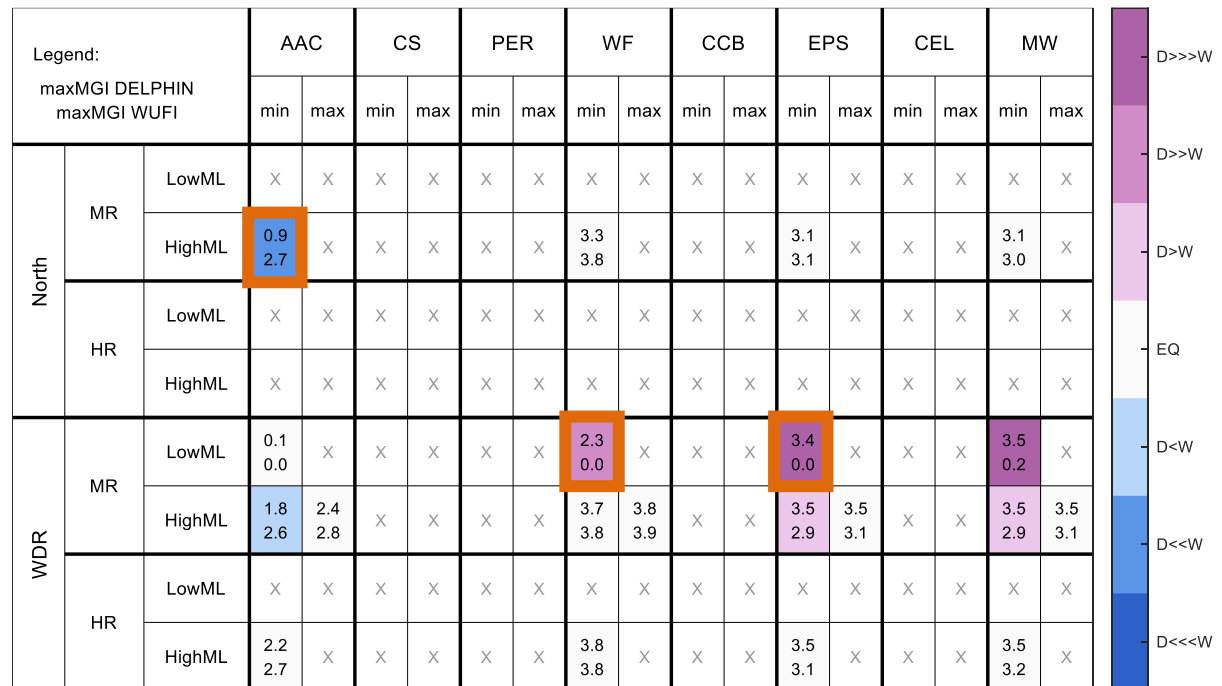


Figure 29. Cross-Tool Differences in maxMGI (Delphin vs WUFI) for wall SC5.

2.3.2.5. Summary

A summary of the comparison between Delphin and WUFI is shown in Table 31.

Table 31. Conclusion from Delphin+WUFI checkup. Parameters: (1) insulation material: AAC- autoclaved aerated concrete, WF – wood fibre, EPS – expanded polystyrene, MW – mineral wool; (2) insulation thickness; (3) wall orientation; (4) internal moisture load (ML). Legends for cells: D = Delphin more critical, W = WUFI more critical, EG = same class regarding 'traffic light' assessment for maxMGI.

(1)	(2)	(3)	(4)	Spain	Poland	Sweden	Scotland
AAC	min	North	LowML	EG	EG	EG	EG
			HighML	EG	W	W	W
		WDR	LowML	EG	EG	EG	EG
			HighML	EG	EG	W	W
	max	North	LowML	EG	EG	EG	EG
			HighML	EG	W	W	W
		WDR	LowML	EG	EG	EG	EG
			HighML	EG	EG	W	W
WF	min	North	LowML	EG	EG	EG	EG
			HighML	W	W	W	EG
		WDR	LowML	EG	EG	EG	D
			HighML	W	W	W	EG
	max	North	LowML	EG	EG	EG	EG
			HighML	W	EG	EG	EG
		WDR	LowML	EG	EG	EG	EG
			HighML	W	EG	EG	EG
EPS	min	North	LowML	EG	D	EG	EG
			HighML	EG	D	EG	EG
		WDR	LowML	EG	EG	EG	D
			HighML	EG	D	W	D
	max	North	LowML	EG	D	EG	EG
			HighML	EG	D	EG	EG
		WDR	LowML	EG	D	EG	D
			HighML	EG	D	W	D
MW	min	North	LowML	EG	D	EG	EG
			HighML	EG	D	EG	EG
		WDR	LowML	EG	D	EG	D
			HighML	EG	D	W	D
	max	North	LowML	EG	D	EG	EG
			HighML	EG	D	EG	EG
		WDR	LowML	EG	D	EG	D
			HighML	EG	D	W	D

3. Indoor climate simulations

The aim of this chapter is to analyse established and newly developed sustainable internal insulation systems regarding their hygrothermal effects on indoor climate under current and future climatic conditions, especially regarding overheating, relative humidity, and the ability of moisture-buffering materials to moderate humidity fluctuations.

Summer comfort and overheating

While rising temperatures imply a reduced heating demand in winter, cooling demand in summer is increasing across Europe and especially in Southern Europe. This affects household energy demand and greenhouse-gas emissions and particularly impacts lower-income households. The increased use of air-conditioning is also considered a catalyst for urban heat islands, thereby further intensifying urban heat stress. It is therefore highly relevant to prioritize passive measures to reduce indoor temperatures before resorting to energy-intensive cooling systems.

In historic buildings, internal insulation systems are often the only conservation-compatible option for improving winter energy efficiency. However, studies indicate that summer overheating risk can increase when internal insulation is installed because the thermal inertia of the historic exterior wall is reduced. Research by Hao (2020) and by Leonardi et al. (2025) examines interactions between energy retrofit, future climate scenarios, and thermal comfort in historic buildings in the Alpine region. These findings make clear that the performance of different insulation options depends on the specific location and context and that the occupant's use of shading and ventilation becomes crucial in avoiding overheating. There is therefore further research potential concerning the transferability of results to different European climate zones, building typologies, and materials.

A study by Lisitano et al. (2021) also addressed the heat and moisture behaviour of different internal insulation systems in historic buildings. Simulations carried out with WUFI Pro for the Monastery of Santa María de Monfero showed that internal insulation worsened summer indoor conditions and led to higher peak temperatures, thereby increasing cooling demand. However, the wall thickness examined there was 100 cm, which is uncommon for typical residential buildings, even in Southern Europe, so transferability is limited.

This leads to a research question: How do different internal insulation systems influence summer thermal comfort in historic buildings under current and future climatic conditions in different European climate zones?

Moisture buffering behaviour

Excessively high or low indoor relative humidity can significantly impair comfort and well-being. A relative humidity between 40% and 60% is generally considered ideal for avoiding adverse

health effects. Mechanical systems can be used to regulate humidity, but these result in increased CO₂ emissions and energy vulnerabilities.

Against this background, interest in the moisture-buffering effect of hygroscopic or porous building materials has grown markedly. These materials respond flexibly to fluctuations in relative humidity by adsorbing or releasing moisture and thereby promote a balanced indoor climate. Studies show that moisture-buffering materials can reduce energy use for air-conditioning and indoor air conditioning by roughly 25–30%. Other research demonstrates that materials with high Moisture Buffer Value can make a significant contribution to stabilizing indoor humidity, while also noting that their effectiveness depends on season, building typology, and climate zone.

This leads to a second question: How do different internal insulation systems in historic buildings influence the regulation of indoor air humidity under specific climatic and typological conditions?

3.1. Methodology

The questions presented here examine how material choice might affect indoor climate in buildings where the implementation of active systems are often problematic or undesirable. The investigation follows a parametric approach. Based on the building typologies defined within the project, two case-study objects were selected as representative references after comparing climatic conditions. To analyse impacts on indoor climate, the investigations were carried out on defined living spaces, using a living room as an exemplary room. Different internal insulation systems were examined, based on the most common solution approaches identified within the project. These include vapour-open, vapour-retarding, and vapour-tight variants. In addition, the newly developed CarbonClay Sinkstone (see Deliverable 2.3) was included in two different versions.

In a first step, the current state of the reference rooms was simulated, and supplementary measures such as ventilation or shading to optimize summer comfort were tested. The predefined internal insulation systems — calcium silicate boards, wood fibre boards, CarbonClay Sinkstone, EPS, and mineral wool in different thicknesses — were then integrated into the models. The analysis of summer discomfort and moisture buffering potential is based on the excess temperature hours, effects on relative humidity, and changes in heating demand.

Based on these findings, ventilation and shading strategies for the more heavily insulated variants were further optimized to reduce overheating risks and derive robust solutions for future climate conditions. Lastly, the same models were simulated under future climate scenarios following RCP 8.5 projections for the year 2050 and compared with the initial state of the reference buildings.

Simulations

Hygrothermal simulations were carried out using WUFI Plus V.3.5.0.1 as simulation software whereas SketchUp 2017 was used to create the building models. A SketchUp plugin allowed zones and building-component properties to be assigned and then transferred directly into WUFI Plus.

3.1.1. For consistency, the same climate data used in the sections above (see section 2.1.2.2) was also used for this part of the work. The simulations were run in batch mode, and the results for all zones and selected components were exported as .txt files and analysed using Python scripts executed in Spyder 6.1.0.

The hygrothermal simulations were first carried out for the base case, which reflects the current or typology-based condition of the building and serves as the comparison basis. The ventilation strategy was designed to achieve acceptable indoor CO₂ values. Starting from this initial state, passive measures such as shading and night ventilation were used to optimize summer thermal comfort. This then provided the basis for integrating the selected internal insulation systems. These were applied in different thicknesses to the existing exterior wall, while the remaining parameters — ventilation, HVAC, and internal loads — remained unchanged. The results for the more strongly insulated variants were then revised with regard to summer comfort and excess temperature hours in order to provide a basis for the future climate scenario 2050 (RCP 8.5) (see Figure 30).

The numerical simulations were run over a period of five years with a maximum time step of one hour. Internal loads were defined using the WUFI Plus database with use-dependent profiles for weekdays and weekends. The airflow model in WUFI Plus was used to model ventilation, taking into account weather, opening behaviour, construction, airtightness, interactions between zones, and the influence on indoor climate and energy demand. Window-opening schedules were implemented by means of daily profiles. Shading devices were modelled using reduction factors according to DIN 4108-2:2024-12 (2024) and likewise controlled by daily profiles.

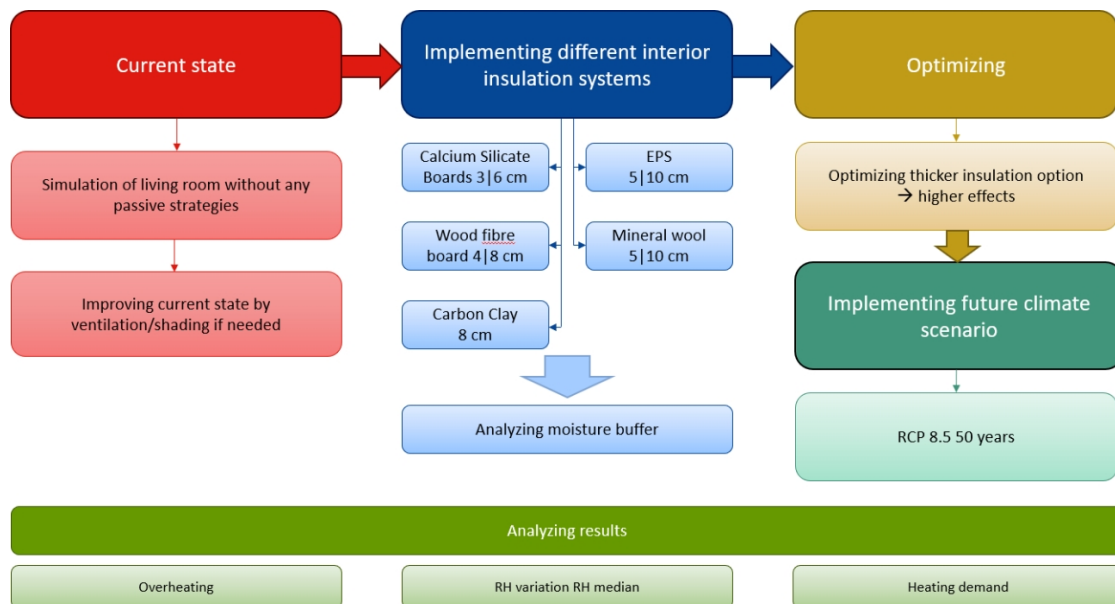


Figure 30. Visualization of the simulation workflow.

Case studies and building typologies

3.1.2.

In the first work package of the FuturHist project, nine building typologies were defined. These are based on typological characteristics such as materiality, geometry, and the historical, artistic, and cultural significance of the buildings. To analyse the impact of different internal insulation systems on indoor climate across climates, the Casa de Pisos in Córdoba and the Kamienica in Kraków were selected as case studies. Both typologies represent typical terraced-house forms of their respective regions and were derived from real buildings that serve in the project as “democases” for the later exemplary implementation of selected measures. The geometric and constructive characteristics of the case-study buildings formed the basis for the 3D simulation models. In some cases, adjustments were made where certain properties deviated too strongly from the defined typology. The goal was not to reproduce the individual building exactly, but rather to represent the respective typology as closely as possible.

3.1.2.1. Casa de Pisos, Córdoba

The south-facing multi-family house contains three dwellings and a storage units distributed over four floors. The load-bearing structure consists of solid brick walls 70 to 90 cm thick laid in lime mortar and plastered on the inside. The windows are single-glazed casement windows. Solar protection is provided by internal shutters and external wooden roller blinds. No centralized heating or cooling systems are installed. Living and sleeping rooms are heated or cooled only occasionally with individual, mostly inefficient appliances.

Despite the generally positive effect of the thick walls on passive thermal regulation, the building frequently shows comfort problems. The causes include insufficient thermal insulation, significant air leakage at the windows, and the difficulty of evenly tempering rooms with high

ceilings. In addition, the vertical organization of the house means that upper floors overheat more strongly in summer and cool down more in winter.

For the investigation, a room on the intermediate floor was selected. Since the focus was on the effects of internal insulation on existing walls, the attic apartment was not analysed. This makes it possible to assess the influence of exterior-wall retrofit measures on indoor climate more clearly.

The analysed room is located on the middle floor of the terraced mid-block building and has a net floor area of 24.9 m². The exterior wall faces south, while the east and west walls adjoin neighbouring apartments and were therefore treated as adiabatic boundaries. The exterior wall consists of massive brick masonry with lime mortar and plaster on both sides and has a total thickness of 74 cm (Table 32). Four south-facing windows are modelled as single-glazed casement windows. The room was assigned WUFI's "Single Household" usage profiles for weekdays and weekends. Space heating with a rated power of 3600 W follows target-temperature-controlled heating periods. Internal wooden shutters and external blinds are available for solar protection. The respective shading and ventilation strategies are summarized in Table 33.

Table 32. Construction elements for Spanish model.

Element	Material/construction	Orientation	U-value Simulation [W/m ² K]	U-value Typology [W/m ² K]
Exterior wall	Lime-cement plaster 2 cm Solid brick ZP 70 cm Lime-cement plaster 2 cm	South (100%) Outside air	1.08	0.76–2.75
Interior wall 1	Lime-cement plaster 1 cm Solid brick ZP 11.5 cm Lime-cement plaster 1 cm	East (50%) West (50%) adiabatic	2.47	0.76–2.75
Interior wall 2	Lime-cement plaster 2 cm Solid brick ZP 76 cm Lime-cement plaster 2 cm	North (100%) adiabatic	1.01	0.76–2.75
Ceiling/floor beams	Ceramic 3 cm Lime gypsum mortar 1 cm Oak 25 cm	Horizontal adiabatic	0.99	1.07–2.60
Ceiling/floor vault	Ceramic 3 cm Lime gypsum mortar 1 cm Loose fill 12 cm Historical gypsum mortar 1 cm	Horizontal adiabatic	2.57	1.07–2.60
Windows	Single-glazed pivot windows	South (100%)	3.92	3.92–5.47

Table 33. Shading and ventilation scenarios for Spanish model.

Cases	Shading	Ventilation
Basic	None	Minimized to acceptable CO ₂ levels, based on usage (weekdays/weekends)
Basic S	May 15– October 15	Same as Basis

Base NVS, Interior insulation NVS	May 15– October 15 As base S	<u>Winter period</u> September 2 nd – May 14 th As base <u>Summer period</u> May 15 th – September 1 st Extended night ventilation from 10 p.m. to 7 a.m.
Optimized NVS interior insulation, Interior insulation RCP 8.5 2050	Apr 1–Nov 15	Same as interior insulation NVS

3.1.2.2. Kamienica, Kraków

The building was erected in the first half of the nineteenth century and partially modernized in 1890. It has four storeys in total, including attic and basement levels. The exterior and interior walls are made of bricks masonry and are mostly plastered. Only the upper storey facing the street remained unplastered for design reasons. The load-bearing walls become thinner with each storey, ranging from 70 cm in the basement to 50 cm on the ground floor and 28 cm in the attic (see Table 34).

Current use can be summarized as mixed residential and commercial. The ground floor is predominantly commercial, while the upper floors contain further commercial units and two apartments.

The analysed room represents the living room of an apartment on the first upper floor. It has a net floor area of 16.48 m² and a clear room height of approximately 4 m. The exterior wall faces southeast, while all other envelope surfaces were assumed to be adiabatic because they adjoin heated zones. The exterior wall consists of 50 cm thick solid brick masonry. Although the actual window has already been replaced by triple glazing, the model used a U-value of 3.18 W/m²K in order to reflect the typical range of the typology.

The apartment is permanently occupied by three people — a couple with one child — and therefore the “Family Household – Living Room 4 Persons” load profiles were used. The room is heated by district heating with an installed power of 2201 W and a setpoint temperature of 20°C. The system is switched off in summer between 1 May and 30 September. Determining a suitable ventilation strategy proved more difficult than in Córdoba because the climate in the early summer months can still involve outdoor temperatures below 10°C. Window opening for night cooling and natural ventilation therefore cannot be used continuously but must be adapted in timing and intensity. The changed use situation also causes higher CO₂ production and higher internal loads, leading to more complex ventilation profiles (see Table 35).

Table 34. Construction elements for Polish model.

Element	Material/construction	Orientation	U-value Simulation [W/m ² K]	U-value Typology [W/m ² K]
Exterior wall	Lime-cement plaster 3 cm Solid brick ZK 44 cm Lime plaster 3 cm	South (100%) Outside air	1.13	1.00–1.60
Interior wall	Lime-cement plaster 3 cm Solid brick ZK 44 cm Lime plaster 3 cm	North (36%) East (36%) West (36%) adiabatic	1.13	1.00–1.60
Ceiling/floor beams	Softwood 5 cm Bitumen 0.07 cm Hardwood 25 cm Softwood 2 cm Lime plaster 2 cm	Horizontal adiabatic	0.34	0.72–1.60
Ceiling/floor vault	Softwood 5 cm Air layer 6 cm Clay filling 6 cm Bitumen 0.07 cm Softwood 2.5 cm Air layer 9.5 cm Softwood 2.5 cm Lime plaster 2 cm	Horizontal adiabatic	0.532	0.72–1.60
Windows	Single-glazed casement windows	South (100%)	3.18	3.18–5.00

Table 35. Shading and ventilation scenarios for Polish model.

Cases	Shading	Ventilation
Base	None	Minimized to acceptable CO ₂ levels, based on usage (weekdays/weekends)
Basic S	July 1 st – September 1 st 7 a.m. to 8 p.m. Factor 1 (closed) 8 p.m.–7 a.m. Factor 0 (open)	As base
Base NVS, Interior insulation NVS	As base S	<u>Winter period</u> September 2 nd – May 14 th As base <u>Summer period</u> June 15 th – September 1 st Extended night ventilation from 6 p.m. to 8 a.m. on weekdays 6 p.m. to 9:15 a.m. on weekends
Optimized NVS interior insulation, Interior insulation RCP 8.5 2050	May 1 st – September 1 st	<u>Winter period</u> September 2 nd – May 14 th as base <i>Additionally</i> May 1 st – June 15 th 9:00 p.m. to 10:30 p.m. <u>Summer period</u> June 15 th – September 1 st as per base NVS, interior insulation NVS

Selection and description of internal insulation systems

3.1.3. The analysed internal insulation systems were selected to be consistent with the other parts of this work (see Section 2.2.1). To compare different effects on indoor climate, the study considered both vapour-open and capillary-active systems as well as vapour-retarding and vapour-tight systems (see Figure 31). Capillary-active, vapour-open systems include calcium silicate boards (3 cm and 6 cm) and wood fibre boards (4 cm and 8 cm). In addition, the material CarbonClay Sinkstone (8 cm) was included in two variants: Mi4, developed primarily as a moisture buffer, and MM2 (8 cm), conceived as an insulating material with hygroscopic properties. Expanded polystyrene (EPS, 5 cm and 10 cm) was used as a vapour-tight variant. For the vapour-retarding build-up, mineral wool (5 cm and 10 cm) with a humidity-variable vapour retarder was investigated.

CarbonClay Sinkstone was still under development when this work was carried out. The variants used in this study, Mi4 and MM2, differ in their composition with regard to the types of biochar and clay used, the mass fraction of biochar, and the addition of natural fibres. Since these materials are not part of the software database, they were manually added based on laboratory test data.

		Capillary active, vapor open				Vapor tight		Smart Vapor		Carbon Clay			
		Caldum silicate		Wood fiber board		EPS		Mineral Wool		Mi4		MM2	
Layer 1	Function	Render		Render		Render		Insulation		Render		Render	
	Material in WUFI Plus	Remmers iQ-fix		Knauf Red Lime Fine		Lime Cement Mortar, course		ISOVER ULTIMATE Contour FSP - 032		Clay Mortar		Clay Mortar	
	Thickness [cm]	1 cm		1 cm		1 cm		5/ 10 cm		1 cm		1 cm	
	Thermal conductivity	0.497		0.47		0.8		0.031		0.4837		0.4837	
	Specific heat capacity [J/kgK]	863		850		850		1030		488		488	
	Water vapor diffusion resistance factor, moisture dependent	0 0.2 0.9 1	18.7 18.7 17.4 15.1	0 	7.9 	0 0.5 0.7 0.8 0.9 0.95	45.89 29.4784 24.0331 17.7259 7.3417 2.1634	0 	1 	0 	11 	0 	11
Layer 2	Function	Insulation		Insulation		Insulation		Smart Vapor Retarder		Insulation		Insulation	
	Material in WUFI Plus	Calcium Silicate AI		Wood fiber insulation Board 1		EPS (heat condo: 0.04 W/mK - density:		INTELLO PLUS (according to German		FH Mi4 Carbon Clay		FH MM2 Carbon Clay	
	Thickness [cm]	3 / 6 cm		4 / 8 cm		5 / 10 cm		0.1 cm		8		8 cm	
	Thermal conductivity dry [W/mK]	0.057		0.0381		0.04		24		0.14		0.0625	
	Specific heat capacity [J/kgK]	1303		1400		1500		2500		1050		1050	
	Water vapor diffusion resistance factor, moisture dependent	0 	5.4 	0 	5.4 	0 	50 	0 0.25 0.715 0.9 1	34000 34000 1700 300 300	0 0.119 0.2244 0.589 0.6944	17 17 13 10 4	0 0.119 0.589	15 15 7
Layer 3	Function	Internal finish		Internal finish		Internal finish		Internal finish		Internal finish		Internal finish	
	Material in WUFI Plus	Mineral reinforced plaster		Knauf red lime fine		Lime Cement Mortar, course		Gypsum Board		Clay Mortar		Clay Mortar	
	Thickness [cm]	1 cm		1 cm		1 cm		1.3 cm		0.6 cm		0.6 cm	
	Thermal conductivity	0.641		0.47		0.8		0.1925		0.4837		0.4837	
	Specific heat capacity [J/kgK]	850		850		850		1384		488		488	
	Water vapor diffusion resistance factor, moisture dependent	0 	17 	0 	7.9 	0 0.5 0.7 0.8 0.9 0.95	45.89 29.4784 24.0331 17.7259 7.3417 2.1634	0 	6.8 	0 	11 	0 	11

Figure 31. Specific material properties and thicknesses of the different internal insulation systems.

3.1.4.

Assessment methods and indicators

3.1.4.1. WTA Guideline 6-5

According to WTA guideline 6-5, "Internal Insulation according to WTA II: Verification of Interior Insulation Systems by Numerical Methods", an internal insulation system is functionally verified if, among other things, a steady cyclic condition is reached, and no inadmissible moisture conditions occur within the construction. A steady cyclic condition means that after an initial start-up phase there is no continuous moisture accumulation in the construction. Verification is based on the total water content of the construction over the annual cycle under a yearly repeating climate data set. The condition is considered achieved when the water content approaches a stable value; a change of less than 1% of the previous year's water content is cited as the criterion.

3.1.4.2. ASHRAE Standard 55-2017

The ANSI/ASHRAE Standard 55-2017 for evaluating overheating in buildings is based on an adaptive model that defines acceptable indoor temperatures as a function of the prevailing mean outdoor temperature. This model was developed specifically for naturally ventilated, user-controlled buildings and considers occupants' ability to adapt their environment to their thermal needs, for example by opening windows or using fans. Compared with DIN-based approaches, which are mainly suited to mechanically conditioned rooms, the ASHRAE approach allows flexible adaptation to climatic conditions and user interaction and therefore assesses thermal stress more realistically in naturally ventilated buildings.

The prevailing mean outdoor temperature serves as the basis for determining acceptable temperature ranges. For the 80% acceptability limit, the adaptive comfort temperature is calculated as:

$$T_{comf} = 0.31 \times T_m + 21.3$$

Since outdoor temperatures in a hot climate such as Córdoba can exceed the standard range in summer, the study follows the approach used by Lingjun Hao and sets the nearest permissible limit as an absolute boundary in such cases. From these values, "overheating degree hours" are derived. In contrast to simple overheating hours, this metric records both intensity (in Kelvin) and duration (in hours) and therefore provides a more complete picture of the comfort conditions.

3.1.4.3. Moisture-buffering behaviour

For the analysis of indoor relative humidity, the methodological approach presented by Larcher et al. (2025) was adopted. The median and the variation range of indoor relative humidity were used to analyse the hygrothermal simulation results. The median characterizes typical moisture conditions in the indoor spaces, while the variation range quantifies humidity fluctuations over the period under study. Analogous to Larcher et al., it was calculated as the difference between the 10th and 90th percentiles to exclude non-representative extreme values.

After an initial analysis it became clear, in line with Larcher et al., that the median relative humidity differs only slightly between the internal insulation systems. Because relative humidity also strongly depends on temperature, its direct informative value for assessing moisture-buffering performance is limited. For this reason, an additional approach was defined: the Moisture Flux at the interior surface of the insulated exterior wall was analysed using the WUFI simulation results. Moisture Flux describes the combined moisture transport, including both liquid and vapour flow. Considering moisture transport at the interior surface allows a targeted evaluation of the moisture-buffering behaviour of the insulation systems and their plaster layers.

3.2. Results

Initial state: reference scenario (pre-retrofit)

3.2.1.1. Heating demand

3.2.1 Despite having approximately similar gross volumes, the two living rooms in the two case studies (Córdoba and Kraków) display very different heating demands because of divergent climatic boundary conditions and constructions (see Table 36). In Córdoba, a heating demand of 1101 kWh was determined, whereas in Kraków the demand exceeds this by more than a factor of three at 3998 kWh. In both cases, the additional use of shading and night ventilation causes a slight increase in heating demand because reduced solar gains mean less passive warming of the thermal mass. However, the relative increase remains very small.

Table 36. Heating demand in kWh.

	Heating energy requirement[kWh]			Increase [%]
	Base	Base S	Base NVS	From base to NVS
Córdoba	1101	1111	1113	1.09
Krakow	3998	3999	4011	0.33

3.2.1.2. Overheating

Both typologies show overheating phases in their initial state. The Casa de Pisos in Córdoba is particularly affected, with 10445 Kh/a of excess temperature hours, indicating pronounced summer comfort problems. The Kamienica in Kraków also shows summer comfort problems, though at a much lower level of 3055 Kh/a.

Based on these findings, adaptation strategies were developed to minimize excess temperature hours. In both cases, daytime shading was first applied. In Córdoba, this significantly reduced overheating because the shading elements effectively mitigated the impact of high summer solar radiation. The internal blinds in Kraków also improved the situation, but there overheating is driven more by outdoor temperatures, higher internal loads, and the lower thermal storage capacity of the building elements than by global radiation alone. To further reduce excess temperature hours, night ventilation was then introduced. This markedly lowered the values in both cases. Especially in Córdoba, the reduction by 99.9% demonstrates the efficiency of climate-sensitive passive adaptation through daytime shading and nocturnal ventilation.

Table 37. Overheating measured in excess temperature degree hours.

Location	Excess temperature degree hours [Kh]		
	Base	Base S	Base NVS
Córdoba	10445	2335	11.7
Krakow	3055	2414	0.5

3.2.1.3. Relative humidity

In the unadapted base state, the case in Kraków (Figure 32 bottom) shows a pronounced seasonal pattern of indoor relative humidity. Median values are around 35% in winter and rise to about 55% in summer; with large variation ranges, especially in summer and autumn. The case in Córdoba (Figure 32 top), by contrast, shows a more even humidity pattern over the year, with medians mostly between 35% and 45% and smaller variation. Only in summer does the median fall to approximately 30–35%. Additionally, the lowest RH in Cordoba occurs during the summer months, while in Krakow the lowest values are calculated for the winter months.

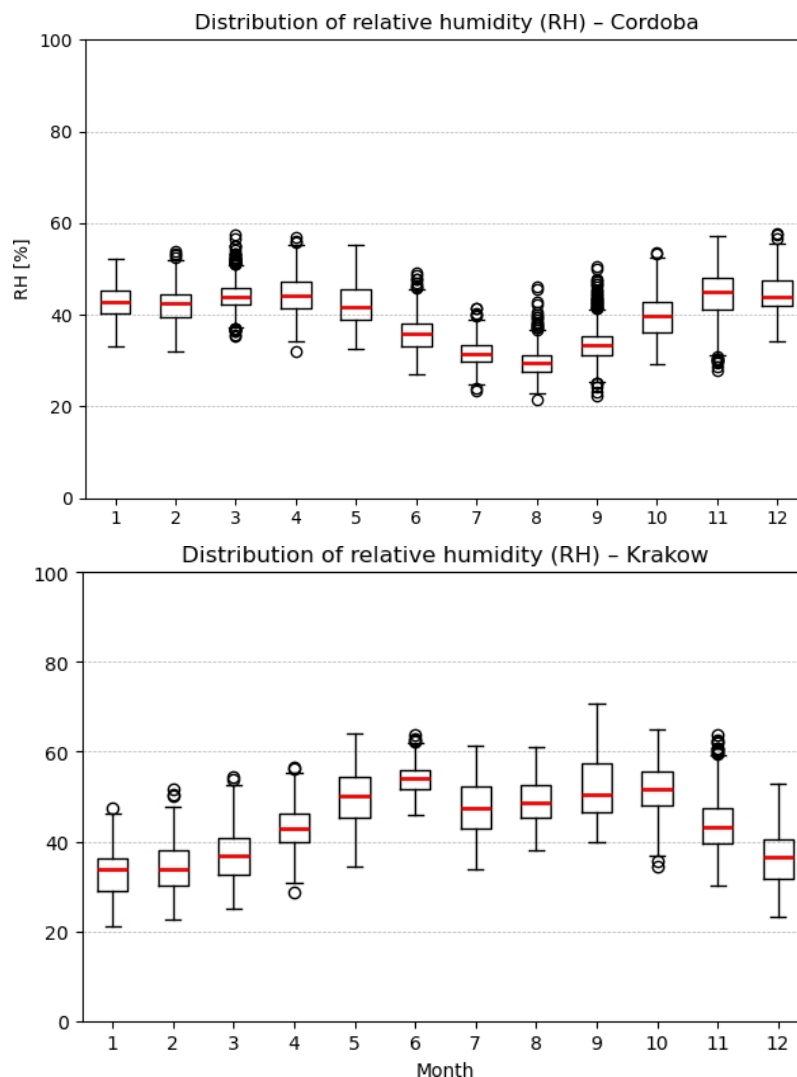


Figure 32. Indoor relative humidity of the base variants in Córdoba (top) and Kraków (bottom).

After the introduction of passive adaptation strategies, especially night ventilation, both cases show a significant rise in relative humidity during summer (see Figure 33 and Figure 34). In Kraków, monthly median values from June to September under night ventilation rise markedly, while in Córdoba the median can rise from roughly 45% to around 67% in July. The variation range also increases strongly when night ventilation is active.

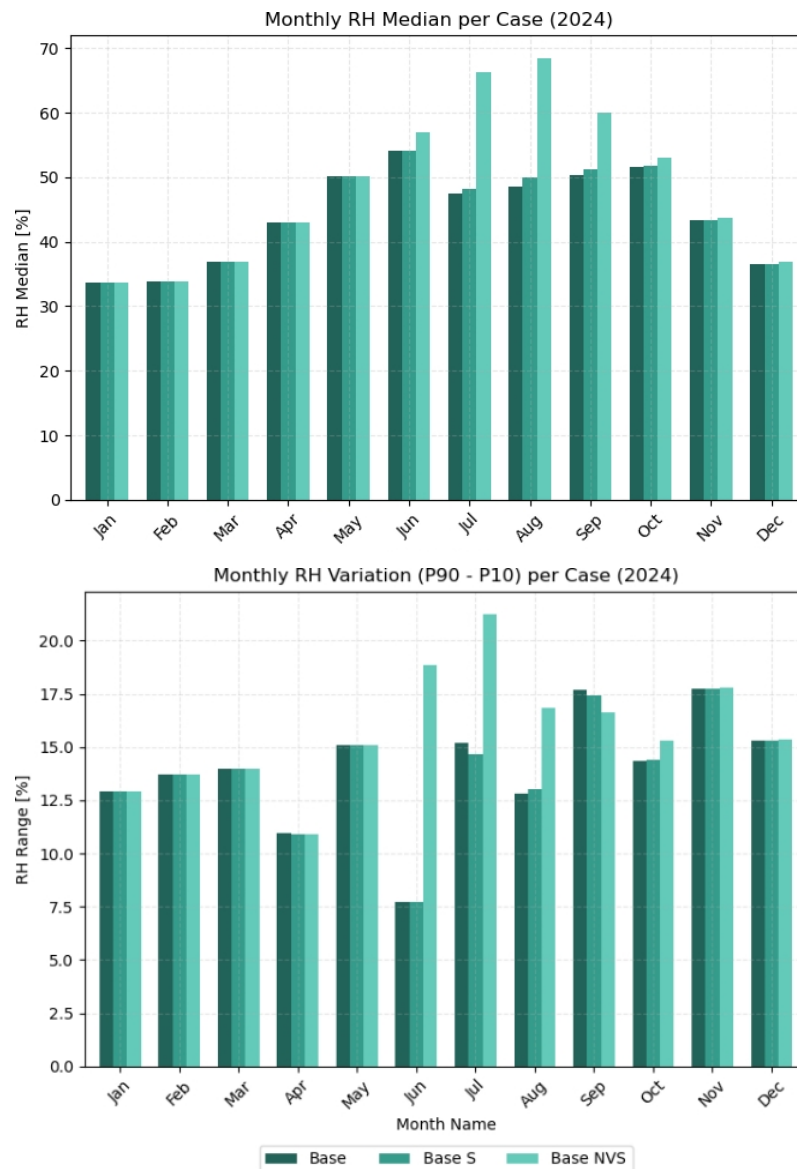


Figure 33. Median (top) and variation (bottom) of relative humidity after implementation of adaptation strategies in uninsulated condition in Cordoba.

This development makes clear that night ventilation is effective in avoiding overheating but can also increase the risk of elevated indoor humidity in summer. This raises the question of whether hygroscopic internal insulation systems with a higher moisture-buffering capacity can dampen the effect.

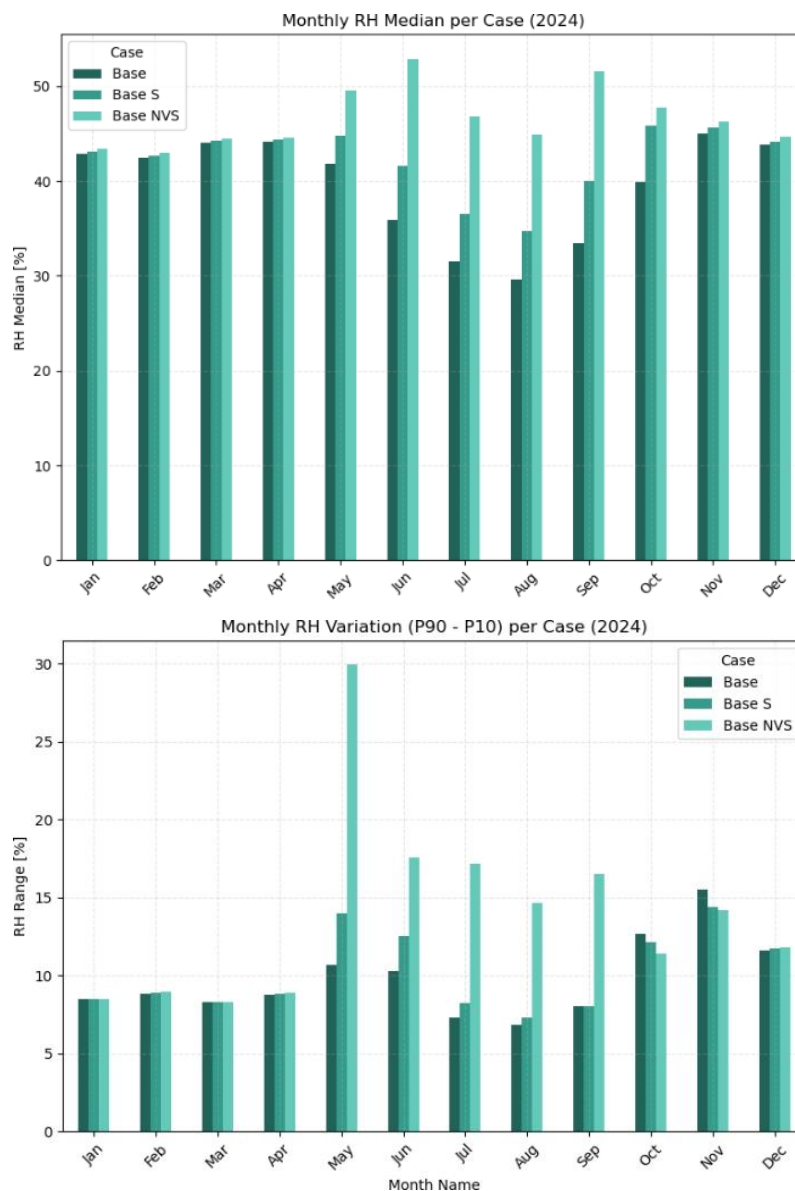


Figure 34. Median (left) and variation (right) of relative humidity after implementation of adaptation strategies in uninsulated condition in Krakow.

Effect of internal insulation systems

This section examines how the selected internal insulation systems affect the indoor climate performance of the representative case studies. The analyses compare the reference state with different retrofit configurations in order to assess their influence on summer comfort, overheating risk, indoor relative humidity, and the moisture-buffering potential of hygroscopic materials. By considering these indicators together, the results highlight both the benefits and possible side effects of internal insulation, supporting the identification of solutions that improve energy performance while maintaining acceptable comfort and hygrothermal conditions.

3.2.2.1. Moisture content assessment according to WTA 6-5

The analysis of the different internal insulation systems under the current climatic conditions of Córdoba and Kraków provides insight into the moisture content evolution after the application of internal insulation and shows the influence of adaptation measures such as shading and night ventilation on the drying behaviour of insulated walls.

The key evaluation criterion according to WTA — the achievement of a steady cyclic condition — confirms that in all investigated variants the annual water content shows a clearly declining trend. Many cases reach the steady cyclic state completely, while others are still in the drying phase but continue to show a steady decrease without ongoing moisture accumulation. Only in the case of the 3 cm calcium silicate board in Córdoba does a very small re-moistening of 0.01% occur in the fifth year.

A comparison of the cases shows that implementing shading and especially night ventilation significantly slows the drying behaviour of the wall construction. In both typologies, the total moisture content behind the insulation decreases annually by roughly 1.5–4% when NVS is used. This is due to on the one hand the lower daytime indoor temperatures and on the other hand to the higher indoor relative humidity caused by night ventilation. Nevertheless, in all investigated cases the long-term moisture level remains below the critical threshold of 95% relative humidity.

3.2.2.2. Impact on heating demand

As expected, the use of internal insulation systems significantly reduces heating demand in both typologies. In the Casa de Pisos, 10 cm mineral wool proved to be the most effective system and reduced heating demand by more than 20% compared with the uninsulated exterior wall. The newly developed CarbonClay Sinkstone materials show different performance: despite both being applied at an 8 cm thickness, MM2 provides a greater reduction than Mi4 due to its lower thermal conductivity.

The same tendency is seen in the Kraków case. Uninsulated reference cases show the highest heating demand, while systems with 10 cm of insulation (mineral wool or EPS), reduce the annual heating demand substantially. In all systems, the savings relative to the uninsulated initial condition amount to at least 20%.

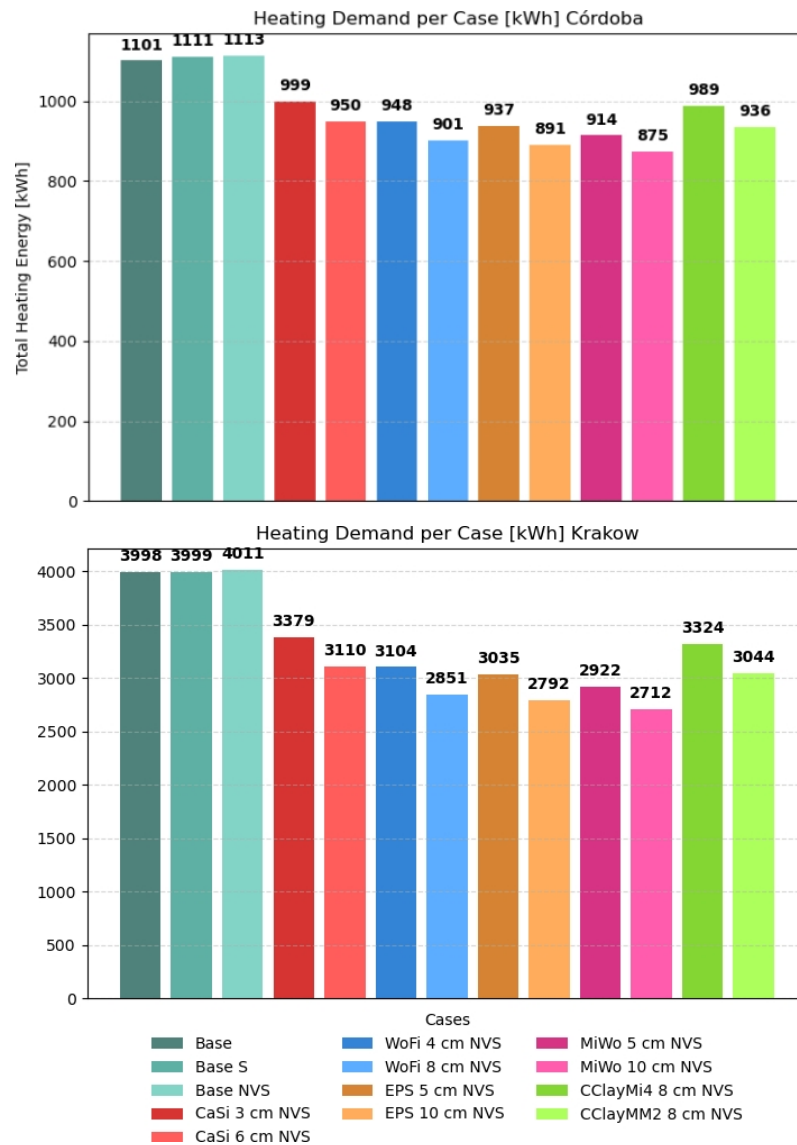


Figure 35. Comparison of heating requirements [kWh/a] for uninsulated and internally insulated variants for Cordoba (top) and Krakow (bottom).

The analysis of remaining energy losses (see Figure 36) shows for both locations that the largest losses occur through ventilation, whereas savings result from the often considerable reduction of transmission heat losses through the exterior walls. Ventilation heat losses remain almost unchanged because the ventilation rates were kept constant. This suggests that a more finely tuned ventilation strategy or the installation of mechanical ventilation could further improve performance.

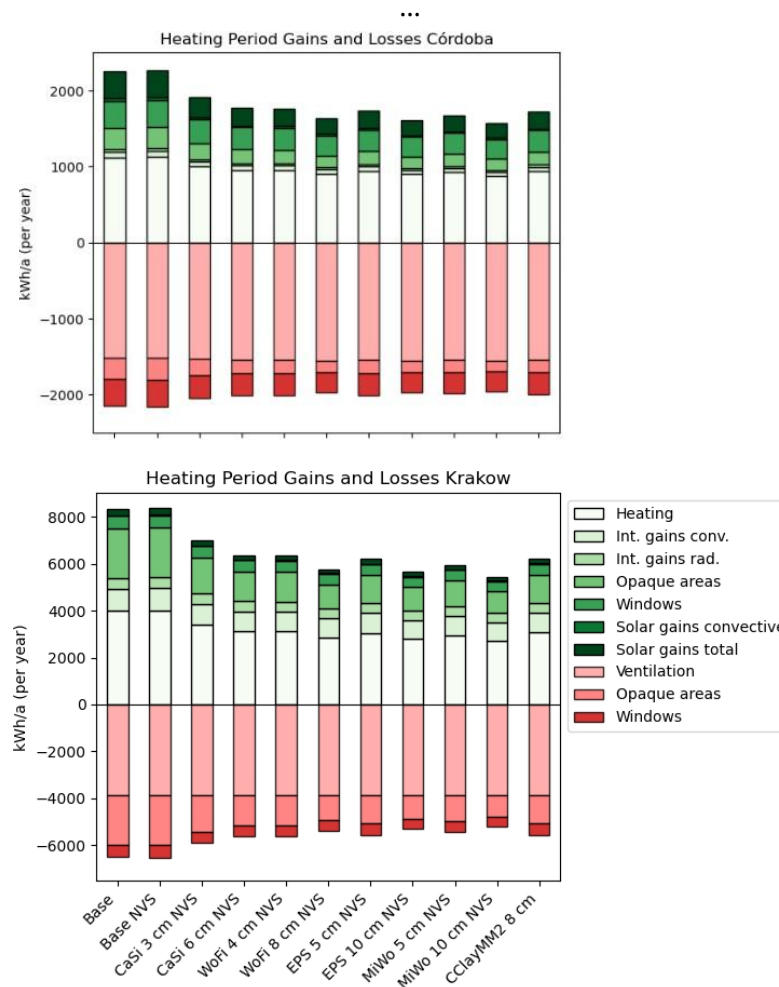


Figure 36. Losses and gains during the heating period for Cordoba (top) and Krakow (bottom).

3.2.2.3. Impact on the risk of overheating

In both climate zones, internal insulation leads to an increase in excess temperature hours compared with the NVS-adapted base case (Table 37). However, this increase does not primarily occur during summer; instead, it shifts to transition months between winter and summer in which no targeted passive strategies such as shading or night ventilation are active.

For Córdoba (see Figure 37), the evaluation shows that although overheating increases overall after internal insulation, the peaks concentrate in April, October, and November. During the summer months, when shading and night ventilation are active, hardly any additional overheating occurs, despite the operative temperature being higher than in the previous months. This is due to how acceptable temperature is calculated in ASHRAE Standard 55-2017 as a function of mean external temperatures. Nevertheless, it demonstrates the efficiency of ventilation and shading.

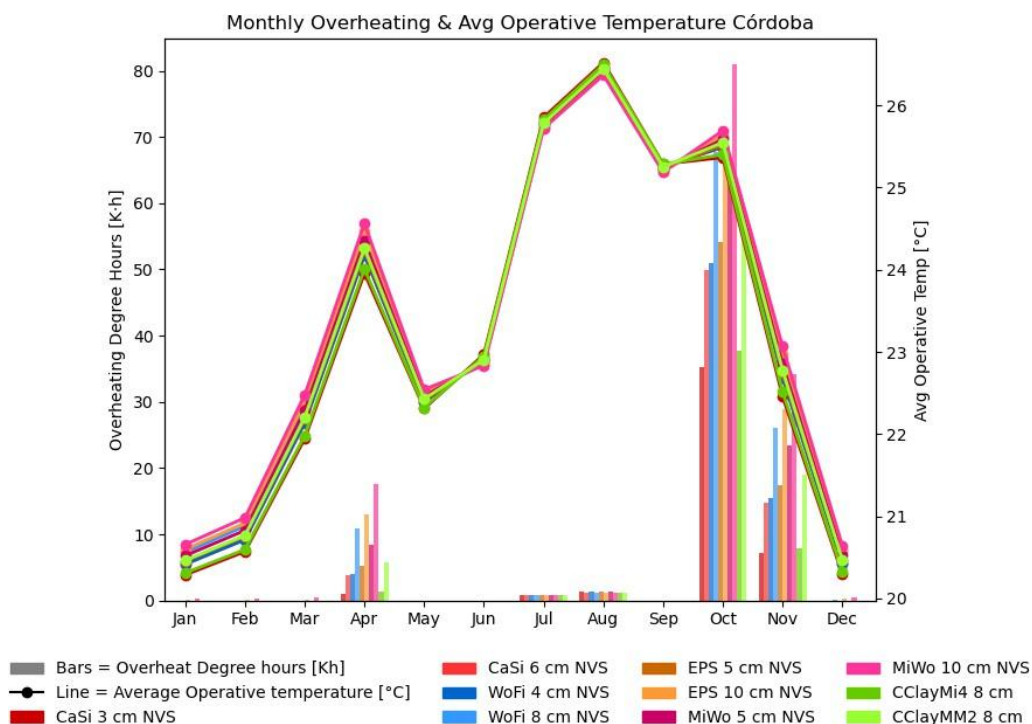


Figure 37. Excess temperature degree hours (left axis) and median operative temperature (right axis), Córdoba.

In Kraków (see Figure 38), the strongest increase occurs in May. Again, during summer with active night ventilation and shading, the insulated cases do not show any relevant additional overheating. A closer comparison of the systems reveals differences: in Kraków, EPS and mineral wool show a stronger absolute increase in excess temperature hours than the other systems; in Córdoba, the overall differences between systems are smaller, although systems such as mineral wool or EPS tend to produce higher overheating values than mineral systems such as calcium silicate or CarbonClay.

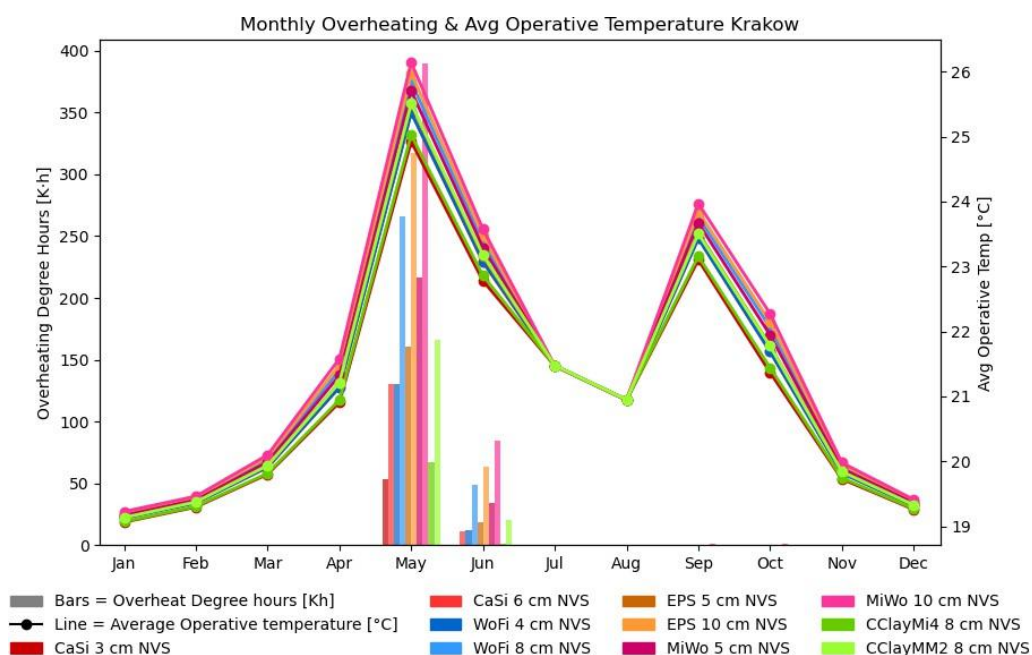


Figure 38. Excess temperature hours and median operative temperature, Krakow.

At the same time, the combination of internal insulation with passive measures performs far better than the unadapted base variants. Even the least favourable insulated case with passive measures causes far fewer excess temperature hours than the initial state without protective measures (see Figure 39). Extending the passive measures for the more strongly insulated variants reduced the values even further, to as little as 3.29 Kh in Córdoba and 1.79 Kh in Kraków.

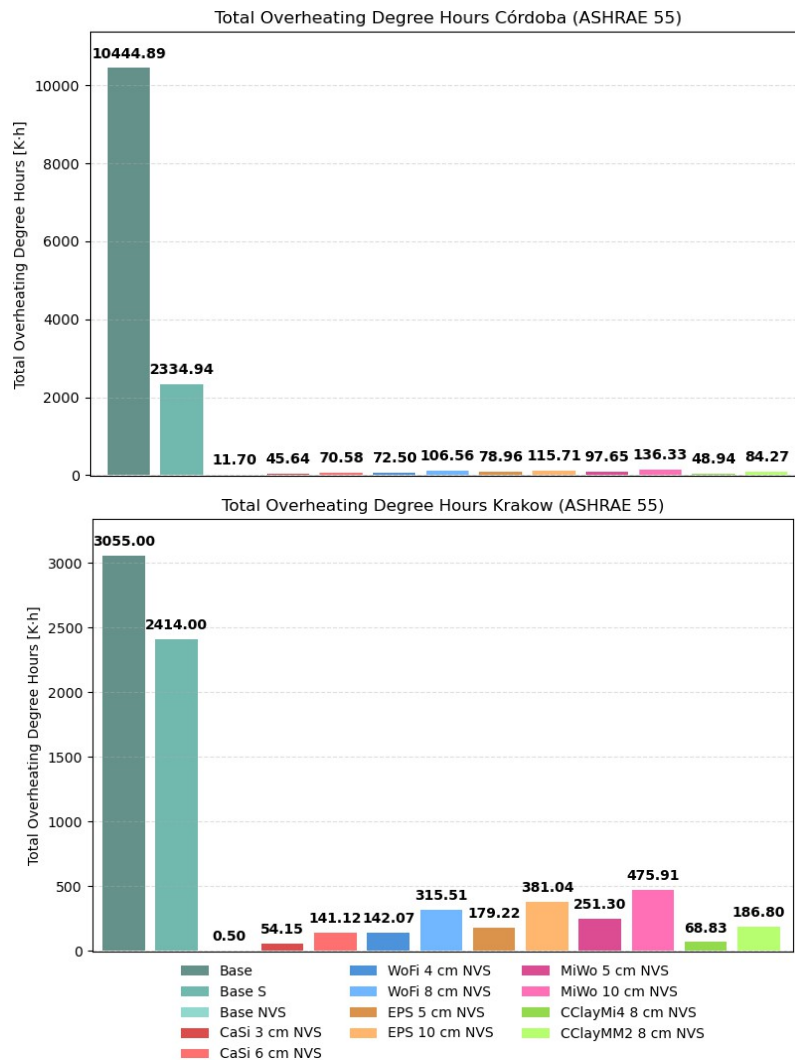


Figure 39. Total excess temperature hours in Córdoba (top) and Krakow (bottom) based on measured climate.

This shows that although internal insulation can increase overheating in the intermediate seasons, the effect can be effectively mitigated through optimized shading and ventilation strategies adapted to outdoor conditions (see Table 38).

Table 38. Excess temperature in degree hours of insulated scenarios.

Internal insulation system	Excess temperature degree hours [Kh]	
	Córdoba	Krakow
CaSi 6 cm NVS per	2.0	0
WoFi 8 cm NVS pro	1.93	0.01
EPS 10 cm NVS per	2.15	0.39
MiWo 10 cm NVS per	3.29	1.79
CaClay Mi4 NVS per	1.80	0
CaClay MM 2 NVS pro	1.93	0

3.2.2.4. Impact on moisture buffering and indoor humidity

The simulation results for Cordoba show only small effects of internal insulation on indoor relative humidity (see Figure 40).

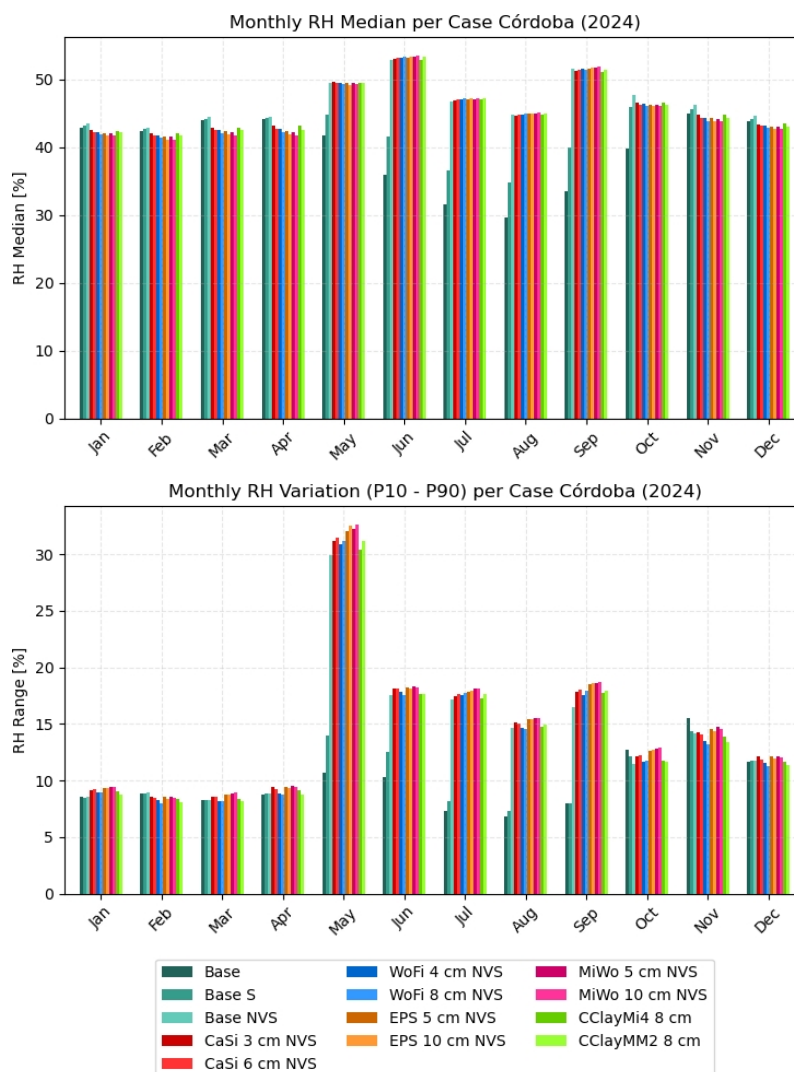


Figure 40. Median relative humidity (top) and variation in relative humidity compared with measured climate data (bottom), Córdoba.

After insulation is implemented, the median relative humidity changes only slightly: it decreases a little in winter and increases slightly in summer. CarbonClay shows the highest winter median, which is attributed to its pronounced moisture-buffering properties that counteract excessive drying of indoor air. The variation of relative humidity also shows only limited differences between systems, but CarbonClay variants generally exhibit the smallest fluctuations.

The evaluation of the moisture variation in the walls resulting from the exchange with the internal climate confirms this picture and identifies CarbonClay as the system with the strongest overall moisture buffering. Calcium silicate shows a medium response, wood fibre a somewhat broader variation, mineral wool only limited effects, and EPS the smallest moisture exchange with the wall surface. A detailed analysis of a four-day period in May confirms that CarbonClay reacts most strongly to moisture peaks by absorbing moisture when indoor relative humidity rises and releasing it again when it falls (see Figure 41 and Figure 42).

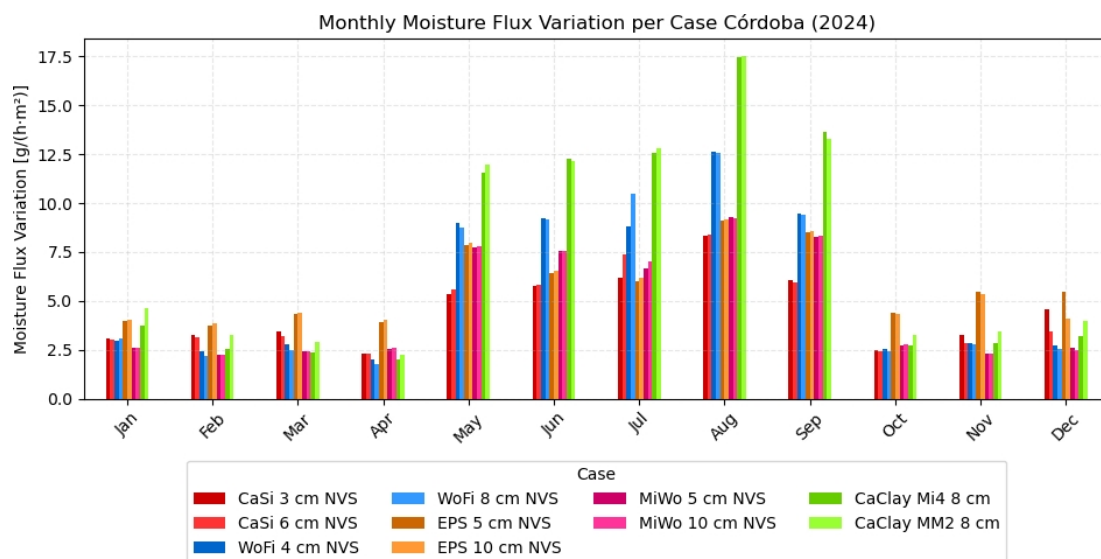


Figure 41. Monthly moisture flux on the inner surface of the exterior wall in Córdoba based on climate data.

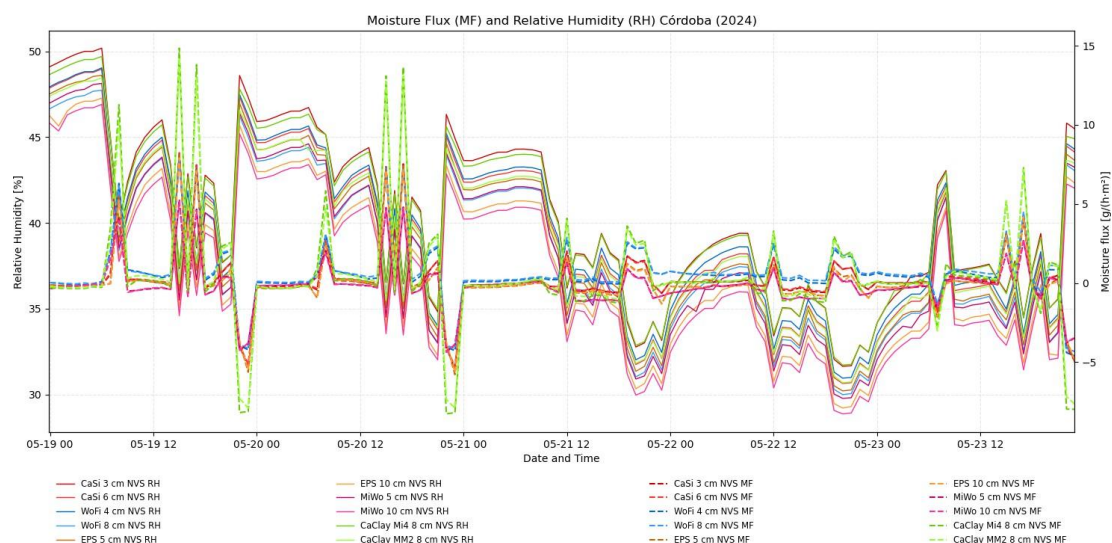


Figure 42. 4-day period of moisture flux on the inner surface of the exterior wall and relative humidity in Córdoba.

In Kraków, on the other hand, the influence of the different insulation systems on indoor relative humidity is more strongly dependent on season and material. In the Kamienica living room, the monthly median relative humidity decreases slightly in winter after internal insulation is installed, while a more pronounced reduction appears in May. During summer, especially in July and August, the influence of insulation is marginal because humidity remains in a critical range of around 70% relative humidity, due to the combination of night ventilation and high internal moisture loads from the family-use profile. In the transition months, however, a general reduction in relative humidity compared with the uninsulated NVS reference can be observed, and material-specific differences become more visible. CarbonClay tends to keep indoor humidity somewhat higher than the other variants.

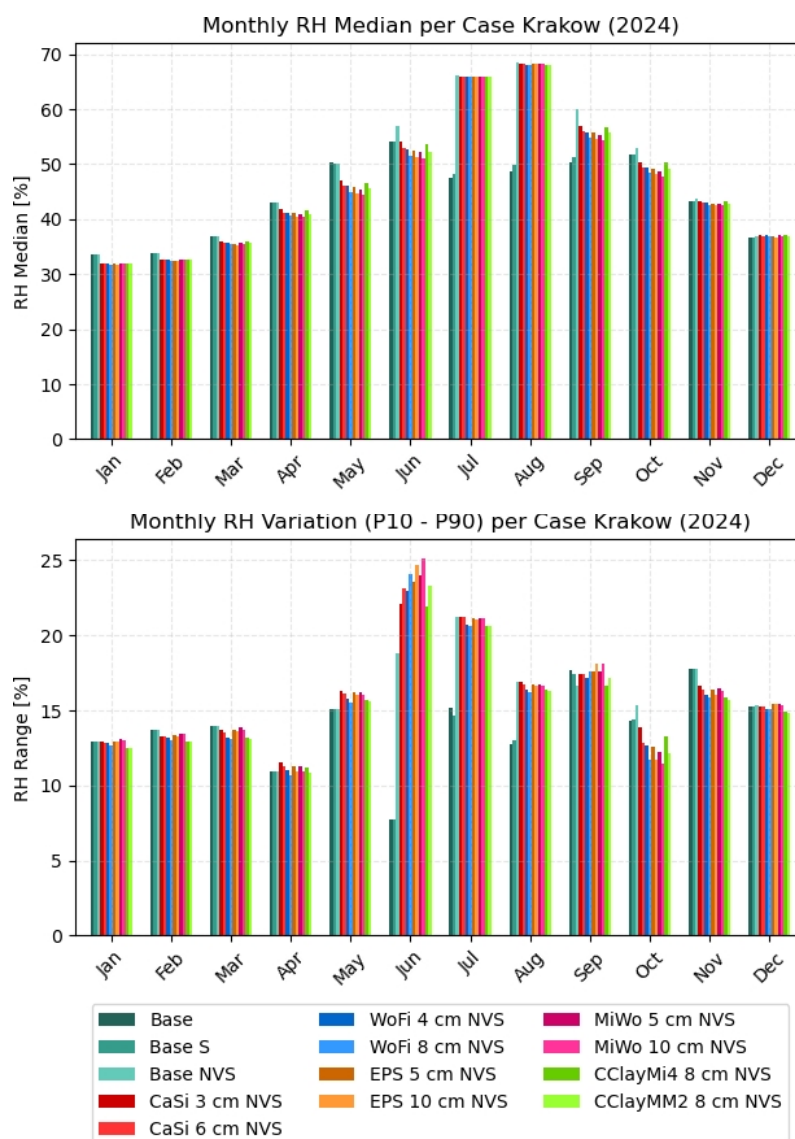


Figure 43. Median relative humidity (top) and variation in relative humidity compared with measured climate data (bottom), Krakow.

The analysis of humidity variation confirms this tendency. Once night ventilation is active, the variation reaches its highest values in June. The insulation systems also intensify fluctuations in relative humidity in May and June, whereas in winter the variation decreases, with CarbonClay

Sinkstone showing slightly smaller changes than the other materials (as seen by the difference in bar heights in Figure 43 bottom). Moisture-flux analysis again demonstrates the strongest buffering effect for the CarbonClay Sinkstone systems. Calcium silicate follows with moderate buffering, EPS with limited buffering, and mineral wool with minimal moisture variation (see Figure 44 and Figure 45).

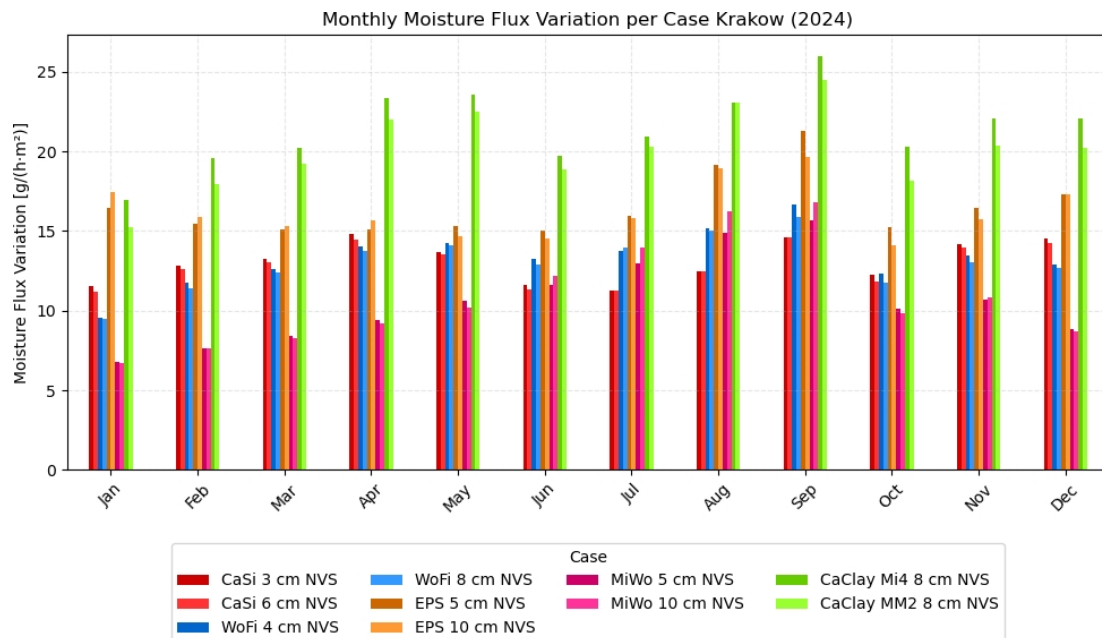


Figure 44. Monthly moisture flux on the inner surface of the exterior wall in Krakow case based on measured climate data.

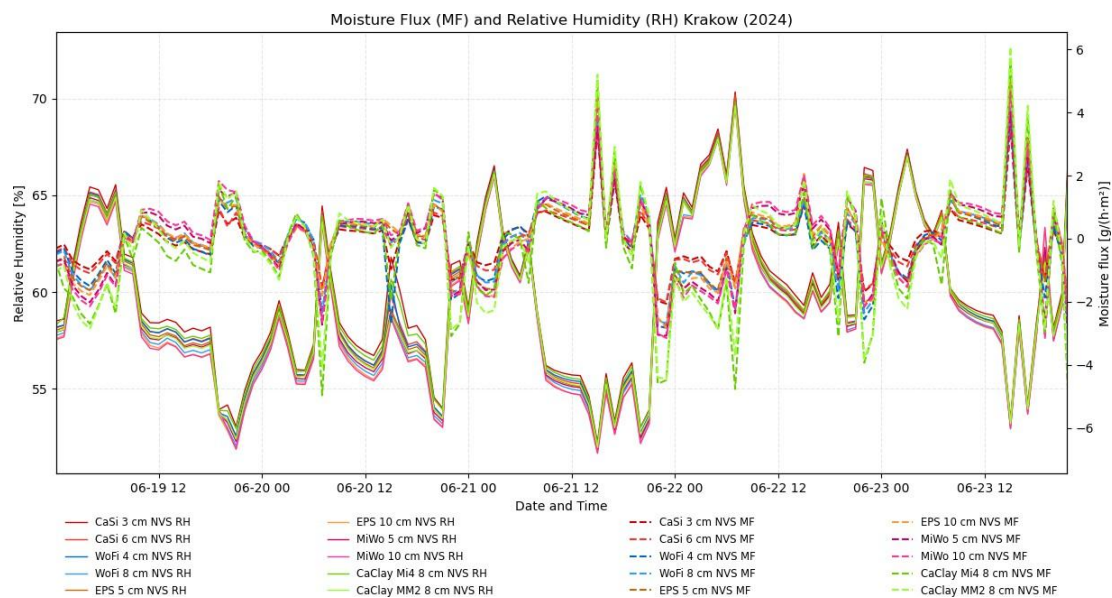


Figure 45. 4-day period of moisture flux on the inner surface of the exterior wall and relative humidity in Krakow case based on measured climate data.

It was also noted that even vapour-tight and vapour-retarding systems such as EPS and mineral wool still show some moisture-flux response, suggesting that the room-side plaster layers have a significant influence on the overall moisture-buffering behaviour.

Future climate scenarios

3.2.3.1. Heating demand

In future climate scenarios, substantial reductions in heating demand can be observed in both Cordoba and Krakow. Although temperatures rise in both regions, there is still a heating demand, see Figure 46.

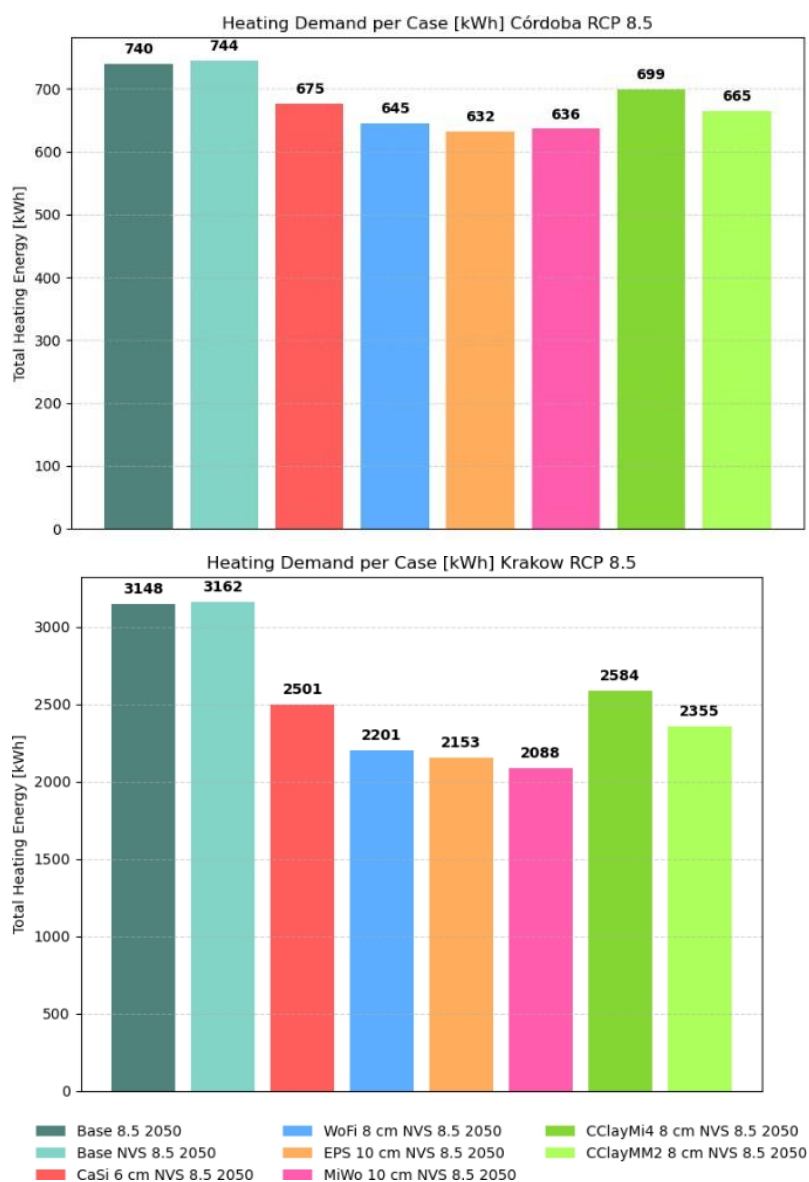


Figure 46. Heating demand [kWh/a] under RCP 8.5 for Córdoba (top) and Krakow (bottom).

In Córdoba, the annual heating demand to maintain an indoor temperature of 20°C in the uninsulated NVS base variant decreases by 373 kWh when the current climate (Figure 35) is compared with RCP 8.5 in 2050. Heating is therefore still needed, but at a lower level. Additional insulation further reduces the heating demand, with the amount depending on the system used.

In Kraków, future climate causes an even larger reduction in annual heating demand: the NVS base scenario decreases by 849 kWh due to climate change alone. The maximum heating-energy saving through internal insulation remains substantial, showing that even in a warmer future internal insulation is still a meaningful strategy for reducing heating demand.

3.2.3.2. Overheating

The simulations under the RCP 8.5 climate scenario for 2050 show how critical future summer periods could become in Córdoba for the Casa de Pisos typology. Without adaptation and with ventilation reduced to the minimum necessary for acceptable CO₂ values, more than 17,000 overheating degree hours are projected. Average operative temperatures in summer rise to above 35°C, representing a serious health risk, especially for vulnerable groups.

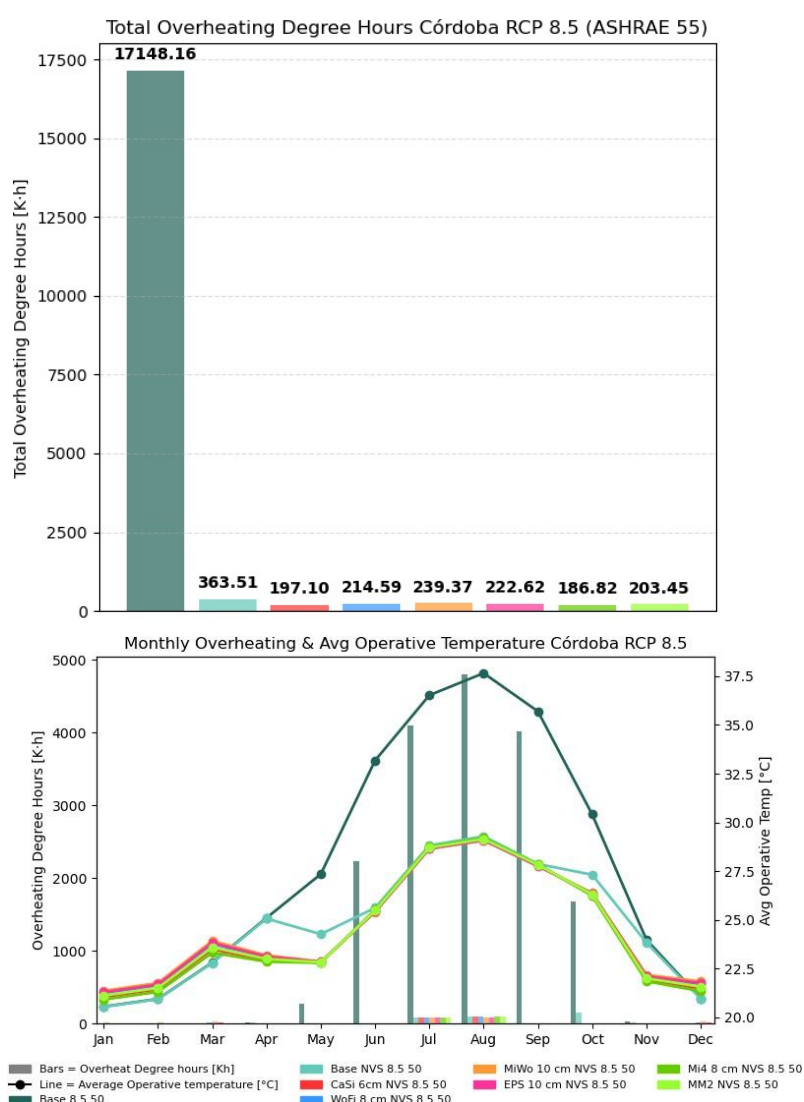


Figure 47. Total excess temperature hours under RCP 8.5 for 2050 (top) and excess temperature degree hours and median operative temperature, Córdoba (bottom).

Against this background, passive strategies become particularly important. The combination of optimized shading and consistent night ventilation reduces the excess temperature hours to

363.51 Kh. Mainly the excellent shading factors of the devices used and effective nocturnal cooling are responsible for this reduction. When the interaction of shading and controlled ventilation is considered, the insulated variants do not show a higher overheating risk than the uninsulated building if passive measures are applied in a coordinated way (Figure 47 top). At the same time, the simulations show that with rising outdoor temperatures the situation worsens in all cases; even in adapted rooms, excess temperature hours increase roughly tenfold or higher compared with current conditions (passing from 11.7 to 363.51 degree hours in the base NVS case). Highly insulating systems can therefore become more critical in summer and require particularly sensitive adaptation strategies (see Figure 48).

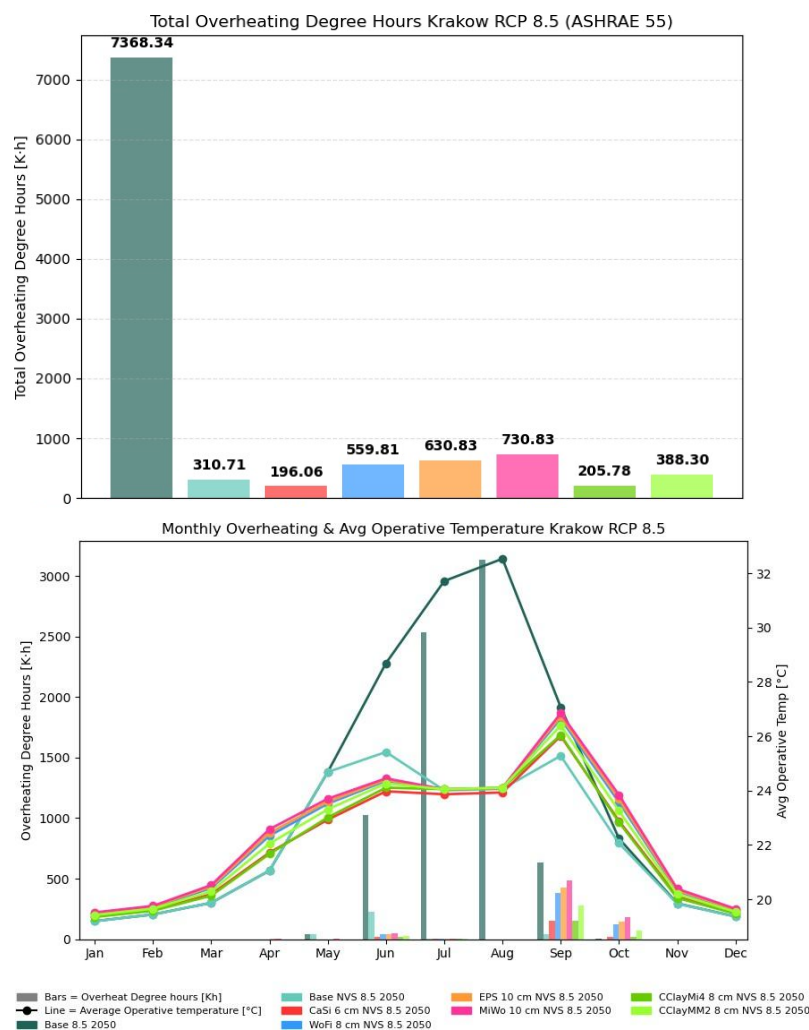


Figure 48. Total excess temperature hours under RCP 8.5 for 2050 (top) and excess temperature degree hours and median operative temperature, Krakow (bottom).

The analysis in Krakow shows that the temperature increase under RCP 8.5 for 2050 has serious implications for thermal comfort and overheating risk in the Kamienica typology. If ventilation remains restricted to a minimum, the projected climate leads to a drastic rise to 7,368 overheating degree hours in the uninsulated case. The adapted uninsulated variant, however, demonstrates that consistently implemented passive measures can considerably reduce summer overheating in Kraków, lowering the value to 310 Kh.

The internal insulation systems react very differently under the more severe future conditions. In both cases, the 10 cm mineral-wool system (MiWo 10 cm) performs worst in summer, expressed by a substantial higher number of excess temperature hours, even though it achieves the highest energy saving in winter. Calcium silicate and CarbonClay Mi4 perform much better, again showing that material selection must be carefully balanced throughout the year. In Kraków, night-time cooling remains a central factor because nocturnal outdoor temperatures are still lower than daytime temperatures, so targeted night ventilation can contribute substantially to reducing overheating. The results suggest that further optimization of ventilation and shading strategies could reduce the values even further, especially in the intermediate seasons.

3.2.3.3. Relative humidity

Comparing the current climate with the RCP 8.5 scenario for 2050 in Córdoba shows only minor changes in the median relative humidity for the non-adapted base variant.

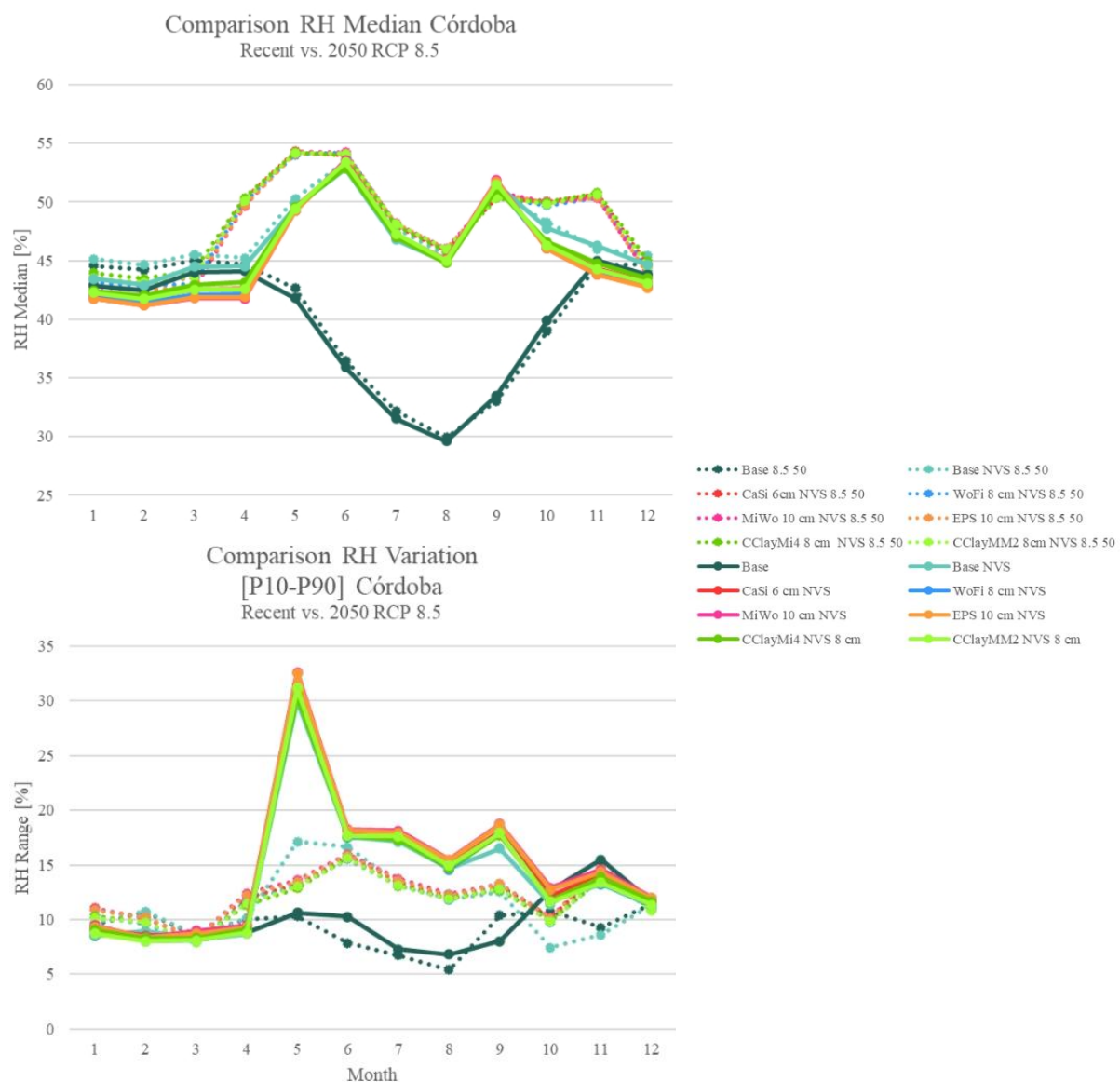


Figure 49. Comparison of humidity dynamics under RCP 8.5 2050 for Córdoba.

In contrast, the variants combining night ventilation and shading (NVS) show consistently higher median values, particularly during the transition months. Differences between insulation systems remain limited under future conditions. The annual humidity pattern also becomes more uniform and less pronounced for all systems with night ventilation, as indicated by the comparison between the solid and dashed lines in Figure 49 (bottom). This is likely linked to warmer night-time temperatures, which may reduce the occurrence of extreme humidity peaks in Córdoba.

The future scenario in Krakow (see Figure 50) generally shows a decrease in relative humidity, except for a slight increase in August. Again, differences between the individual systems are small; the stronger influence comes from the climate trend itself. The highest relative humidity values are still expected in July and August. Variation increases slightly from January to April, but June remains the month with the widest fluctuation band. For Kraków, this suggests that installing a ventilation system may be justified to avoid critical humidity levels. Even under the RCP 8.5 scenario, no relaxation of the indoor humidity situation is apparent.

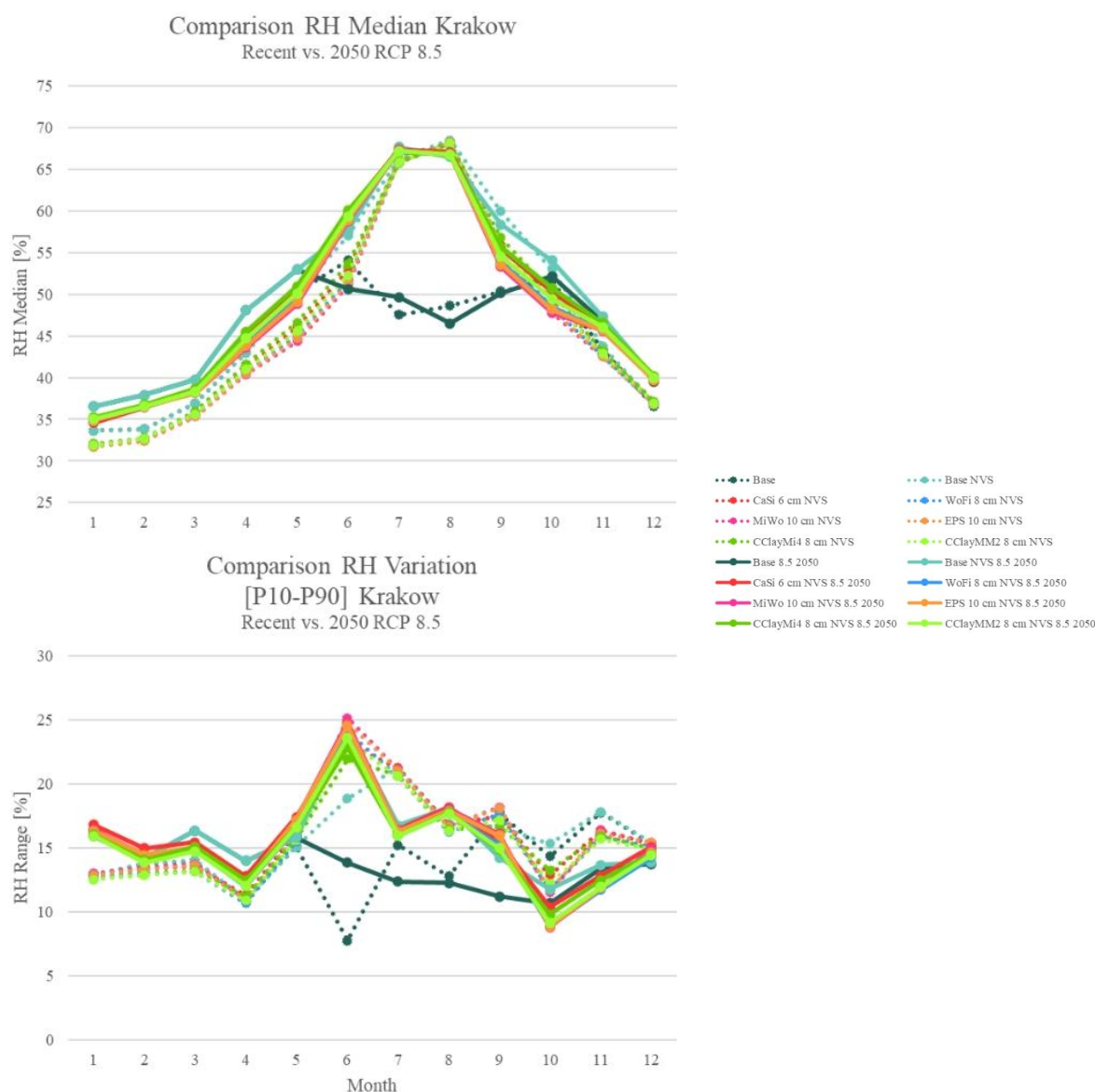


Figure 50. Comparison of humidity dynamics under RCP 8.5 2050 for Krakow.

3.3. Discussion

The investigation clearly shows that sustainable passive retrofit concepts have a significant influence on the indoor climate of historic buildings and generate complex interactions between energy demand, summer comfort, and moisture dynamics.

As expected, internal insulation in both investigated typologies and climate zones proves to be an effective strategy for reducing heating demand. Larger insulation thicknesses and systems with low thermal conductivity, especially mineral wool, show pronounced efficiency under both current and future climatic conditions. Even in the RCP 8.5 scenario for 2050, internal insulation remains a central component of sustainable retrofit measures, because a seasonal heating demand persists despite milder winters.

At the same time, the results show that while internal insulation substantially reduces the heating demand, it can also increase the risk of summer overheating if passive strategies are not adapted. Because of the reduced thermal storage capacity, both typologies react more sensitively to solar gains and internal loads in the transition and summer months. This risk would increase further under future climate conditions. Crucially, however, overheating scenarios do not occur when adequate passive adaptation measures such as shading and night ventilation are implemented consistently. The simulations clearly show that these measures effectively compensate for the lower storage capacity caused by internal insulation, significantly reduce thermal stress, and avoid critical indoor temperatures. Summer comfort can therefore be ensured even under future more severe climatic conditions.

The analysis of moisture behaviour highlights the importance of material properties within internal insulation systems. Systems with high sorption capacity such as CarbonClay stabilize indoor humidity and dampen moisture peaks, whereas mineral wool and especially EPS show only limited buffering capacity. Moisture fluxes at the interior wall surface also show that the room-side plaster layer plays a major role in hygric behaviour and therefore must not be neglected in the system design.

Overall, the findings demonstrate that an integrated consideration of energy, hygrothermal, and comfort-related aspects is essential for future-proof retrofits of historic buildings. Internal insulation is shown to be an effective and robust measure when combined with suitable passive strategies and material-appropriate detailing. A carefully coordinated selection of insulation materials, functional interior plasters, and adaptive user measures (such as ventilation and shading strategies) can not only reduce energy demand sustainably but also ensure a thermally comfortable indoor climate under present and future conditions. In this sense, professionally planned internal insulation is a key element for the long-term preservation and climate resilience of historic building fabric.

4. Components' integration

This section describes the work performed in Task 2.6 of the FuturHist project on the integration of components (beam heads, ceiling, roof and floor connections, windows) in the building envelope. Practical recommendations for the implementation of insulation systems are developed, and junctions resulted from the integration of components are detailed. These recommendations targeted at practitioners, pay special attention to the topics of airtightness, measures to protect against driving rain and rising damp as well as the risks of condensation and mould growth around the thermal bridges.

First, the general background on thermal bridges, airtightness, driving rain protection, rising damp and application of internal insulation is described (Section 4.1). Secondly, practical solutions for components' integration and junctions of the considered building typologies are discussed (Section 4.2). Finally, exemplary thermal bridges of the building typologies are assessed in relation to thermal losses and mould formation risk.

4.1. General Background

4.1.1. Thermal bridges

Good thermal insulation requires proper components' integration and junction design. At junctions, there is generally a risk of additional heat loss and lower internal surface temperatures during the heating season. This results in increased heating energy consumption and the possibility of condensation and/or mould growth. It should be noted that such thermal bridges are generally more relevant in highly insulated buildings than in uninsulated ones. In internally insulated constructions, the thermal bridge effect is most relevant and can account for up to one-third of the total transmission heat loss (Hauser, 1993). In (refurbished) existing buildings, the focus is often on the effects of thermal bridges on room-side surface temperatures and the resulting potential mould problems. The risk of mould growth is generally assessed by the temperature factor f_{Rsi} specified as follows (DIN EN ISO 10211):

$$f_{Rsi} = \frac{T_{si} - T_e}{T_i - T_e}$$

T_{si} °C denoting the lowest temperature at the internal surface, T_e °C and T_i °C the external and internal air temperatures, respectively. For the German standard conditions of $T_e = -5^\circ\text{C}$, $T_i = 20^\circ\text{C}$ and $RH_i = 50\%$, DIN EN ISO 10211 define the minimum temperature factor $f_{Rsi, \min} = 0.7$ to avoid mould risk. The same threshold can be assumed for the cases of Scotland, Poland and Sweden, considered in FuturHist. For warm climates, e.g., Spain, the enerPhit guidelines (Passive House Institute, 2016) report a minimum temperature factor to avoid mould risk of $f_{Rsi, \min} = 0.55$.

The additional transmission heat losses caused by thermal bridges are characterized by thermal bridge loss coefficients. Thermal bridge losses for linear thermal bridges are quantified by the linear thermal transmittance Ψ W/(m K):

$$\psi = L - \sum U_i \ell_i$$

L W/K denoting the thermal coupling coefficient obtained from a simulation of the component, U_i W/(m² K) the thermal transmittance of the 1-D component i and ℓ_i m the length over which the value U_i applies.

Air tightness

4.1.2 Air leaks (infiltration and exfiltration) through the building envelope can occur in individual building components (e.g., windows that do not close properly or are insufficiently sealed), at joints (e.g., roof connection to the exterior wall) or penetrations (e.g., chimneys) of the building envelope. It is important to minimize air leaks, which can lead to a loss of comfort (e.g., local drafts), additional heat losses and moisture related damage to building components. A tight building envelope is also essential for the proper operation of a ventilation system. When using a mechanical ventilation system, especially with heat recovery, it is essential that the air is directed through the designated supply and exhaust air openings to achieve efficient operation.

To establish a good foundation for a tightly constructed building envelope, it is advisable to consider the airtightness concept early on during the planning phase. This is particularly important also in planning refurbishing interventions. The basis of an airtightness concept is shown schematically in Figure 51 (a), in which the continuous airtight layer is denoted as a red line. The blue dots represent simplified leaks, such as electrical sockets in interior and exterior walls, light fixtures in ceilings, or the floor-wall junction. The weak points in the airtightness layer are marked with black circles. These are transitions between building components (e.g., wall-roof junctions) or penetrations of building components (e.g., chimneys or ventilation pipes).

Exemplary connections' details are provided in Figure 51 (b-e). Figure 51 (b) shows an example of how an airtight layer (membrane) of a rafter roof should be connected to a masonry wall. This airtight layer must be permanently and securely connected to both components, and a stress-free connection must be executed to prevent failure of the airtight layer (tearing of the foil) when the building components move. Prefabricated collars are available as sealing measures for penetrations (Figure 51, c), while sealing of membrane junctions can be executed using adhesive tape, compounds and/or mechanical securing (Figure 51, d, e). The average air exchange rate resulting from infiltration ranges between 0.07 and 0.7 h⁻¹ (Häupl et al., 2013). The lower value occurs in a very airtight building (new construction standard), while the higher value can occur if there are significant leaks (leaky windows, open joints in the airtight layer of the heat-transferring building envelope).

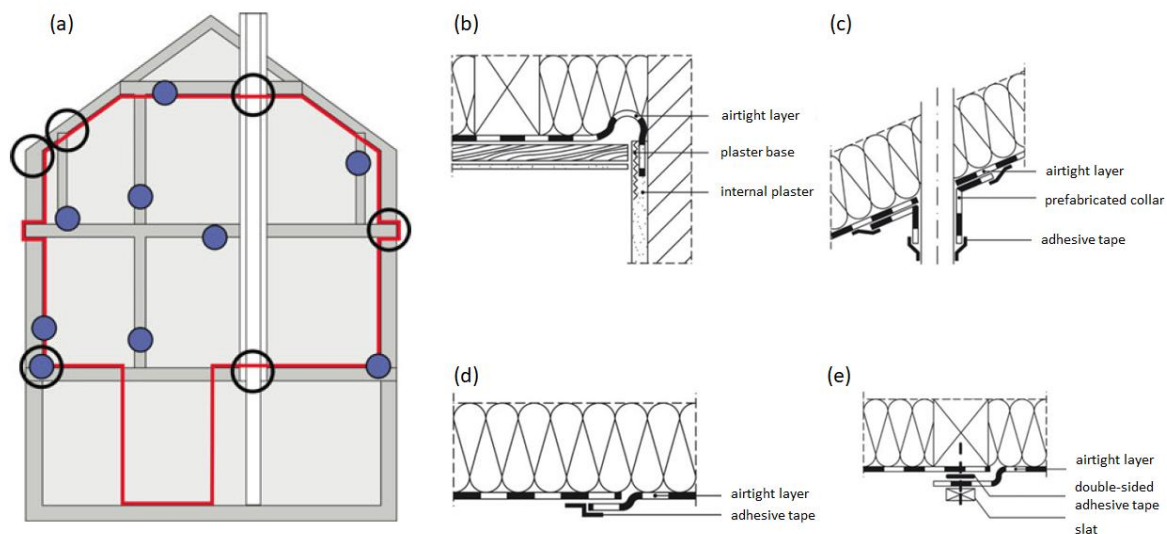


Figure 51. Schematic diagrams for the detailed execution of the airtight layer reproduced from (Häupl et al., 2013): (a) simplified representation of weak points (black circles) and leaks (blue points) in the airtight layer (red line); (b) connection of an airtight layer to a masonry wall; (c) sealing of a penetration of the airtight layer; (d) bonding of membranes; (e) use of double-sided adhesive tape or an adhesive compound and mechanical securing.

4.1.3. Driving rain protection

Driving rain on facades occurs when falling raindrops are deflected from their path by the wind. Therefore, the intensity of driving rain exposure on a facade is determined by the wind direction, wind speed, precipitation intensity, and wind flow at the building envelope. Wind speed increases with height above ground. Due to the relatively high wind speed at the building edges, recognizable in Figure 52 by the closely spaced streamlines, driving rain exposure reaches its peak values there.

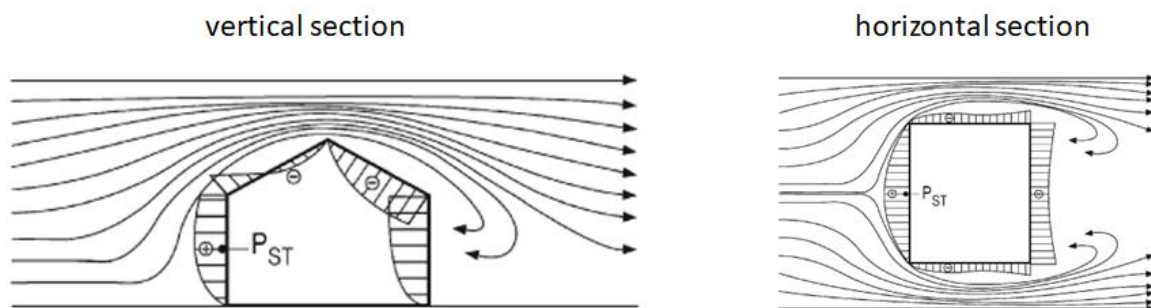


Figure 52. Wind streamlines and wind pressure distribution on a building envelope, reproduced from (Häupl et al., 2013).

The potential damage caused by wind-driven rain, particularly to non-frost-resistant building materials, must be considered. From an aesthetic perspective, efflorescence, streaks of dirt, erosion, biological growth, and other issues are common consequences of rain exposure. Such hazards might be exacerbated by inadequately designed or even missing drip edges on window sills, verges and parapets.

Existing standards (e.g., DIN 4108-3) provide recommendations for selecting measures against driving rain on exterior walls. The building is classified into one of three exposure groups according to predefined criteria (precipitation amount, building height, building location, regional rain and wind conditions). A facade can be protected against driving rain by proper design of the facade's surface, the structure of the wall cross-section, and by building protection measures on the facade's surface. Design measures include steeply sloping roofs, large roof overhangs, recessed facade surfaces, water-draining cornices, etc. (Figure 53).

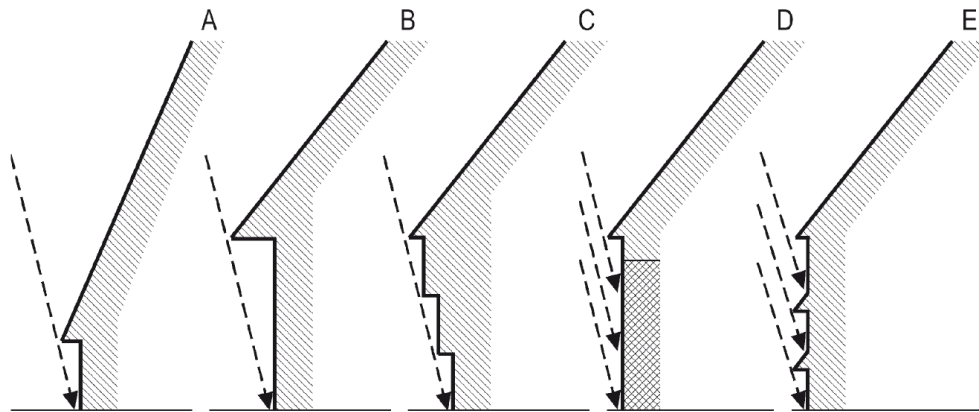


Figure 53. Protection against driving rain through facade design reproduced from (Häupl et al., 2013): a roof extending far down (A); large roof overhang (B); recessed facade surface (C); building protection measures (D); water-draining cornices (E).

The resistance of a wall to driving rain must always be assessed based on the entire wall cross-section (Figure 54): On the one hand, a homogeneously constructed wall can be made of a material that naturally absorbs little or only slowly, or with a sufficiently large wall thickness to ensure sufficient moisture storage capacity (Figure 54 A). On the other hand, a ventilated shell can be installed in front of the wall to keep out the rain (Figure 54 B). Shingles and panels on supporting structures or ventilated facing brickwork work in this way. The protective shell must be resistant to rain and frost. Alternatively, an impermeable layer can be incorporated into the wall (Figure 54 C), e.g., mortar layer, hydrophobic insulation layer or a bituminous sealing layer. Finally, the surface of a wall can be treated with paints, mineral plasters, or impregnating agents, so that it no longer exhibits capillary action (Figure 54 D). The risk of cracks requires in this case more consideration than in case A, because the rainwater running down the wall surface is concentrated on the cracks. This can be counteracted by crack-bridging coatings or, in the case of cracks with a gap width of < 0.3 mm, by hydrophobic treatment (Häupl et al., 2013).

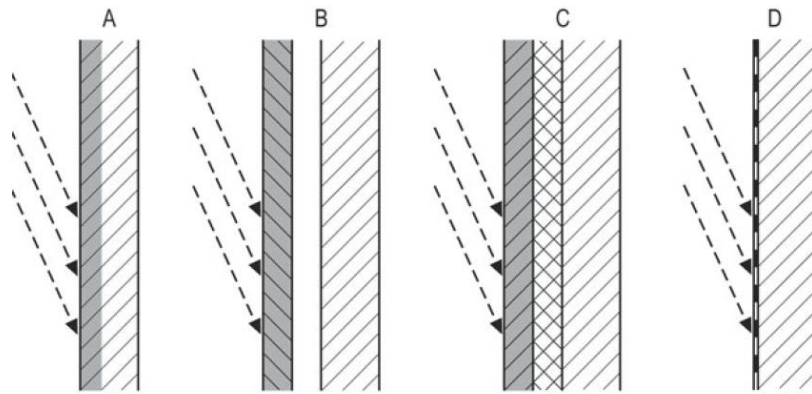


Figure 54. Operating principles of the driving rain tightness of wall cross-sections reproduced from (Häupl et al., 2013): building material with low or slow water absorption (A); ventilated shell on the outside (B); water-thigh layer in the wall (C); surface protection layer on the outside (D).

The option of treating exposed concrete, masonry, plaster, aerated concrete, etc., with impregnating agents or coatings to prevent water absorption is widespread, proven, and economical. Impregnation with silicones is very popular for exposed masonry because it does not alter the appearance of the wall surfaces and is inexpensive. Adequate protection is however provided only when the formulation of the coating is matched to the nature, porosity, and water vapor permeability of the substrate (Emery et al., 2007).

Facade plasters are almost always protected with coatings, thus extending their service life. From a building physics perspective, the aim of these measures is to reduce capillary water absorption, which is why only products effective in this respect should be used. Requirements for plasters and coatings for protection against driving rain are specified in existing standards (e.g., DIN 4108-3).

4.1.4.

Rising damp

Rising damp is when liquid water migrates due to capillary forces in porous building materials, e.g., masonry, from below the ground level, into and through the construction (Blumberga et al., 2020). Moisture accumulation in walls due to rising damp can appear visibly by darkening the wall to a certain level above the ground (Figure 55).

According to (Franzoni, 2014) rising damp “*threatens both conservation and performance of ancient masonries, as it is responsible for*” degradation of ancient building materials (e.g., due to exposure to freeze-thaw-cycles, efflorescence formation, biological decay), unsuitable indoor thermal-hygrometric conditions, poor thermal insulation efficiency of the external walls, and decrease in mechanical performance of the masonry. Strategies for removal or mitigation of rising damp can be categorized based on four basic principles which are:

1 - reduction of the water flux in ingress (e.g., via sub soil-drains, here the masonry is not directly involved in the intervention);

2 – reduction of overall sorptivity of the wall, by decreasing the wettability of materials, or by reducing the wall cross-section (e.g., via wall cutting, chemical injections);

3 – enhancement of the water evaporation rate from the masonry (e.g., via Knapen tubes, wall base ventilation, restoration plasters, heating of the wall surface);

4 – exploitation of electrokinetic effects due to active or passive electro osmosis (placing electrodes both in the moist wall and in the soil).

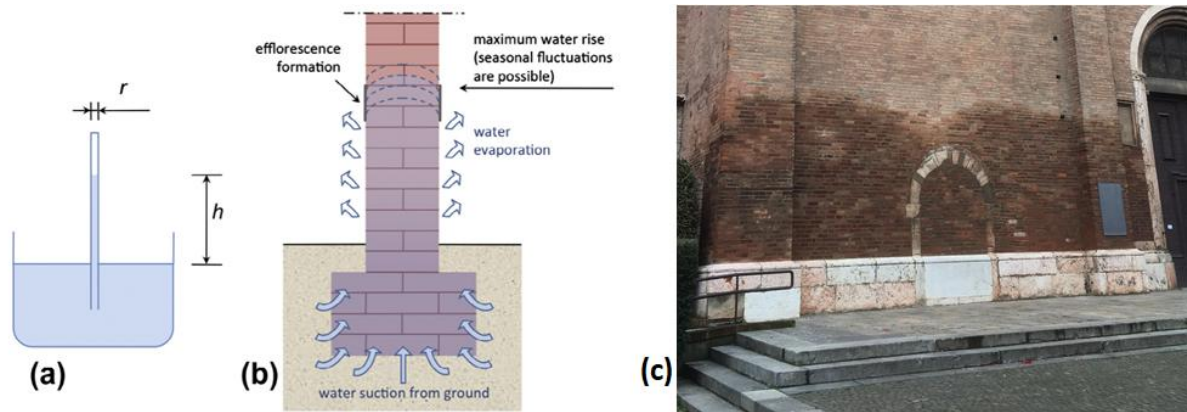


Figure 55. (a) Height h of water rise in an ideal capillary tube of radius r and (b) schematic representation of water capillary rise in masonry reproduced from (Franzoni, 2014); (c) effect of rising damp on a historic brick wall (photo by M. Bianchi Janetti).

4.1.5. Internal insulation

Internal insulation requires careful planning and execution, especially at junctions between different building components. It might reduce the drying potential of the façade, which remains cooler and humid in winter, and emphasize moisture related risks such as cracks formation due to freeze thaw cycles. Moreover, internal insulation has the potential to exacerbate harmful thermal bridges, resulting in significantly reduced interior surface temperatures. According to previous studies concerning proper planning and execution of internal insulation (Blumberga et al., 2020; Feist, 2005) and considering the results reported in Section 2 of this report on the effect of climatic and weather conditions on the hygrothermal behaviour of insulation systems, following prerequisites have to be fulfilled before applying internal insulation:

- Is the wall to be insulated affected by rising damp? If so, rising damp must first be removed. A review on methods for hindering rising damp can be found in (Franzoni, 2014).
- Is the wall to be insulated exposed to wind driven rain? If so, proper driving rain protection shall be considered, depending on the expected rain load. The water absorption behaviour of the existing external render shall be assessed (available methods for in-situ assessment are described in the FuturHist deliverable D2.6). In case cracks are present in the external render, these must be repaired. The impact of different rain loads

on the hygrothermal behaviour of internal insulation is studied in Section 2 of this report while measures for a proper protection against wind driven rain are discussed above in Section 4.1.3.

- Leaks (e.g., in water pipes) that bring moisture in the wall to be insulated must be repaired.
- Wet building materials (e.g., plaster repairs) must dry out before the internal insulation is installed.
- Water pipes (heating pipes, hot water pipes, cold-water pipes) embedded in the wall to be insulated must be shut off and drained (no internal insulation is permitted in areas with active water pipes).

To reduce the risk of mould formation, insulation must be properly planned by choosing adequate materials and insulation thickness so that at the internal surface (even with furniture) the temperature factor $f_{Rsi} > 0.7$ (or in warm climates $f_{Rsi} > 0.55$, Passive House Institute, 2016). If internal insulation is installed, supplementary insulation extending to the window frame (≥ 20 mm) is essential. This can also be implemented as an insulation wedge if there is insufficient space (Passipedia.de, 2026).

At the floor-wall connection (Figure 56, left), on the top side, connection of the wall insulation to standard impact sound insulation (≥ 25 mm) is generally sufficient. An insulation wedge might be required on the underside of the floor. At the internal walls-external wall connection (Figure 56, right), internal insulation that terminates at interior walls usually leads to low temperatures; if furniture is placed there, risk of mould formation increases. As a practical solution, supplementary insulation along the interior wall, insulation wedges or heat-conducting plates (if a non-protruding solution is needed) are recommended.

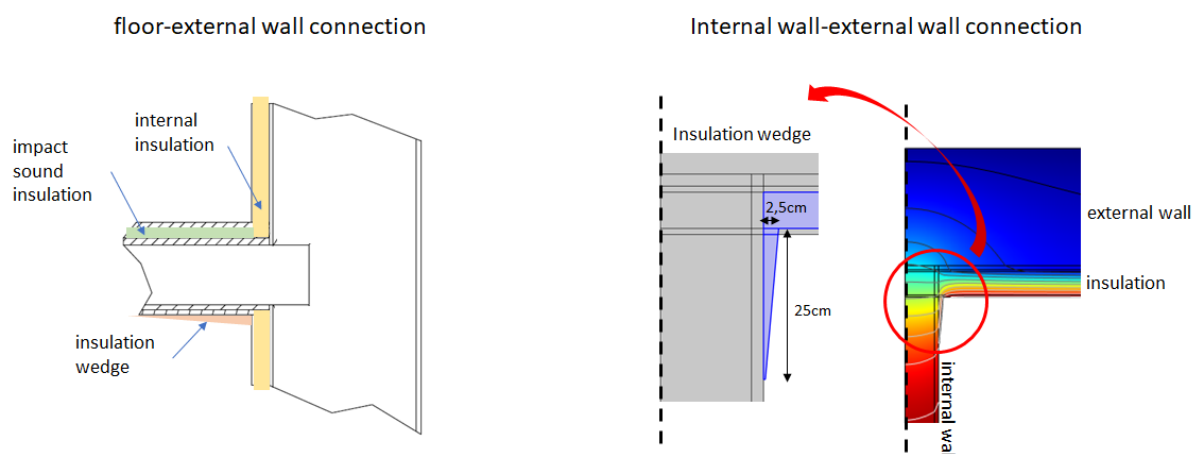


Figure 56. Proper insulation of the floor-external wall connection (left) and internal wall-external wall connection (right).

4.2. Components' integration in the building typologies

In this section, selected solutions for proper component integration and junction design are assessed against the building typologies defined in deliverable D1.2 of FuturHist. These typologies, shown in Table 39, represent key historic residential and public building types from the respective countries (Spain, Poland, Sweden, UK (Scotland)).

Table 39. Building typologies and labels used to describe each typology in Table 41 and Table 42.

Nr	Country	Name	Label
1	Spain	<i>Casa de pisos</i> terraced tenement building (1600–1920)	ES1*
2	Spain	<i>Patio de vecinos</i> terraced courtyard tenement building (1600–1920)	ES2
3	Poland	<i>Kamienica</i> terraced tenement building (1750–1945)	PL1*
4	Poland	<i>Willa miejska</i> garden-city/urban villa (1900–1945)	PL2
5	Sweden	<i>Monumentalbyggnad</i> monumental public building (1850–1920)	SE1*
6	Sweden	<i>Flerbostadshus functionalism</i> functionalist multi-family housing block (1920–1945)	SE2
7	Scotland	<i>Georgian cottage</i> detached cottage (1750–1850)	SC1*
8	Scotland	<i>Georgian tenement</i> terraced tenement building (1750–1850)	SC2*
9	Scotland	<i>Victorian terraced house</i> terraced house (1850–1920)	SC3

*Typology with demo case.

To gather detailed information on each typology in relation to components' integration, an online workshop was conducted. Participants included typology experts, building physics specialists, and other FuturHist partners involved with the demonstration cases from these countries.

A questionnaire to select suitable solutions for components' integration and junction design involving insulation systems was formulated and presented in a multiple-choice format, with mandatory comments required. The questions addressed issues such as airtightness, driving rain protection, rising damp mitigation as well as mitigation of heat losses and mould growth risk around the thermal bridges (Table 40).

Answers and accompanying notes explaining the rationale for each selection were collected and subsequently applied as filters to the comprehensive list of solutions. This process allowed assessment of the applicability of each solution to a given typology, categorizing them as 'not required', 'not compatible', 'compatible but not implemented', 'implemented in a demo case' and 'information missing'. The category 'not required' might include solutions which in a specific building typology would not bring any advantage from a technical perspective, e.g., due to the lack of major threats (rising damp, wind driven rain exposure) or considering that the building typology already disposes of alternative, more suitable solutions. The category 'not compatible' instead, refers to solutions which might be beneficial from a technical perspective but are not compatible with conservation constraints. A compilation of the notes gathered for each of the four countries involved and the full assessment of all solutions are provided below.

The collected information highlights the influence of building typology and protection level on the selection, design, and implementation of energy retrofit interventions. It also reveals variability in technical possibilities and decision-making priorities between countries. Table 41 and Table 42 include notes on the applicability of solutions for junctions and components' integration in the different building typologies.

Table 40. Questions regarding junction solutions.

Nr	Checkpoint	Question	Considered options
1	Energy losses, condensation and mould risk	How to minimize the energy losses (Ψ -Value) and/or condensation/mould risk at the internal surface (f_{Rsi} -value) of thermal bridges?	☐ <i>Insulation wedge or supplementary insulation</i> ☐ <i>Heat-conducting plate</i>
2	Airtightness	How is the airtight layer designed?	☐ <i>Internal plaster</i> ☐ <i>Concrete component</i> ☐ <i>Airtight membrane (e.g., polyethylene film)</i> ☐ <i>Taped or glued panels (e.g. OSB, gypsum, plywood panels)</i>
3	Airtightness	How to ensure airtightness at junctions?	☐ <i>Adhesive tape</i> ☐ <i>Joint sealing</i> ☐ <i>Lip seal</i>
4	Driving rain protection	How to ensure proper driving rain protection at the facade?	☐ <i>External plaster</i> ☐ <i>Rainscreen cladding</i> ☐ <i>Hydrophobic treatments</i> ☐ <i>Roof overhangs</i> ☐ <i>Door and windows pulled back from the front of the facade</i>
5	Driving rain protection	How to ensure proper driving rain protection at junctions?	☐ <i>Dimpled membrane</i> ☐ <i>Baseboard finishing profile with drip edge</i> ☐ <i>Profile with runoff stream</i>
6	Rising damp	How to avoid/minimize rising damp?	☐ <i>Injection with special hydrophobic paraffin</i> ☐ <i>Placement of moisture barrier</i>

Table 41. Notes on junction solutions for Spanish and Polish building typologies; for typologies with a demo case (ES1 and PL1). Specific considerations on the application are included.

Nr	Question	Spain (ES1)	Spain (ES2)	Poland (PL1)	Poland (PL2)
1	Energy losses, condensation and mould risk How to minimize the energy losses (Ψ -Value) and/or condensation/mould risk at the internal surface (f_{Rsi} -Value) of thermal bridges?	Insulation wedge: Compatible, but not implemented for practical reasons (balance between risk and gains). Heat conductive plate: It might be effective, but we are not sure how it will be installed. It has not been considered in this case.	Insulation wedge: It might be required at the ground floor due to lack of capillary active layer. Heat conductive plate: Same as for typology ES1.	Insulation wedge: Not applied in the demo case, but potentially suitable in this building typology. In DC internal insulation is applied only at the ceilings, no condensation on the connection expected. In the typology sometimes arch ceilings are present, then the insulation wedge is hard to install - not practical in this situation. Heat conductive plate: Compatible, but this solution is not well known in Poland, not really used in practice.	Same as for Typology PL1.
2	Airtightness How is the airtight layer designed?	Internal plaster: Compatible with the building typology; implemented in the DC for thermal reasons (thermal plaster), rather than airtightness. Airtight concrete layer: No concrete component in this typology. Airtight membrane: Depending on whether the roof construction already contains a wood-based layer of panels, an airtight membrane is required or not. Therefore, it is not implemented in the DC, having already a layer of wood-based panels.	Same as for Typology ES1.	Internal plaster as airtight layer already applied in the DC, on the walls and ceilings. Airtight concrete layer: No concrete component in the DC, only in some renovated buildings some ceilings changed to concrete ones, but it not common in this typology. Airtight membrane: the DC's attic being unheated, this solution is not required; if the attic is reused, it could be used.	Internal plaster compatible with the typology, also on walls and ceilings. Airtight concrete layer: typology from later period, so more concrete ceilings and basements are present. Airtight membrane and taped or glued panels same situation as for typology PL1

Nr	Question	Spain (ES1)	Spain (ES2)	Poland (PL1)	Poland (PL2)
		Taped or glued panels: Depending on whether the roof construction already contains a wood-based layer of panels, such a layer might be a relevant solution. Therefore, it is not implemented in the DC.		Taped or glued panels: compatible and will be implemented on walls and ceiling in the DC.	
3	Airtightness How to ensure airtightness at junctions?	Adhesive tape: It is compatible, but is not implemented (acc. to the knowledge of the group) in the DC as other options are chosen (fibre mesh and clay adhesive, fibre mesh and CSG lime). Joint sealing: Especially for windows. Lip seal: Not compatible with historic windows (with the frame inserted in the wall). In other cases, it might be relevant when renovating windows not closing sufficiently tight, depending on the type of construction (connection to the wall).	Same as for Typology ES1.	Adhesive tape: Applicable for mechanical ventilation joints (as probably will be the case in the DC); otherwise, this solution is not common: usually no exposed beams in this typology, therefore adhesive tape not necessary for beams' junctions. Joint sealing: Similar answer as above. Lip seal: implemented in the DC, for example in the NABA system (already installed in the stress test at UIBK); probably also used for windows & doors.	Same as for Typology PL1.
4	Driving rain protection How to ensure proper driving rain protection at the facade?	External plaster: In the case of protected facade, only for restoration. Rainscreen cladding: Not compatible due to heritage issues.	Same as for Typology ES1.	External plaster: relevant for the building typology; in the DC, new solution from NABA as well as other surfaces with mineral wool/wood wool insulation on the rear facade of the building are planned to be plastered,	External plaster: it depends on the building, many different architectural styles, outside facade with bricks, plaster or wooden cladding, some buildings even out of wooden framing (rare).

Nr	Question	Spain (ES1)	Spain (ES2)	Poland (PL1)	Poland (PL2)
		Hydrophobic treatments: Not considered to be required due to limited load of driving rain. Further, heritage issues might hinder the use. Modification of the roof overhang is not compatible due to heritage issues. Doors and windows pulled back from the front of the façade: Usually they are already pulled back to avoid overheating.		front facade lower part already plastered. Rainscreen cladding: not possible in this typology. Hydrophobic treatments: not planned in DC, probably not necessary, compatible with typology, depends on specific building, some of them have more exposed brick of worst quality, then this solution might be needed. Roof overhang: not important overhang in DC and typology. Doors and windows pulled back from the front of the façade: due to conservation reasons not changed during renovation, as it has an impact on the external image of the building, only if the original position was pulled back.	Rainscreen cladding: possible for this typology, more architectural diversity between cases. Hydrophobic treatments: needed only in special case of damage, e.g., mechanical - cracks, Overall, less need than Kamenica (PL1), Willa commonly with garden and threes in front - so less driven rain on the building facade. more variability in the typology, Roof overhangs commonly not big enough, but in some cases mansard roofs. Doors and windows pulled back from the front of the façade: same as typology PL1.
5	Driving rain protection How to ensure proper driving rain protection at junctions?	Dimpled membrane: Not used in the DC as the facade at the basement is not part of the renovation. Normally a plinth is used. Baseboard finishing profile with drip edge: Often used below the windows and the top of the facade, but not used in the DC, as the facade is not touched.	Same as for Typology ES1.	Dimpled membrane: Compatible with typology, but actively discouraged because membrane visible and looks bad – bucket mebrane in Polish “folia kubelkowa”. Baseboard finishing profile with drip edge: Probably not implemented in DC (not defined), but compatible with typology.	Same as Typology PL1.

Nr	Question	Spain (ES1)	Spain (ES2)	Poland (PL1)	Poland (PL2)
		Profile with runoff stream: Especially at windows.		Profile with runoff stream: Not used in Poland, could be compatible in some special cases.	
6	Rising Damp How avoid/minimize rising damp?	Injection with special hydrophobic paraffin: Not sure whether this measure is compatible with the building typology; the intervention in the DC does not include the building's basement. Placement of moisture barrier: Same as above.	Same as for Typology ES1.	Injection with special hydrophobic paraffin: Not required in DC because walls in the basement are dry, compatible with typology, used in some cases. Placement of moisture barrier: Probably better idea, because it's easier to identify critical places in comparison to injections.	Same as Typology PL1.

Table 42. Notes on junction solutions for Swedish and Scottish typologies; for typologies with a demo case (SE1, SC1 and SC3), specific considerations on the application are included.

Nr	Question	Sweden (SE1)	Sweden (SE2)	Scotland (SC1)	Scotland (SC2)	Scotland (SC3)
1	Energy losses, condensation and mould risk How to minimize the energy losses (Ψ -Value) and/or condensation/mould risk at the internal surface (f_{Rsi} -value) of thermal bridges?	Insulation wedge: compatible in the internal side of the building, e.g., at window reveals, ceiling and interior walls. Heat conductive plate: not known/applied in this building typology so far.	Insulation wedge: generally, not required since exterior insulation can be applied.	Insulation wedge: In the case of suspended timber floors can be applied in-between or under the joists. Heat conductive plate: just for the junction with floor, not possible at ceiling in case cornice is present.	Insulation wedge: no insulation applied in this DC, not compatible in the intermediate floor because of compatibility with cornicing and skirting boards, same issue in the case of wall-to-wall connection (cornicing and skirting); technically feasible, practically might be difficult to hide, issues also with doors; custom details needed to see how to solve the implementation for the different junctions. Heat conductive plate: just junction with floor, not ceiling (cornice)	Same as SC2
2	Airtightness How is the airtight layer designed?	Internal plaster: the walls and ceilings are generally plastered; possible cracks between ceiling and wall must be filled. Airtight concrete layer: not relevant; Airtight membrane: generally applied at roofs. Taped or glued panels: possible at roofs.	Internal plaster: same as SE1. Airtight concrete layer: concrete floors and intermediate ceilings might be present. Airtight membrane: generally applied at roofs (in case of heated attic). Taped or glued panels: possible at roofs.	Internal plaster: walls and ceiling easy to redo because of lack of decoration plastering on the hard (on the stone wall without secondary structure). Airtight concrete layer: originally never found, in some cases might have been rebuilt as concrete (solid ground floor).	Internal plaster: the implementation might be difficult because it is applied on secondary lath structure and decoration (cornicing and skirting) might be present; application on hard might be possible but not always recommended because it might hinder the drying potential of the construction (compatible but challenging,	Same as SC2

Nr	Question	Sweden (SE1)	Sweden (SE2)	Scotland (SC1)	Scotland (SC2)	Scotland (SC3)
				Airtight membrane and taped or glued panels: applicability depending on the heritage significance.	not a conservation sensitive approach). Airtight concrete layer: same as SC1 typology. Airtight membrane and taped or glued panels: strong reservation (mostly about technical compatibility) it is not current practice.	
3	Airtightness How to ensure airtightness at junctions?	Adhesive tape, Joint sealing and lip seal: window connected to the wall with sealing tape outside; inside, gaps are filled with hemp wool, in combination with tape at the window's frame if the frame is not removed (the fixed part of frame is usually left in the building).	Same as for Typology SE1.	Adhesive tape: in theory yes as long as there are no details (cornicing etc); before the application, possible movement or expansion of the taped elements or materials shall be considered. Joint sealing: not very invasive; that makes it easy to install in most cases. Lip seal: it might work, but practical installation seems complicated.	Same as for Typology PL1.	Same as SC2
4	Driving rain protection How to ensure proper driving rain protection at the facade?	External plaster: is usually in good state; if changed, generally replaced with insulating plaster. Rainscreen cladding: not compatible.	External plaster: usually plastered. Rainscreen cladding: not compatible; Hydrophobic treatments: we do not; roof overhang: roof overhangs are generally present but less pronounced than in SE1;	External plaster: implemented. Rainscreen cladding: potentially compatible in a few cases that were built like that (but quite rare).	External plaster: only in few cases you will find rendered walls, as a typology you wouldn't expect to find any external render. Rainscreen cladding: not part of the original design (stone wall was meant to be visible as the decoration of the building).	Same as SC2

Nr	Question	Sweden (SE1)	Sweden (SE2)	Scotland (SC1)	Scotland (SC2)	Scotland (SC3)
		Hydrophobic treatments: missing information on the applicability of this measure; facades can be composed by different materials (natural stone, bricks). Roof overhang: generally, roof overhangs of 30 cm-100 cm are present. Doors and windows pulled back from the front of the façade: the windowsill can be covered by sheet metal.	Doors and windows pulled back from the front of the façade: the windowsill can be covered by sheet metal.	Hydrophobic treatments: (maybe) as long as vapour movement is allowed. More comfortable applying to a render than to the ashlar walls. Roof overhang: not compatible. Doors and windows pulled back from the front of the façade: just slightly recessed from the wall façade. Wall is thinner where you have windows	Hydrophobic treatments: concerns about durability/compatibility and aesthetics. Roof overhang: not compatible. Doors and windows pulled back from the front of the façade: Same as for typology SC1.	
5	Driving rain protection How to ensure proper driving rain protection at junctions?	Dimpled membrane: generally, not used in SE1. Baseboard finishing profile with drip edge: stone covered with metal sheet, generally, already implemented. Profile with runoff stream: generally, already used in the original windows.	Dimpled membrane: typical for typology SE2. Baseboard finishing profile with drip edge: stone covered with metal sheet. Profile with runoff stream: generally, already used in the original windows.	Baseboard finishing profile with drip edge: the render goes down to the ground traditionally (and cannot be changed).	Profile with runoff stream: mostly on the front façade (you won't find decoration on the rear wall).	Same as SC2

Nr	Question	Sweden (SE1)	Sweden (SE2)	Scotland (SC1)	Scotland (SC2)	Scotland (SC3)
6	Rising Damp How to avoid/minimize rising damp?	Rising damp is generally not an issue (a drainage is present around the building and no brick foundation is present). Yet, if a rising damp protection shall be needed, the injection with special hydrophobic paraffin is considered less destructive and more compatible relative to placement of a moisture barrier (not reversible).	Same as for Typology SE1.	The normal approach is not blocking any moisture transport and rather facilitate drying. Injection with special hydrophobic paraffin: considered not reversible, thus not compatible with conservation constraints. Placement of moisture barrier: you can find some details with slates or even bitumen as damp-proof course. As alternative, favouring drying solutions like sacrificial plaster or ventilation cavities (ventilating under the suspended timber floor with grids integrated on the bottom of the façade, although most cottages have solid ground floors)	Same as Typology SC1.	Same as SC2

A review of all solutions regarding their limitations in each typology is shown in Table 43. Solutions are marked "not required" **X**, "not compatible" **XX**, "compatible but not implemented" **✓**, "implemented in the DC" **✓✓**, "information missing" **?**.

This cross-referenced approach allows designers and decision-makers to quickly identify solutions that might be applicable to a given building type and the limitations to be considered. The goal is to support informed choices during the planning of energy retrofits, especially in heritage-sensitive contexts.

Key takeaways in this respect are:

- Measures for *reducing heat losses and mould risk at thermal bridges* (e.g., insulation wedges) do not generally contrast with conservation issues. At least, in case no cornices or decoration at the internal surface are present, as for instance might occur in Scottish building typologies.
- Most solutions available to *increase airtightness* are in general accepted in all considered building typologies; although application might be challenging and requires careful planning and implementation.
- More critical is finding *conservation compatible solutions for driving rain and rising damp protection*, some of which are very invasive and might require intervention and modification of the facade as well as load bearing walls.
- Concerning *rising damp protection*, solutions which facilitate the drying of the construction (e.g., via sacrificial plaster or ventilation cavities) are generally preferred relative to invasive solutions (paraffine injection, moisture barrier).

Table 43. Assessment of measures and solutions for proper design of the building envelope, including junctions and integration of components, for each typology. "not required" (X), "not compatible" (XX), "compatible but not implemented" (✓), "implemented in the DC" (✓✓), "information missing" (?).

Topic	Solution	ES 1*	ES 2	PL 1*	PL 2	SE 1*	SE 2	SC 1*	SC 2*	SC 3
Energy losses/mould	Insulation wedge	✓	✓	✓	✓	✓	X	✓	✓	✓
Mould/moisture	Heat-conducting plate	?	?	✓	✓	?	?	✓	✓	✓
Airtight layer	Internal plaster	✓✓	✓	✓✓	✓	✓✓	✓	✓✓	✓	✓
Airtight layer	Concrete layer	XX	XX	XX	✓	XX	✓	XX	XX	XX
Airtight layer	Air thigh membrane	✓	✓	✓	✓	✓	✓	✓	✓	✓
Airtight layer	Taped or glued panels	✓	✓	✓✓	✓	✓	✓	✓	✓	✓
Airtight junctions	Adhesive tape	✓	✓	✓✓	✓	✓✓	✓	✓	✓	✓
Airtight junctions	Joint sealing	✓✓	✓	✓✓	✓	✓✓	✓	✓	✓	✓
Airtight junctions	Lip seal	✓	✓	✓✓	✓	✓✓	✓	✓	✓	✓
Rain protection	External plaster	✓	✓	✓✓	✓	✓✓	✓	✓✓	XX	XX
Rain protection	Rainscreen cladding	XX	XX	XX	✓	XX	XX	✓	XX	XX
Rain protection	Hydrophobic treatment	X	X	✓	✓	?	?	✓	XX	XX
Rain protection	Roof overhangs	XX	XX	XX	✓	✓✓	✓	XX	XX	XX
Rain protection	Doors/windows pulled back	X	X	XX	XX	?	?	XX	XX	XX
Rain protection	Dimpled membrane	✓	✓	✓	✓	X	✓	XX	XX	XX
Rain protection	Profile with drip edge	✓	✓	✓	✓	✓	✓	XX	XX	XX
Rising damp	Runoff stream	✓✓	✓	✓	✓	✓✓	?	XX	✓	✓
Rising damp	Paraffin injection	?	?	✓	✓	X	X	XX	XX	XX
Rising damp	Moisture barrier	✓	✓	✓	✓	XX	XX	XX	XX	XX

*Typology with demo case.

4.3. Exemplary thermal bridges of building typologies

In this section, exemplary thermal bridges of the building typologies reported in Table 39 are investigated. In particular, the linear thermal transmittance ψ and temperature factor f_{Rsi} are calculated for each thermal bridge and the impact of the insulation's design (i.e., insulation thickness and extension on the building component) on these parameters is discussed. As mentioned above, the linear thermal transmittance and temperature factor quantify the thermal losses and the risk of surface mould formation, respectively. The values of linear thermal transmittance reported in this study refer to the internal dimension of the building. The investigated thermal bridges are documented in Table 44.

Table 44. Investigated thermal bridges for each building typology.

Nr	Thermal bridge	Building typology	Model	Insulation system
1	External wall-basement	PL1; PL2	2D	External insulation NABA
2	External wall-roof (heated attic)	PL1; PL2	2D	External insulation NABA (wall); Mineral wool (roof)
3	External wall-ceiling (unheated attic)	PL1; PL2	3D	External insulation NABA (wall); internal insulation NABA (ceiling)
4	External wall-floor over arcaded gallery	SP1	3D	Internal insulation calcium silicate (wall); internal insulation mineral wool (ceiling)
5	External wall-internal wall	SC1	2D	Internal insulation calcium silicate
6	External wall – windows frame	SP1	2D	Internal insulation calcium silicate (wall)

4.3.1. External wall-floor connection of Polish typologies with unheated basement

Figure 57 shows a typical plinth detail of the external wall-floor connection of Polish typologies with unheated basement. In these building typologies, the floor is made of brick or concrete, depending on whether it is original or if it has been replaced in previous interventions. The load bearing wall and the plinth are made of bricks. Thermal insulation is applied on the external side of the wall and below the floor. As thermal insulation, the biochar-based panel developed by NABA (FuturHist deliverable D2.5) is applied ($\lambda = 0.057 \text{ W/(m K)}$). The linear thermal transmittance ψ and temperature factor f_{Rsi} of the thermal bridge are calculated for different insulation thicknesses b . The length of the plinth insulation L is varied as well, to investigate the impact of

this parameter of the thermal bridge. For thermal losses toward the unheated basement, a temperature correction factor of 0.7 has been considered, as worst-case scenario according to (Häupl et al., 2013).

Figure 58 and Figure 59 show U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} of the external wall-basement connection obtained as results of the simulation for brick and concrete floors, respectively. The following conclusions can be drawn (Figure 58):

- the linear thermal transmittance ψ significantly decreases with the length of the plinth insulation (L);
- for sufficiently large insulation thickness ($b > 10$ cm), the thickness has no significant impact on the linear thermal transmittance of the thermal bridge;
- reducing the insulation thickness (b) leads to a significant decrease in the temperature factor;
- the temperature factor remains above the limit of 0.7 even for the uninsulated component ($b = 0$), due to significant thickness of the wall; the risk of mould growth on the surface is therefore considered moderate in this case.

The above considerations hold for both a brick and a concrete floor (Figure 59), although in the latter case the linear thermal transmittance is significantly higher, due to the higher thermal conductivity of concrete relative to the brick.

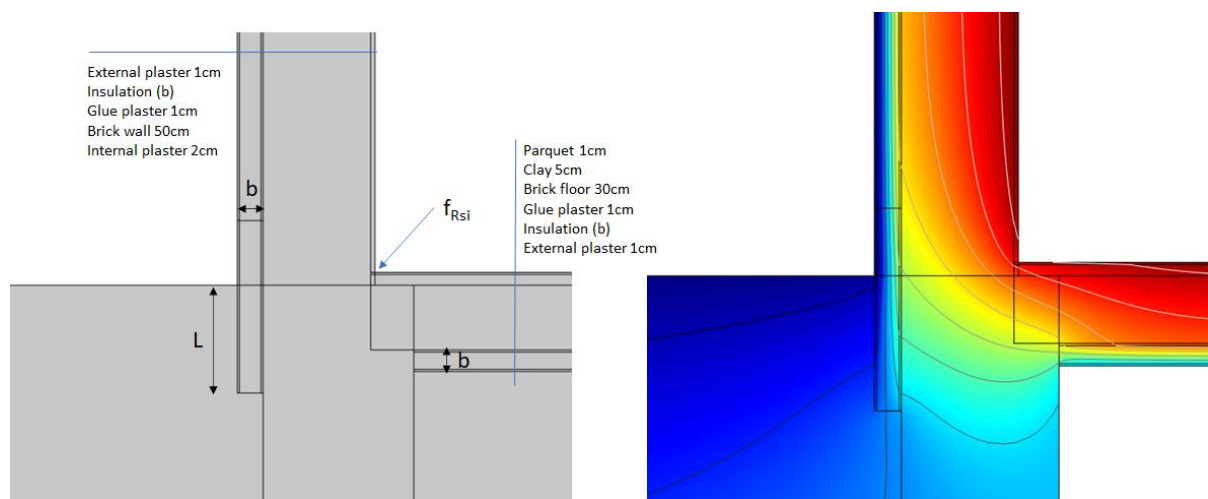


Figure 57. Left: exemplary external wall-floor connection of the Polish typologies with unheated basement and brick floor; right: temperature distribution in the building component.

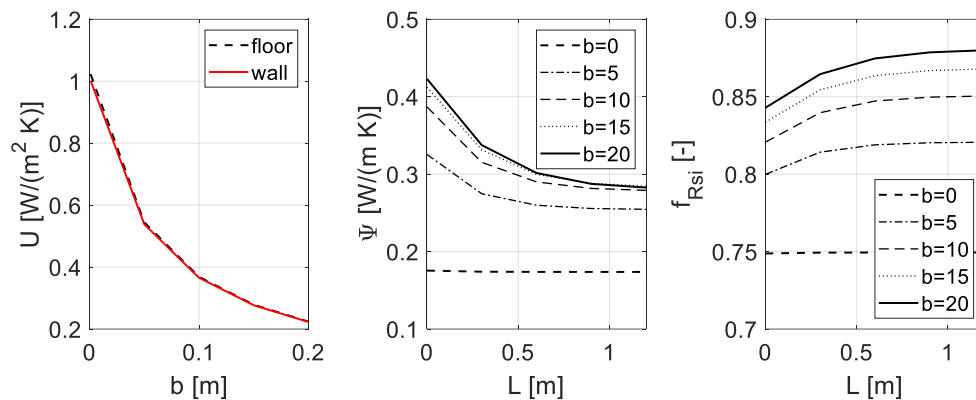


Figure 58. U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} of the external wall-basement connection of the Polish typologies with unheated basement and brick floor, depending on the insulation thickness (b) and the length of the plinth insulation (L). Based on simulations with the software COMSOL.

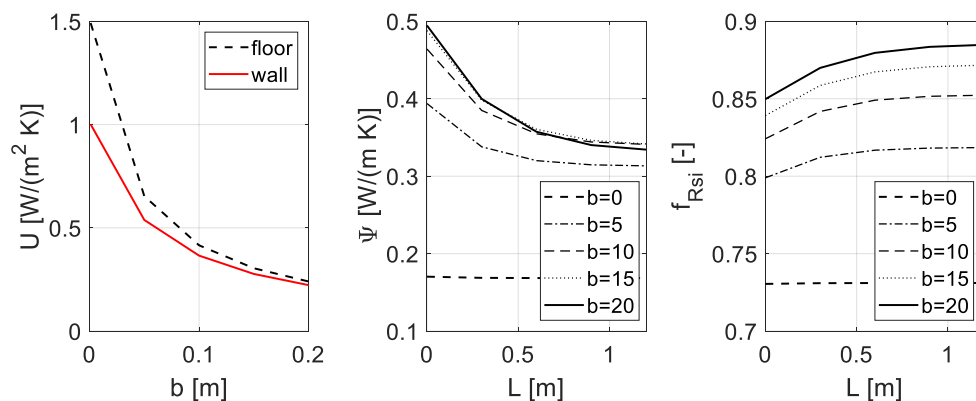


Figure 59. U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} of the external wall-basement connection of the Polish typologies with unheated basement and concrete floor, depending on the insulation thickness (b) and the length of the plinth insulation (L). Based on simulations with the software COMSOL.

4.3.2. External wall-roof connection of Polish typologies with heated attic

Figure 60 shows an exemplary external wall-roof connection with heated attic, as can be found in both Polish typologies. Thermal insulation (mineral wool) is applied between the timber rafters of the roof over the entire rafter thickness (20 cm), while the load bearing brick wall (Table 44) is insulated on the external side with biochar-based panels developed by NABA ($\lambda = 0.057 \text{ W/(m K)}$, FuturHist deliverable D2.5). The roof covering is composed of 25 mm thick timber slabs overlapped by a 5 mm thick metal sheet (e.g., galvanized steel). Wall top insulation (e.g., mineral wool) is planned to reduce thermal loss through the junction.

Figure 61 shows U-value, linear thermal transmittance ψ and temperature factor f_{Rsi} for the considered external wall-roof connection. The thickness of the external insulation (b) and of the wall top insulation (L), respectively, are varied, to investigate their impact on the thermal bridge. The importance of applying insulation on the top of the wall is evident, considering that it significantly reduces linear thermal transmittance and increases the temperature factor. For

instance, applying insulation of thickness $L=160$ mm on the top of the wall can reduce the linear thermal transmittance up to one fourth and increase the temperature factor of more than 10% relative to the uninsulated case, depending on the wall insulation thickness. Increasing the wall insulation thickness contributes to reducing the linear thermal transmittance and increases the temperature factor as well.

It must be noted that the temperature factor remains above the limit of 0.7 even for the uninsulated component due to the significant thickness of the wall; the risk of mould growth at the surface is therefore considered moderate also in this case.

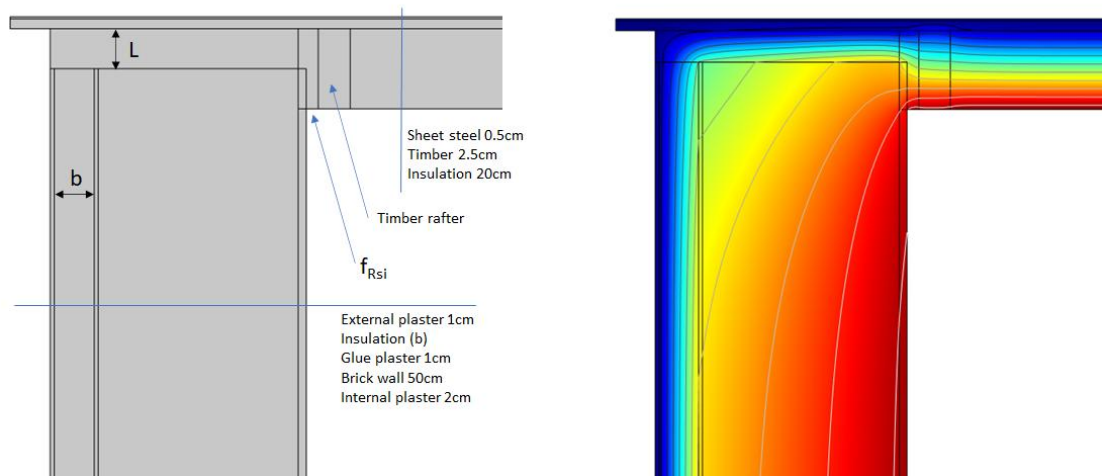


Figure 60. Left: exemplary external wall-roof connection of the Polish typologies with heated attic and brick floor; right: temperature distribution in the building component.

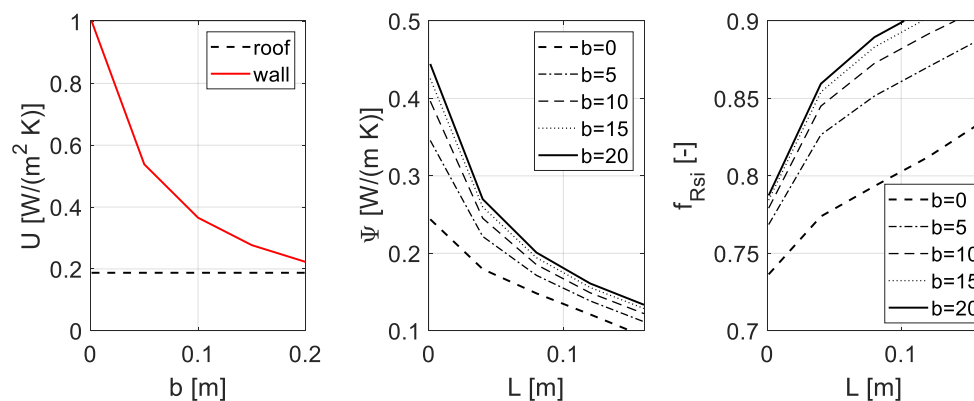


Figure 61. U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} for external wall-roof connection of the Polish typologies with heated attic and brick floor, depending on the thickness of the wall insulation (b) and the thickness of the wall top insulation (L). Based on simulations with the software COMSOL.

4.3.3. External wall-ceiling connection of the Polish typologies with unheated attic

Figure 62 shows the external wall-ceiling junction with unheated attic, as can be found in the Polish typologies (roof above the attic is not shown in the drawing). The typical timber ceiling with earthen infill is sustained and connected to the external wall (Table 44) by timber beams. The load bearing brick wall is insulated on the external side with biochar-based panels developed by NABA ($\lambda = 0.057 \text{ W/(m K)}$; FuturHist deliverable D2.5) while internal insulation is applied below the ceiling. Placing the insulation below the ceiling is required in cases for which the flooring of the unheated attic must be conserved and cannot be covered by insulation. This was, for instance, a requirement in the refurbishment of the FuturHist demonstrator building in Krakow.

The insulation system of the ceiling is composed of the CarbonClay board developed by NABA ($\lambda = 0.1 \text{ W/(m K)}$; FuturHist deliverable D2.3) and fixed to the existing timber ceiling with slats and screws. The space between board and ceiling is filled by thermal insulation composed of wood fibre and clay ($\lambda = 0.044 \text{ W/(m K)}$). A vapour retarder is installed on the above the board, to reduce moisture penetration into the insulation and avoid condensation and mould risk.

In the calculation of the linear thermal transmittance ψ and temperature factor f_{Rsi} , a temperature correction factor of 0.7 has been considered for the thermal losses toward the unheated attic, as worst-case scenario according to (Häupl et al., 2013). Figure 63 shows U-value, linear thermal transmittance ψ and temperature factor f_{Rsi} of the external wall-ceiling connection. The thicknesses of the wall insulation (L) and ceiling insulation (b) have been varied, to investigate the impact of these parameters of the thermal bridge. It can be observed that the thickness of wall insulation (b) is most relevant in this case, while ceiling insulation thickness (L) appears less important. Increasing insulation thicknesses on the wall and ceiling leads to a reduction of ψ and an increase of f_{Rsi} .

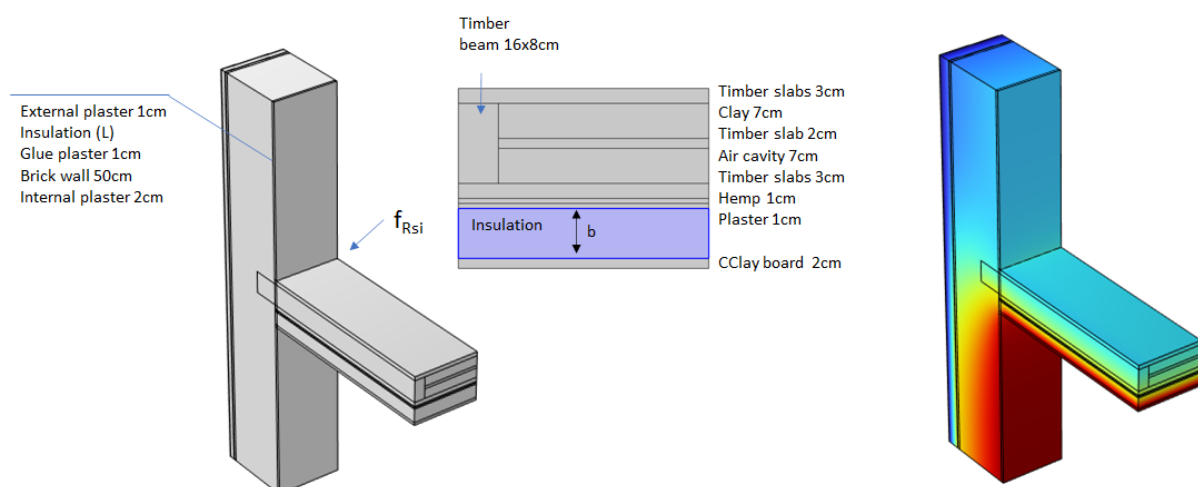


Figure 62. Left: exemplary external wall-ceiling connection of the Polish typologies with unheated attic and timber ceiling with earthen infill; right: temperature distribution in the building component.

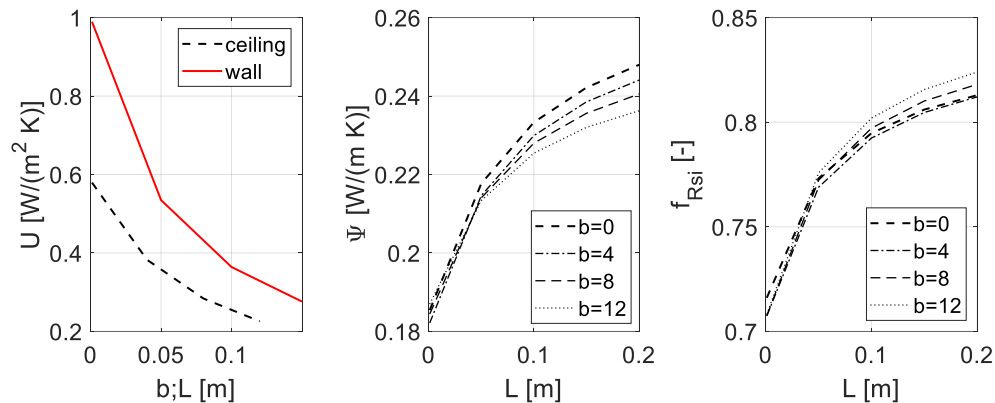


Figure 63. U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} of the external wall-ceiling connection of the Polish typologies with unheated attic and timber ceiling, depending on the thickness of the wall insulation (L) and the thickness of the ceiling insulation (b). Based on simulations with the software COMSOL.

4.3.4. External wall-floor connection of the Spanish typology ES1

In typology ES1 (Casa de pisos, terraced tenement building 1600–1920), floors are typically made of wooden joists and plaster vaults cast in situ, or a vaulted ceiling finished with a 6 cm reinforced concrete slab (as, e.g., in the historic wing of the FuturHist demonstrator building in Cordoba). The wooden joints rest on load-bearing walls of solid brick. The first-floor slab might exhibit substantial energy losses, as it is located above the arcaded gallery of the Plaza and therefore in contact with the outside air. For this reason, it was suggested to install insulation both above the floor and on the internal side of the load bearing wall. To minimize heat losses, it is important that floor and wall insulation form a continuous layer.

In Figure 64a the wall-floor connection with internally insulated wall and floor is shown. For the thermal bridge and temperature factor assessment, two possible scenarios concerning the insulation of the floor are considered. In the first scenario, the original flooring (tiles) is conserved. To allow positioning of thermal and acoustic insulation (e.g., mineral wool panels) tiles are temporarily removed and subsequently replaced over the insulation (Figure 64b). In the second scenario, a polyethylene sheet and vinyl flooring are placed over the insulation instead of original tiles (Figure 64c). This second scenario allows saving a few centimetres of the room height, due to less thickness relative to the original flooring. For the wall insulation, calcium silicate ($\lambda = 0.057 W/(m K)$) is applied in both considered scenarios. The thermal conductivity of this insulation is nearly the same as the one expected for the panel developed by CSG (FuturHist deliverable D2.2), which will be installed in the demo case. In Figure 64d, the temperature distribution in the construction (original tiles flooring) for floor insulation and wall insulation of thickness $L = 5$ cm and $d = 4$ cm, respectively, is shown.

First, the variant in which existing tiles flooring is conserved is investigated. Figure 65 shows U-values of the wall and floor, linear thermal transmittance and temperature factor of the external wall-floor connection for different thickness of wall and floor insulation. The linear thermal

transmittance is determined in relation to the internal dimensions of the building. It can be observed that it decreases with increasing thickness of wall and floor insulation. Increasing insulation thickness of both wall and floor also increases the temperature factor.

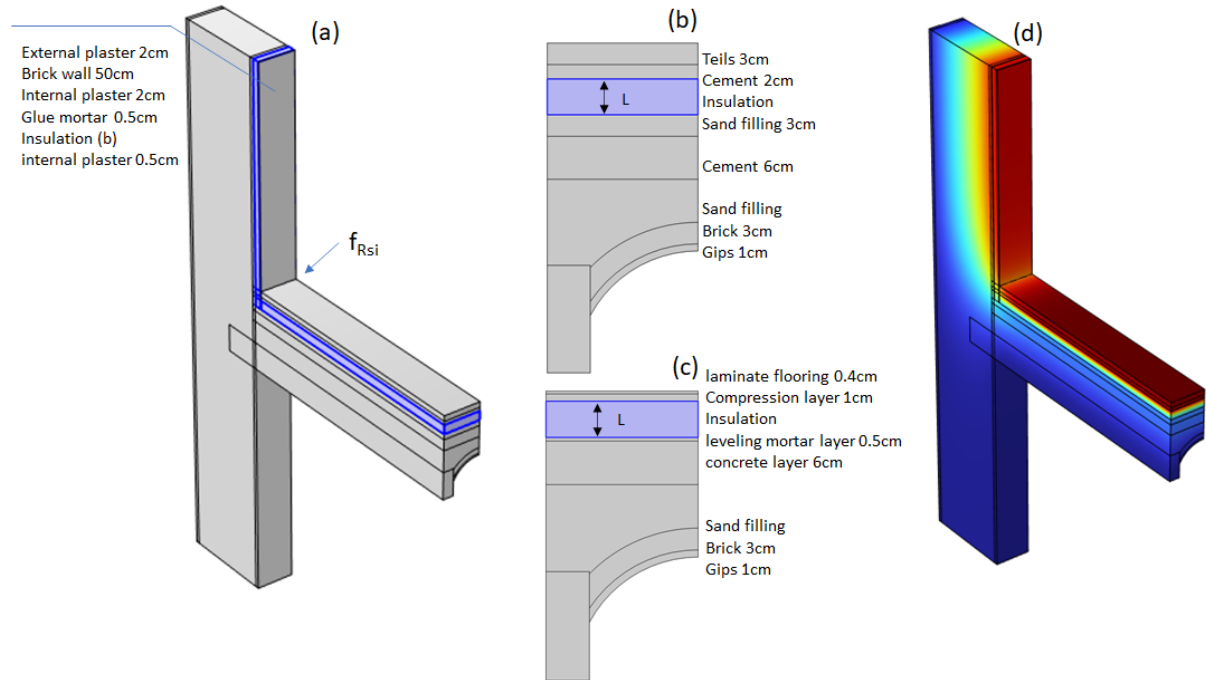


Figure 64. (a) Exemplary external wall-ceiling connection at the first-floor slab of the Spanish typology ES1 (Casa de pisos, terraced tenement building 1600–1920); (b) section on the ceiling with tiles flooring; (c) section of the ceiling with vinyl flooring; (d) temperature distribution in the building component.

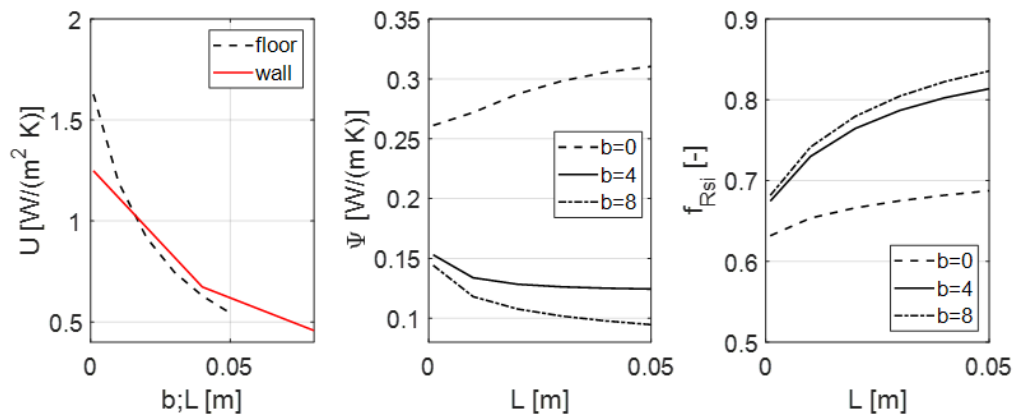


Figure 65. U -values, linear thermal transmittance ψ and temperature factor f_{Rsi} for the external wall-floor connection of the Spanish typology ES1 (with tiles flooring), depending on the thickness of the wall insulation (b) and the thickness of the floor insulation (L). Based on simulations with the software COMSOL.

Similar results are obtained in case the original flooring is replaced by a polyethylene sheet and vinyl flooring, which however presents slightly higher U -values of the floor for the same insulation thickness (Figure 66).

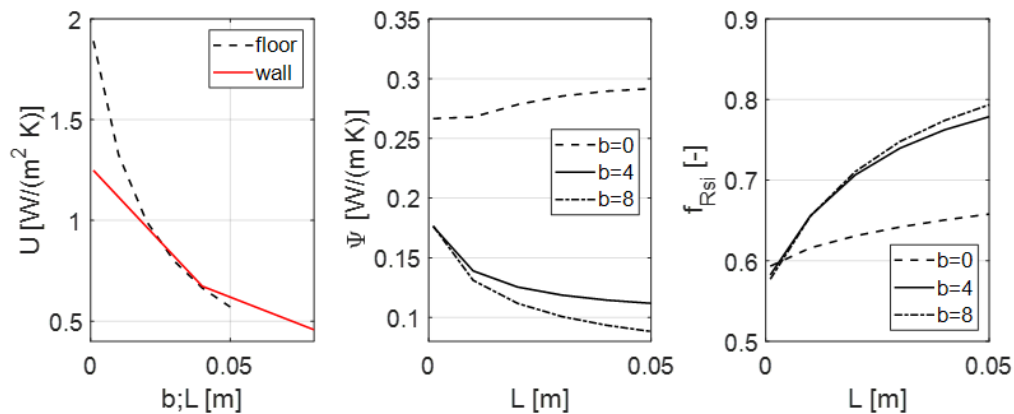


Figure 66. U -values, linear thermal transmittance ψ and temperature factor f_{Rsi} for the External wall-ceiling connection of the Spanish typology ES1 (vinyl flooring), depending on the thickness of the wall insulation (b) and the thickness of the floor insulation (L). Based on simulations with the software COMSOL.

4.3.5. External wall-internal wall connection of the Scottish typologies

In the considered Scottish typologies, internal walls may carry the superimposed loads of upper floors and walls, or they may be not loadbearing. Structural movement, alterations and new uses may result in the application of unintended loads on internal walls. In old buildings, it should not be assumed that any partitions are non-loadbearing; floor and wall construction, loading patterns and beam sizes should be investigated by a survey.

Internal walls of constant thickness, other than those which contain flues or support common stairs, may also carry floor joints. The thickness of internal walls varies from 150 mm to 300 mm. Internal walls were sometimes built of stone up to ground or first floor level, above which they were generally built of bricks. Internal walls give lateral support to external walls and vertical support to upper floors. Stone walls were generally constructed of random rubble sandstone and plastered on the hard.

In Figure 67 an exemplary external wall-internal wall connection of the Scottish typology SC1 (*Georgian cottage*, detached cottage 1750–1850) is shown. The effect of applying an insulation wedge at the external wall-internal wall junction is investigated in Figure 68. The internal insulation and the insulation wedge are both made of calcium silicate in this example, while both internal and external walls are made of sandstone (thermal conductivity $\lambda = 2.87 \text{ W/(m K)}$). It can be observed that the insulation wedge significantly reduces the linear thermal transmittance and increases the temperature factor. Only applying an insulation wedge $f_{Rsi} > 0.7$ is reached, which is a necessary condition for a mould safe surface.

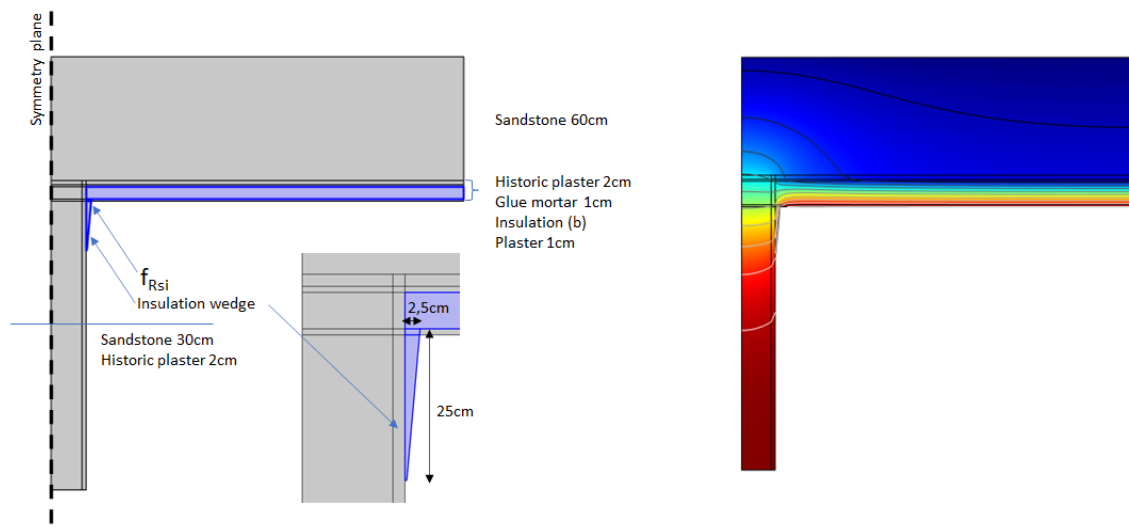


Figure 67. Exemplary external wall-internal wall connection of the Scottish typology SC1 with insulation wedge (left) and temperature distribution in the building component (right).

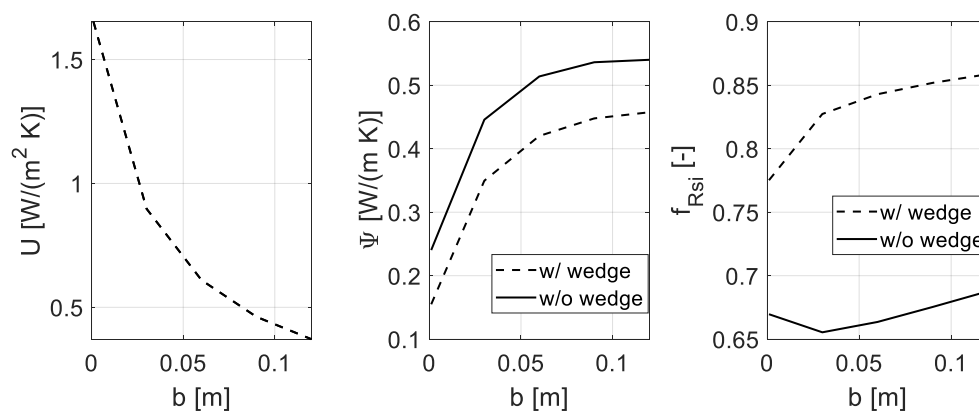


Figure 68. U-values, linear thermal transmittance ψ and temperature factor f_{Rsi} for the external wall-internal wall connection of the Scottish typology SC1, depending on the thickness of the wall insulation (b); results with (w/) and without insulation wedge (w/o) are compared. Based on simulations with the software COMSOL.

4.3.6. External wall-window's frame Spanish typology ES1

In Figure 69, an exemplary external wall-window frame junction, as can be found in the Spanish typology ES1, is shown. The window is upgraded by replacing the original glazing with a vacuum glazing ($U = 0.7$ W/(m² K)), while the original frame is conserved (FuturHist deliverable 2.7). The thermal performance of the wall-window frame junction can be improved by applying insulation plaster ($\lambda = 0.042$ W/(m K)) on the window reveal. The original internal plaster ($\lambda = 0.82$ W/(m K)) can be removed and replaced with insulation plaster, without need of additional space and to remove the original window frame. On the other hand, to allow application of additional insulation between frame and wall, removing the original window frame would be necessary. This

solution is also investigated, as if applicable it allows further reduction of thermal losses and mould growth risk at the window frame-wall connection.

In Figure 70, the wall's U-value, linear thermal transmittance ψ and temperature factor f_{Rsi} are reported for the investigated detail, depending on the insulation thickness (L). Four cases are considered: (a) no measure applied, (b) normal plaster on the window reveal and insulated frame-wall junction, (c) insulation plaster on the window reveal and uninsulated frame-wall junction (d) insulation plaster on the window reveal and insulated frame-wall junction; the temperature factor f_{Rsi} is reported at two different positions: (1) glass-frame junction and (2) frame-wall junction (the former is not influenced by the insulation thickness).

In case (a) (no measure applied), the linear thermal transmittance ψ ranges between 0.3 and 0.5 W/(m K), depending on the insulation thickness (L), with the temperature factor f_{Rsi} ranging between 0.5 and 0.4. As expected, case (d) represents the most effective configuration, with a reduction of the linear thermal transmittance ψ between 0.1 and 0.3 W/(m K), depending on the insulation thickness (L) and increase of the temperature factor f_{Rsi} at the frame above 0.7.

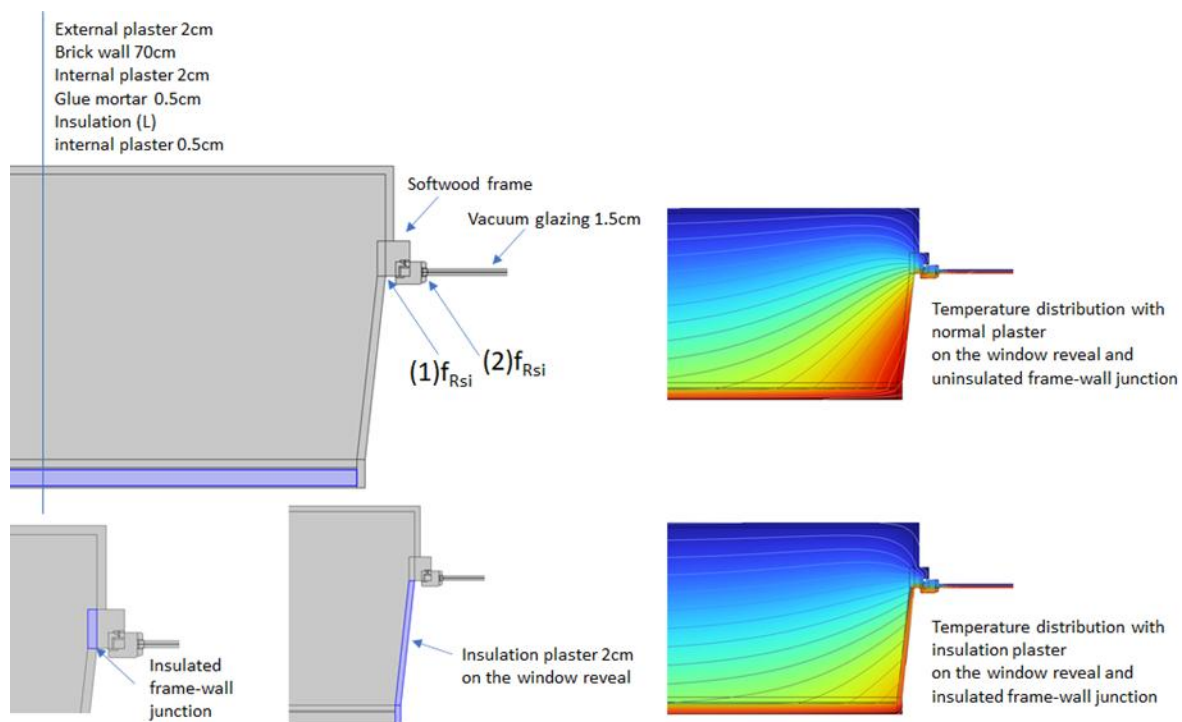


Figure 69. Exemplary external wall-window frame junction as can be found in the Spanish typology ES1 (left) and temperature distribution in the building component (right); the thermal performance can be improved by applying insulation plaster on the window reveal and, if possible, insulating the frame-wall junction.

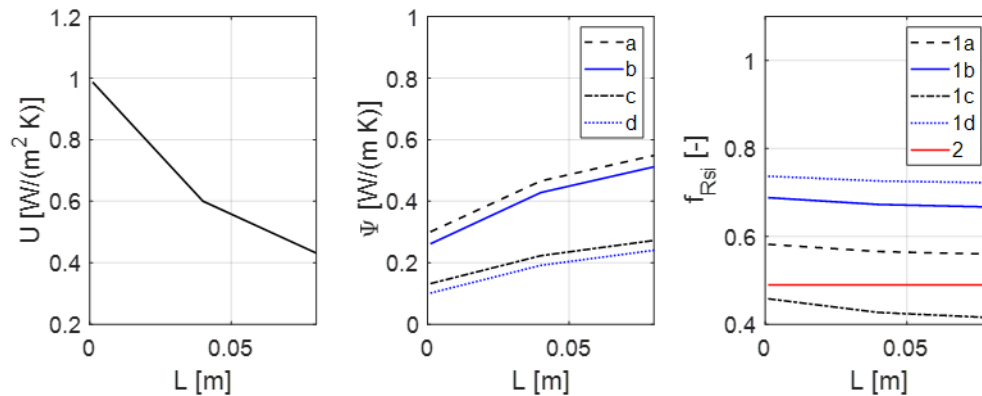


Figure 70. Wall's U-value, linear thermal transmittance ψ and temperature factor f_{Rsi} for the external wall-window frame junction, depending on the insulation thickness (L); four cases are considered: (a) normal plaster on the window reveal and uninsulated frame-wall junction, (b) normal plaster on the window reveal and insulated frame-wall junction, (c) insulation plaster on the window reveal and uninsulated frame-wall junction (d) insulation plaster on the window reveal and insulated frame-wall junction; the temperature factor f_{Rsi} is reported at two different positions: (1) glass-frame junction and (2) frame-wall junction. Based on simulations with the software COMSOL.

4.3.7. Conclusions on the investigated thermal bridges

The analysis of exemplary thermal bridges of the considered building typologies highlighted the importance of proper insulation solutions (i.e., by applying adequate insulation thickness and extension on the building component, choice of suitable insulation materials, application of insulation wedges). This enables, even in challenging refurbishment of historic buildings, significant reduction of heat loss and mould growth risk at the internal surface. Key takeaway in this respect are:

- The extension of the plinth insulation at *foundations of buildings* with unheated basement has major impact on the linear thermal transmittance.
- At *roof-wall junctions of buildings with heated attics*, installing an insulation layer between the top of the wall and the roof is essential to reduce thermal losses and increase the temperature factor.
- At *wall-ceiling junctions of buildings with unheated attics* with externally insulated walls and internal insulation below the ceiling (e.g., Polish demo case), the linear thermal transmittance significantly decreases by increasing the thickness of external insulation.
- *Internally insulated external wall-ceiling connections*, with ceiling exposed to external air (e.g., arcaded gallery of the Spanish demo case) requires sufficiently thick floor insulation, properly connected to the wall insulation.

- *Internally insulated external wall-internal wall junctions of natural stone* (e.g., Scottish building typologies) might require insulation wedges to avoid mould risk at the corner (internal surface).
- External wall-window's frame junctions require adequate insulation; applying insulation plaster on the window reveal is a space-saving, conservation-compatible solution, particularly suitable in internally insulated buildings with less space available at the window's reveal (e.g., in the Spanish building typology ES1).

5. Summary

This report summarizes various aspects concerning retrofit of historical buildings, with a special focus on internal insulation: 1D hygrothermal simulations, indoor climate assessment, and thermal-bridge analysis.

Hygrothermal analysis

Internal moisture load is the primary driver of risk across all climates. High moisture load consistently elevates Mould Growth Index (MGI) and can move assemblies from moisture-safe to risky. Low moisture load typically ensures safe performance, with the notable exception of highly rain-exposed Scottish cases where even these cases can remain moisture unsafe.

Wind-driven rain (WDR) is the main external differentiator between climates. In Spain and Sweden, increasing rain has limited effect on classification; in Poland (especially without external plaster) and, most decisively, in Scotland, WDR changes risk assessment.

Material sensitivity follows a stable hierarchy. Autoclaved aerated concrete (AAC) and clay-cork boards (CCB) are robust and predominantly within moisture-safe solutions across climates. Wood fibre (WF) and cellulose (CEL) are the most sensitive and frequently reach risky results under high moisture inside and high rain; calcium silicate (CS) and perlite (PER) sit in between and require careful detailing under elevated loads.

Orientation effects depend on climate. In drier settings (Spain, Poland, Sweden), the north façade is generally more critical due to limited solar drying. In Scotland, the WDR façade (west, 270°) dominates risk because extreme rain loads overwhelm any solar-driven drying benefit.

Future climate (RCP 8.5, 2070) generally lowers risk but not universally. Warmer temperatures reduce MGIs in Spain and Poland, but in colder/wetter contexts (Sweden, Scotland) increased moisture availability can offset benefits, leading to mixed, material-specific outcomes (notably for cellulose).

Comparison between software tools

A comparative hygrothermal assessment of internally insulated historic walls using two established simulation tools (Delphin and WUFI) was conducted. Across multiple climates, wall configurations, and insulation materials, relative humidity and temperature values at the insulation-masonry interface were calculated and translated into mould-risk classifications to identify robust versus sensitive design choices.

Cross-cutting notes for materials

Many of the observed discrepancies between the tools occur in cases where the interface relative humidity sits close to the mould-growth threshold used in this study. In that narrow band, even small shifts in predicted humidity, arising from differences in how the tools represent moisture storage, capillary transport, or thermal conductivity, can tip a case from “safe” to “at risk,” or vice versa.

Improving consistency between the tools would likely come from harmonising the material descriptions that govern behaviour at high humidity. Aligning the sorption and liquid-transport functions – particularly for autoclaved aerated concrete (where WUFI tends to be higher), and for expanded polystyrene and mineral wool (where Delphin tends to be higher) – should reduce cross-tool gaps and yield more consistent risk classifications.

Autoclaved aerated concrete (AAC)

The two tools generally agree, but when indoor moisture is high, WUFI tends to predict a higher mould risk than Delphin, often by about one classification step. Outside of these demanding conditions, their results are effectively the same.

Wood fibre (WF)

Results align closely between the tools. Noticeable differences arise mainly when a thin wood-fibre layer is used under demanding moisture and rain exposure, where WUFI tends to predict a higher risk. When thicker wood-fibre layers are used, both tools converge on similarly high risk, indicating effective agreement at that severity.

Expanded polystyrene (EPS)

Delphin often indicates a higher mould risk than WUFI, particularly on rain-exposed façades and in otherwise borderline situations where small changes tip the outcome. There are isolated exceptions where WUFI becomes more critical under very demanding exterior and interior loads, but in more benign settings the tools agree.

Mineral wool (MW)

The pattern mirrors EPS. Delphin frequently reports higher risk while WUFI remains low, especially on rain-exposed façades in borderline conditions. In a few demanding cases WUFI is higher, but broadly the most common divergence is Delphin predicting more critical outcomes than WUFI.

Indoor climate simulations

Indoor climate simulations show that internal insulation can improve winter performance and reduce heat losses, but its influence on indoor comfort is strongly dependent on climate, building typology, insulation material and user-controlled passive strategies.

In particular, the results indicate a potential increase in summer overheating risk, especially under future climate scenarios and in cases where internal insulation reduces the beneficial thermal inertia of massive historic walls. At the same time, hygroscopic and vapour-open systems can contribute to stabilising indoor relative humidity by buffering moisture peaks, although their effectiveness varies across climates and construction types.

As a next step, these simulation results should be validated against monitored indoor climate data from representative case-study buildings. This should include seasonal measurements of temperature, relative humidity, ventilation patterns, and occupant use of shading or night cooling. The planned implementation of selected measures in the Spanish and Polish FuturHist demonstrators, together with the ongoing longitudinal monitoring campaign, will make it possible to compare simulated performance with empirical evidence.

Additional sensitivity analyses will also help to better quantify the combined effects of occupancy patterns, ventilation rates, moisture production, material sorption properties and future weather files, so that the proposed insulation strategies can be translated into more robust, climate-specific design recommendations for historic buildings.

Thermal bridge analysis and integration of components

Analysis performed on thermal bridges and integration of components in the (insulated) building envelope (Chapter 4) addresses specific factors potentially affecting the durability of the construction as well as indoor hygiene and comfort.

Design recommendations and solutions in relation to thermal loss, risk of mould growth, airtightness, driving rain protection and rising damp are discussed with special focus on FuturHist building typologies. Key takeaway in this respect are:

- Measures for *reducing heat losses and mould risk* at thermal bridges (e.g., insulation wedges) do not generally contrast with conservation issues; at least, in case no cornices or decoration at the internal surface are present.
- Most solutions available to *increase airtightness* are in general accepted in all considered building typologies; although application might be challenging and requires careful design and implementation.

- More critical is finding *conservation compatible solutions for driving rain and rising damp protection*, some of which are very invasive and might require intervention and modification of the facade as well as load bearing walls.

The analysis of exemplary thermal bridges of the considered building typologies highlighted the following aspects:

- *Proper insulation design* (i.e., adequate insulation thickness and extension on the building component, choice of suitable insulation materials, application of insulation wedges) enables, even in challenging refurbishment of historic buildings, significant reduction of heat loss and mould growth risk at the internal surface.
- *At foundations of buildings with unheated basement*, linear thermal transmittance significantly decreases with the length of the plinth insulation.
- *At roof-wall junctions of buildings with heated attics*, it is important to install a sufficiently thick insulation layer between the top of the wall and the roof.
- *At wall-ceiling junctions of buildings with unheated attics with externally insulated walls and internal insulation below the ceiling* (e.g., Polish demo case), the linear thermal transmittance significantly decreases by increasing the thickness of external insulation.
- *Internally insulated external wall-ceiling connections*, with ceiling exposed to external air (e.g., arcaded gallery of the Spanish demo case) requires sufficiently thick floor insulation, properly connected to the wall insulation.
- *Internally insulated external wall-internal wall junctions of natural stone* (e.g., Scottish building typologies) might require insulation wedges to avoid mould risk at the corner (internal surface).
- *External wall-window's frame junctions* require adequate insulation; applying insulation plaster on the window reveal is a space-saving, conservation-compatible solution, particularly suitable in internally insulated buildings with less space available at the window's reveal (e.g., in the Spanish building typology ES1).

Outlook

Internal insulation is widely used to retrofit historic buildings, even though it can introduce moisture and related risks. This report examines how internal insulation performs across different contexts, identifying both potential problems and practical solutions.

A broad parametric study of mould risk in four European settings shows that performance depends strongly on the specific conditions of use: façade orientation, exposure to wind-driven rain, indoor moisture levels, and local climate. The most critical combinations consist of high indoor moisture or wet, rain-exposed environments (as in Scotland). Although future climates are generally projected to be warmer and drier, this will not universally eliminate mould-growth risks. The most effective risk-reduction strategies are to control indoor humidity, ideally through reliable ventilation, and, in more challenging contexts, to select robust insulation options such as autoclaved aerated concrete, which performed best among the investigated systems. A next step is to benchmark commonly used systems against new solutions developed in FuturHist.

Comparison of two widely used hygrothermal tools underscores how important careful model setup and interpretation are for risk assessment. While results are often similar, differences in material data from built-in libraries can shift outcomes from “very safe” to “very risky.” Robust conclusions require material properties that reflect the actual existing wall and the intended insulation; future work should delve deeper into material datasets to pinpoint the sources of differences.

Impact of internal insulation on indoor climate is also significant. Better insulation improves the thermal envelope, but indoor conditions can become better or worse depending on weather, internal moisture generation, and insulation type. Summer overheating is a particular concern under future conditions. Simulation results will be validated in next months with measurements from FuturHist demonstration cases.

Finally, detailing matters: junctions at windows, roofs, and foundations can create thermal bridges and unintended heat losses if not designed carefully. External rain-protection measures can be especially challenging to implement sensitively, as they may affect the historic façade more than typical interior measures.

Overall message: Internal insulation can be a safe and effective retrofit strategy for historic buildings when tailored to the building and climate, supported by moisture control, robust material choices, careful detailing, and verification. The analysis supports a positive but cautious outlook.

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7. Annexes

7.1. Parameters for indoor climate simulations

7.1.1. CarbonClay Mi4

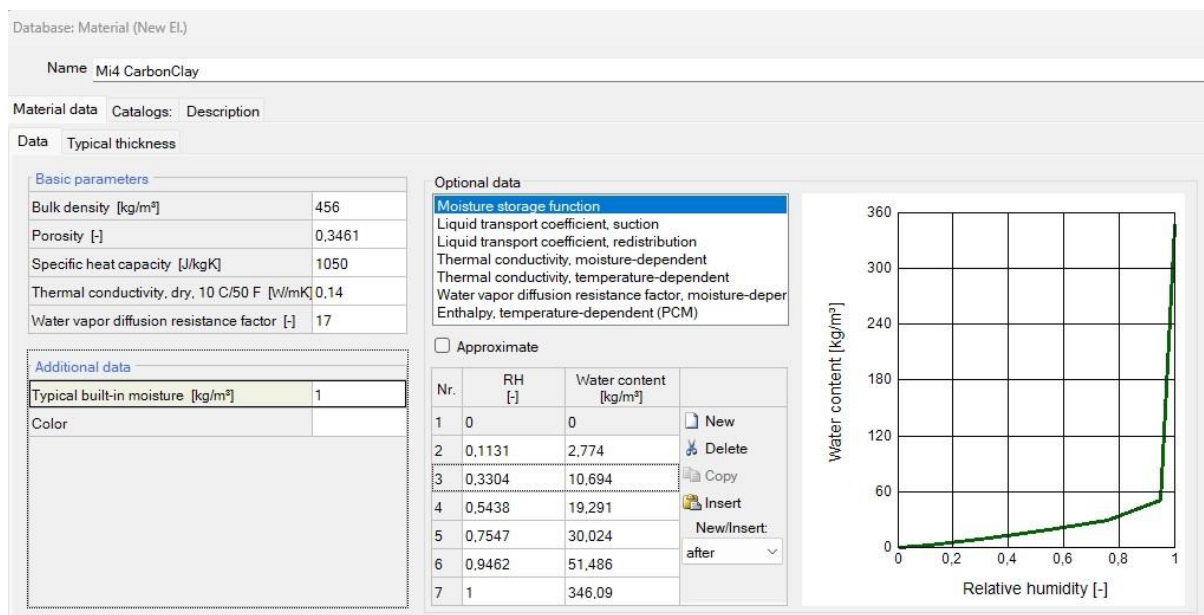


Figure 71. CarbonClay Mi4: Moisture storage function.

D2.8 / Report on assessment of insulation systems for the envelope's retrofit including components' integration

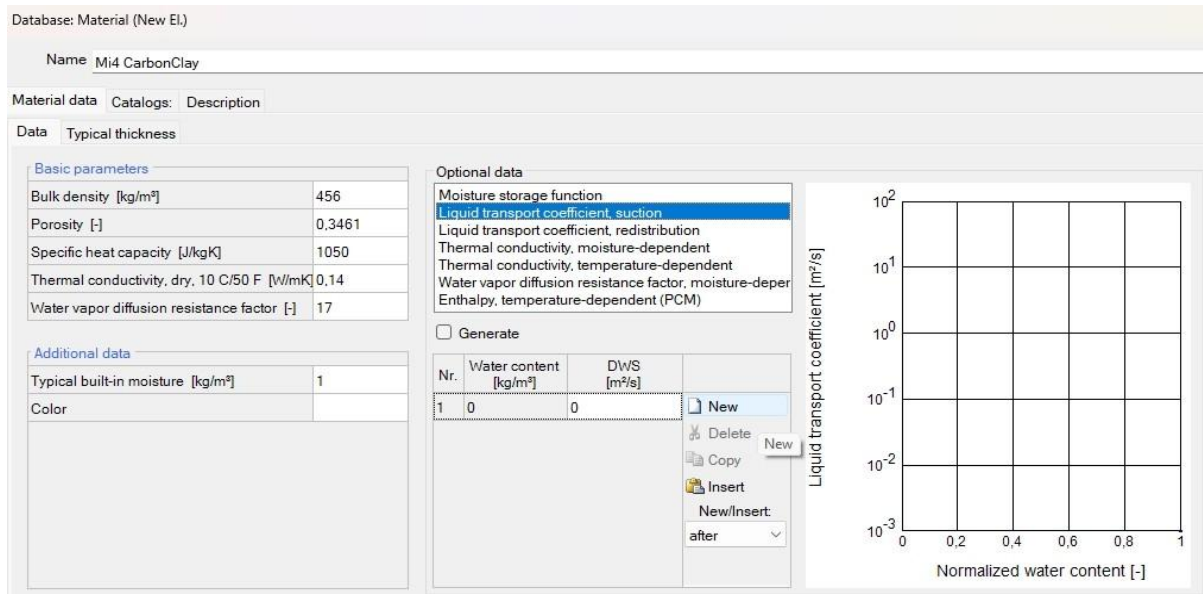


Figure 72. CarbonClay Mi4: Liquid transport coefficient, suction.

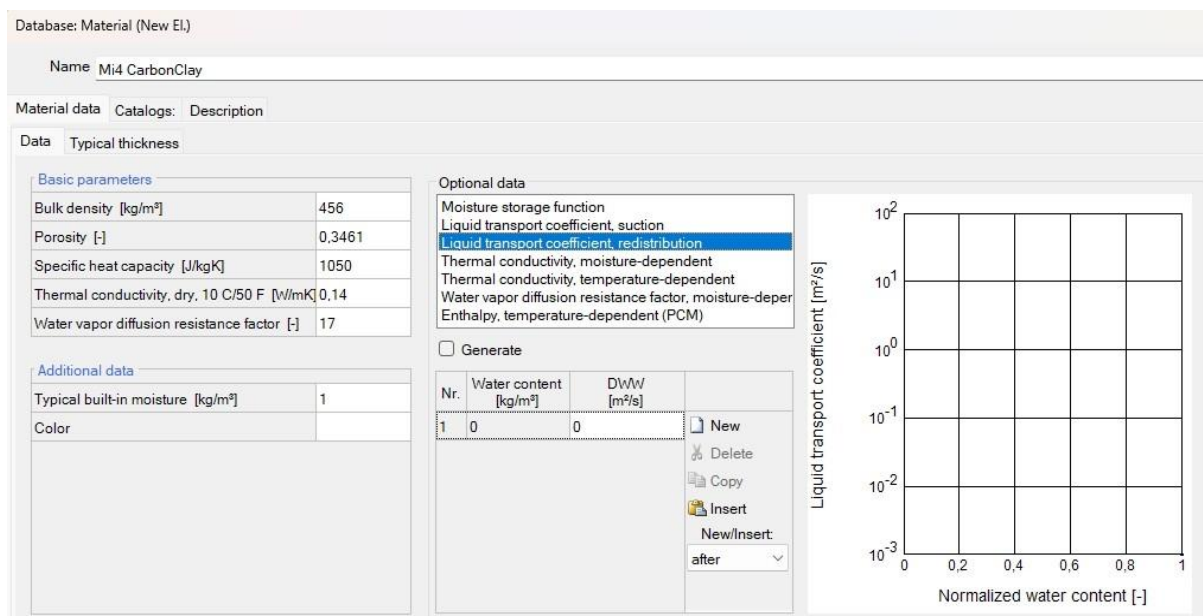


Figure 73. CarbonClay Mi4: Liquid transport coefficient, redistribution.

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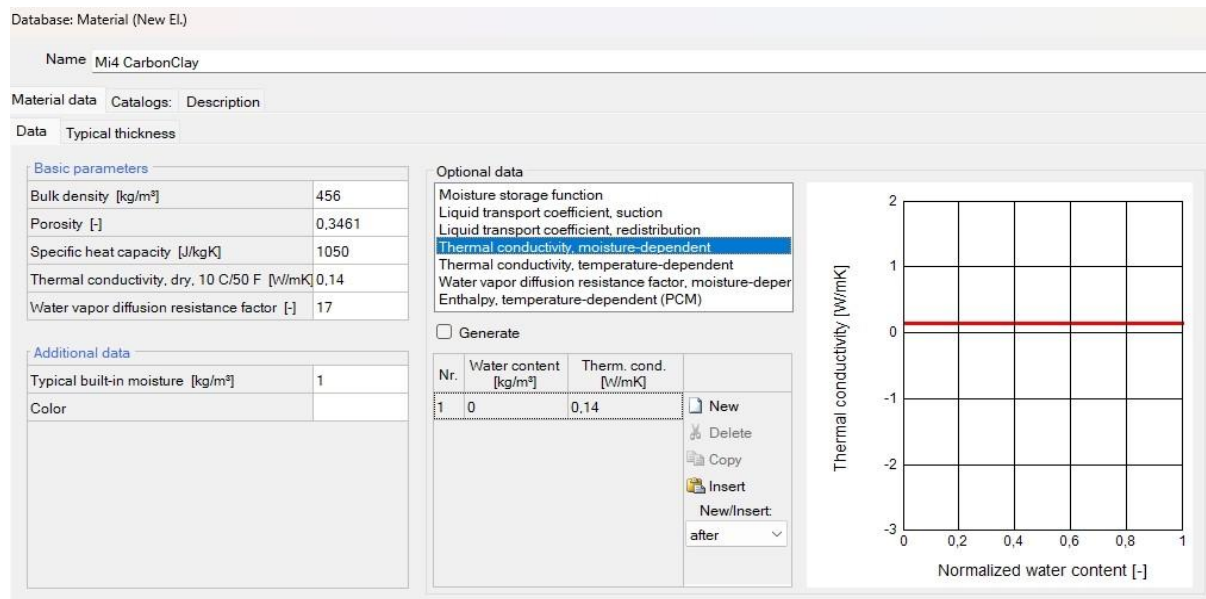


Figure 74. CarbonClay Mi4: Thermal conductivity, moisture-dependent.

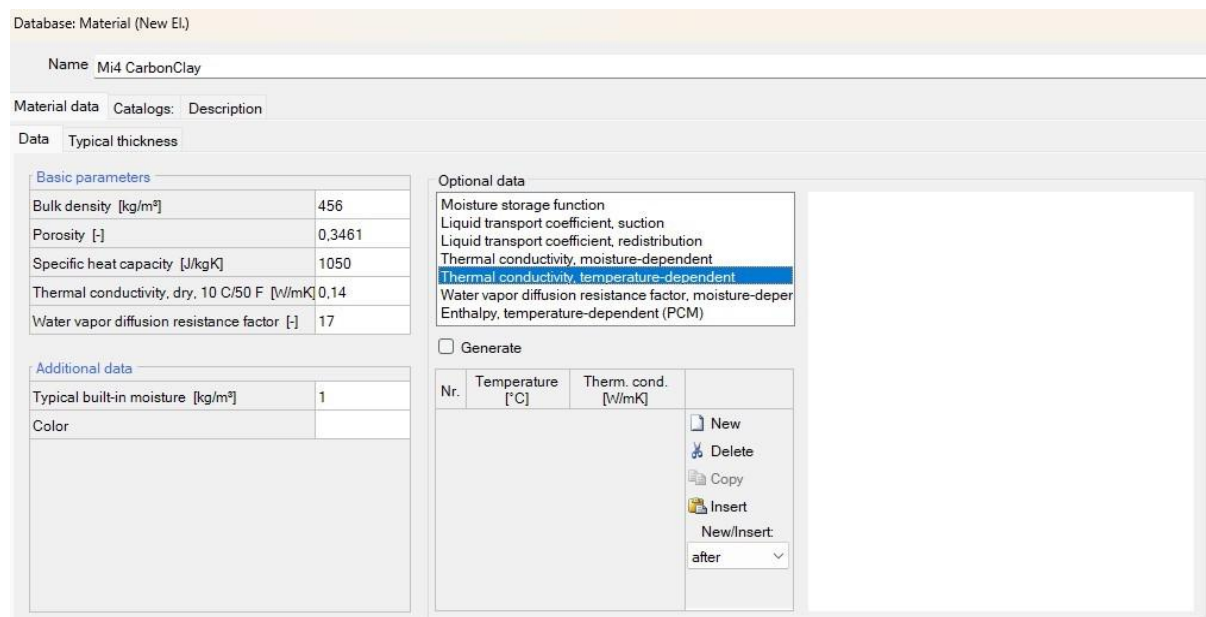


Figure 75. CarbonClay Mi4: Thermal conductivity, temperature-dependent.

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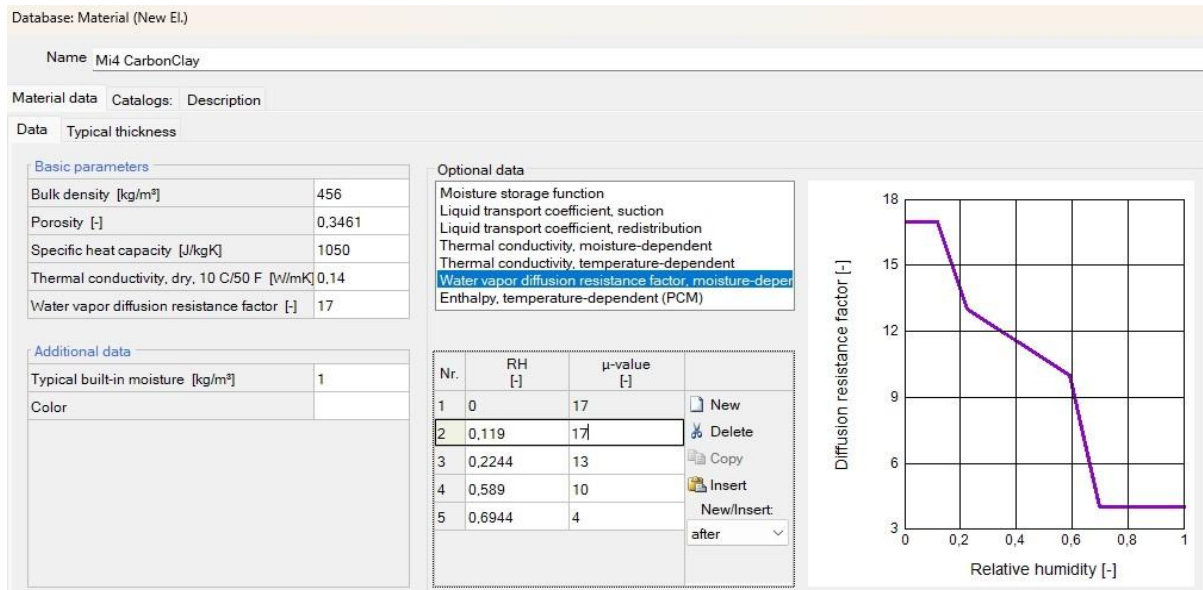


Figure 76. CarbonClay Mi4: Water vapor diffusion resistance factor, moisture-dependent.

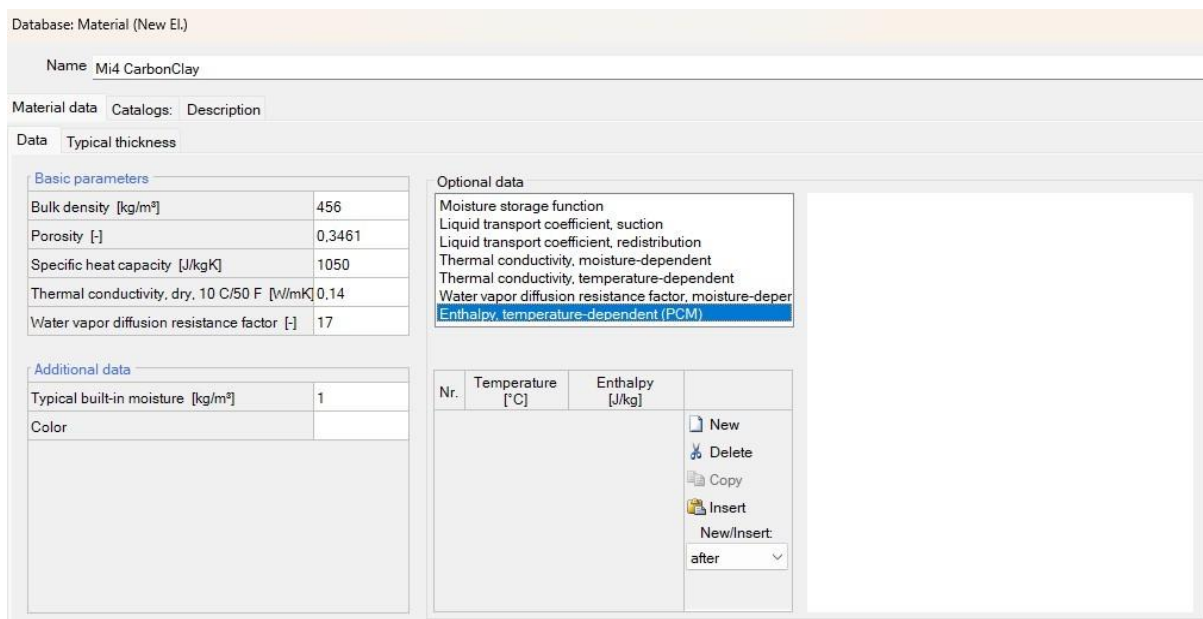


Figure 77. CarbonClay Mi4: Enthalpy, temperature-dependent.

7.1.2. CarbonClay MM2

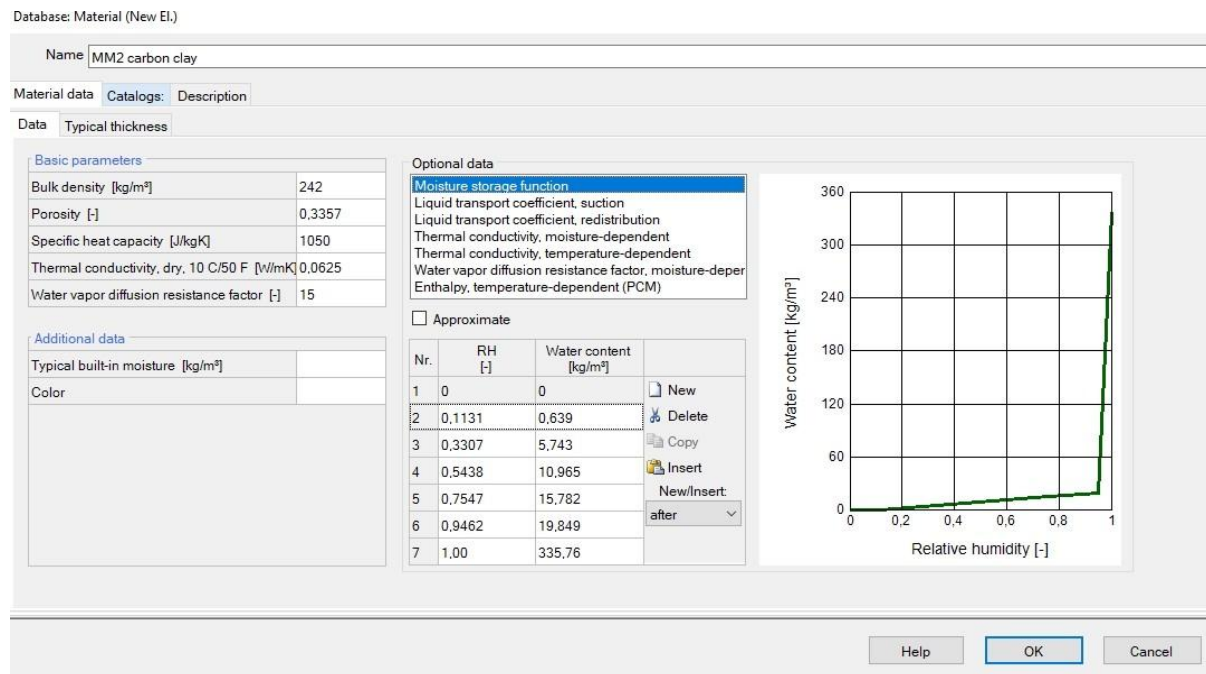


Figure 78. CarbonClay MM2: Moisture storage function.

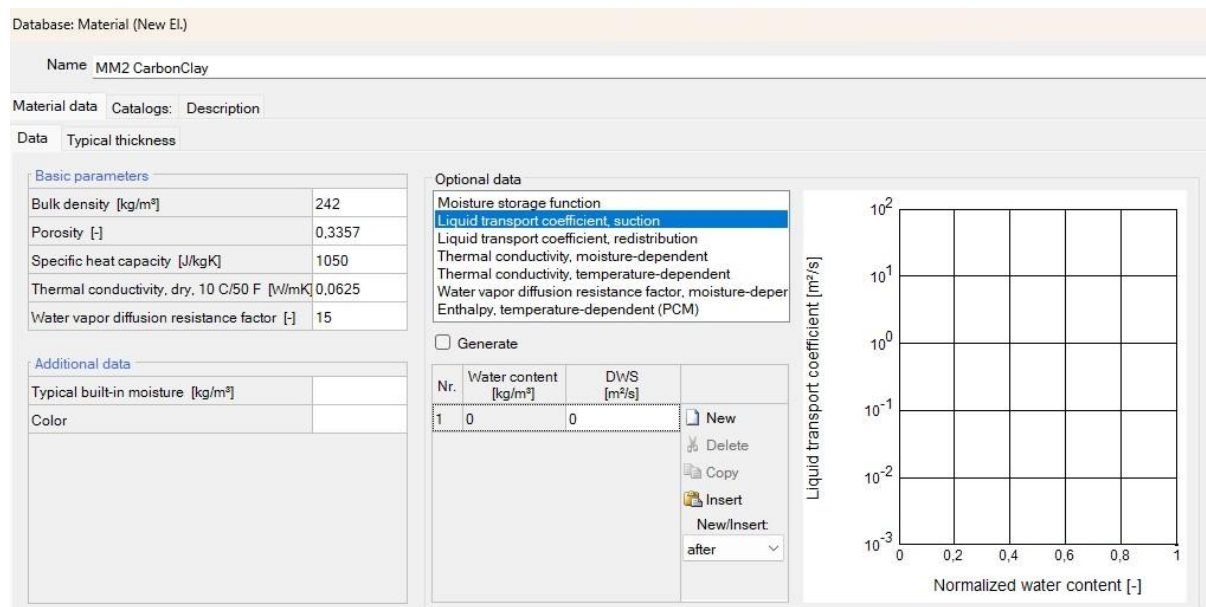


Figure 79. CarbonClay MM2: Liquid transport coefficient, suction.

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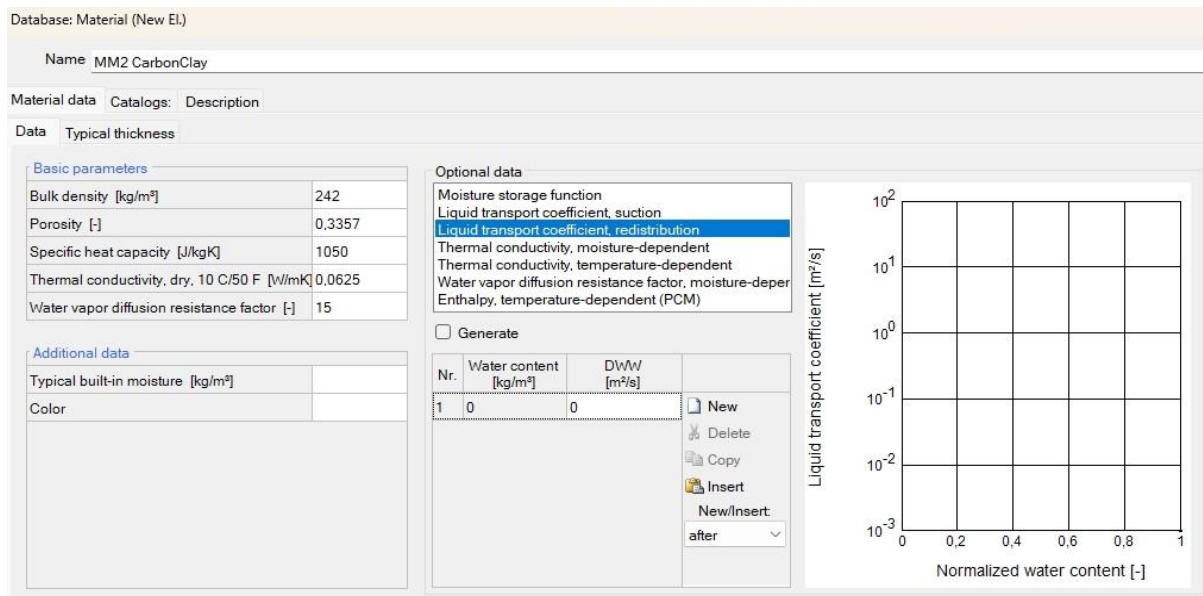


Figure 80. CarbonClay MM2: Liquid transport coefficient, redistribution.

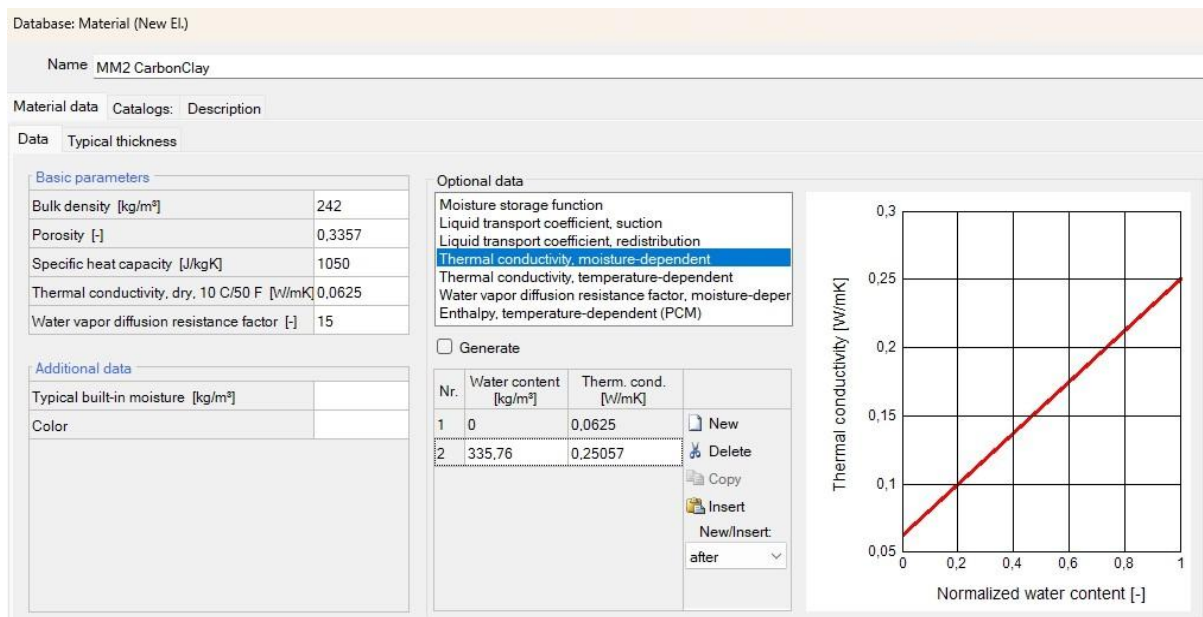


Figure 81. CarbonClay MM2: Thermal conductivity, moisture-dependent.

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Database: Material (New El.)

Name: MM2 CarbonClay

Material data Catalogs: Description

Data: Typical thickness

Basic parameters	
Bulk density [kg/m³]	242
Porosity [-]	0,3357
Specific heat capacity [J/kgK]	1050
Thermal conductivity, dry, 10 C/50 F [W/mK]	0,0625
Water vapor diffusion resistance factor [-]	15

Optional data	
Moisture storage function	
Liquid transport coefficient, suction	
Liquid transport coefficient, redistribution	
Thermal conductivity, moisture-dependent	
Thermal conductivity, temperature-dependent	
Water vapor diffusion resistance factor, moisture-deper	
Enthalpy, temperature-dependent (PCM)	

☐ Generate

Nr.	Temperature [°C]	Therm. cond. [W/mK]

New
Delete
Copy
Insert
New/Insert:
after

Figure 82. CarbonClay MM2: Thermal conductivity, temperature-dependent.

Database: Material (New El.)

Name: MM2 CarbonClay

Material data Catalogs: Description

Data: Typical thickness

Basic parameters	
Bulk density [kg/m³]	242
Porosity [-]	0,3357
Specific heat capacity [J/kgK]	1050
Thermal conductivity, dry, 10 C/50 F [W/mK]	0,0625
Water vapor diffusion resistance factor [-]	15

Optional data	
Moisture storage function	
Liquid transport coefficient, suction	
Liquid transport coefficient, redistribution	
Thermal conductivity, moisture-dependent	
Thermal conductivity, temperature-dependent	
Water vapor diffusion resistance factor, moisture-deper	
Enthalpy, temperature-dependent (PCM)	

☐ Generate

Nr.	RH [-]	μ-value [-]
1	0	15
2	0,1190	15
3	0,5890	7

New
Delete
Copy
Insert
New/Insert:
after

Relative humidity [-]	Diffusion resistance factor [-]
0	15
0.1190	15
0.5890	7
1	7

Figure 83. CarbonClay MM2: Water vapor diffusion resistance factor, moisture-dependent.

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Database: Material (New El.)

Name MM2 CarbonClay

Material data Catalogs: Description

Data Typical thickness

Basic parameters

Bulk density [kg/m³]	242
Porosity [-]	0.3357
Specific heat capacity [J/kgK]	1050
Thermal conductivity, dry, 10 C/50 F [W/mK]	0.0625
Water vapor diffusion resistance factor [-]	15

Additional data

Typical built-in moisture [kg/m³]	
Color	

Optional data

- Moisture storage function
- Liquid transport coefficient, suction
- Liquid transport coefficient, redistribution
- Thermal conductivity, moisture-dependent
- Thermal conductivity, temperature-dependent
- Water vapor diffusion resistance factor, moisture-deper
- Enthalpy, temperature-dependent (PCM)

Nr.	Temperature [°C]	Enthalpy [J/kg]	
			New
			Delete
			Copy
			Insert
			New/Insert
			after

Figure 84. CarbonClay MM2: Enthalpy, temperature-dependent.

7.1.3. Casa de Pisos, Córdoba

7.1.3.1. Planning documents Casa de Pisos

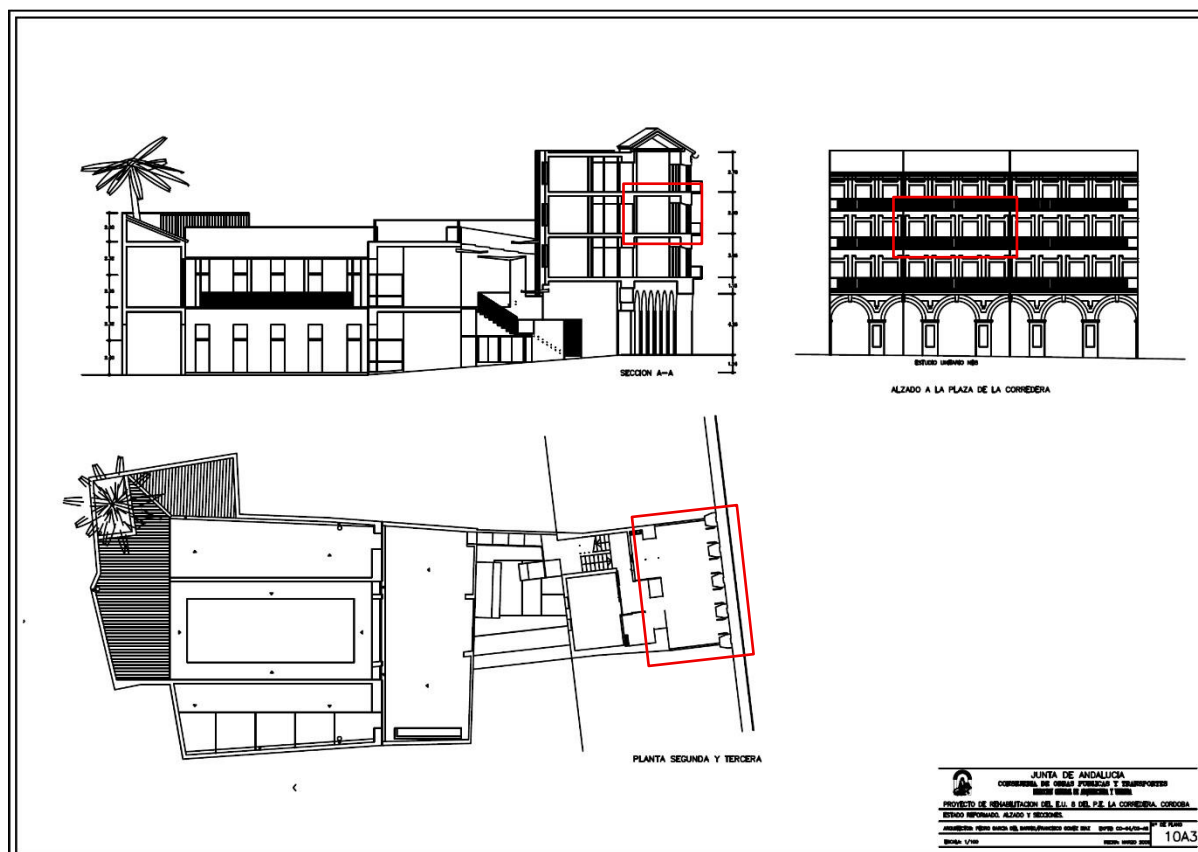


Figure 85. Planning documents, not to scale, plans by Pedro Garcia del Barrio and Francisco Gomez Diaz, March 2006.

7.1.3.2. Ventilation and shading parameters

Table 45. Córdoba window characteristics: ventilation. Component 2: Air flow model data.

Discharge coefficient (open) [-]	0.6
Width (openable part) [m]	1.16
Height (openable part) [m]	1.84
Optional data (if not defined, default value will be assumed)	
Flow exponent calculated [-]	
Flow exponent (closed) [-]	0.65
Flow coefficient calculated [dm³/(sm²Pan)]	
Flow coefficient (closed) [dm³/(sm Pan)]	0.22

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Table 46. Córdoba window characteristics: Shading. Basic data.

Uw -mounted [W/m²K]	3.92
Frame factor	0.6
Solar energy transmittance hemispherical	0.8
Long wave radiation emissivity (mean glazing/frame)	0.8

Table 47. Córdoba Characteristic values Shading elements. Solar protection (Id 1): blinds & shutters.

Solar exposure for shading device [-]	0.19
Thermal resistance solar protection [m²K/W]	0.058
Thermal resistance cavity [m²K/W]	0.083
Operation mode	Schedule

7.1.3.3. Ventilation profiles Córdoba

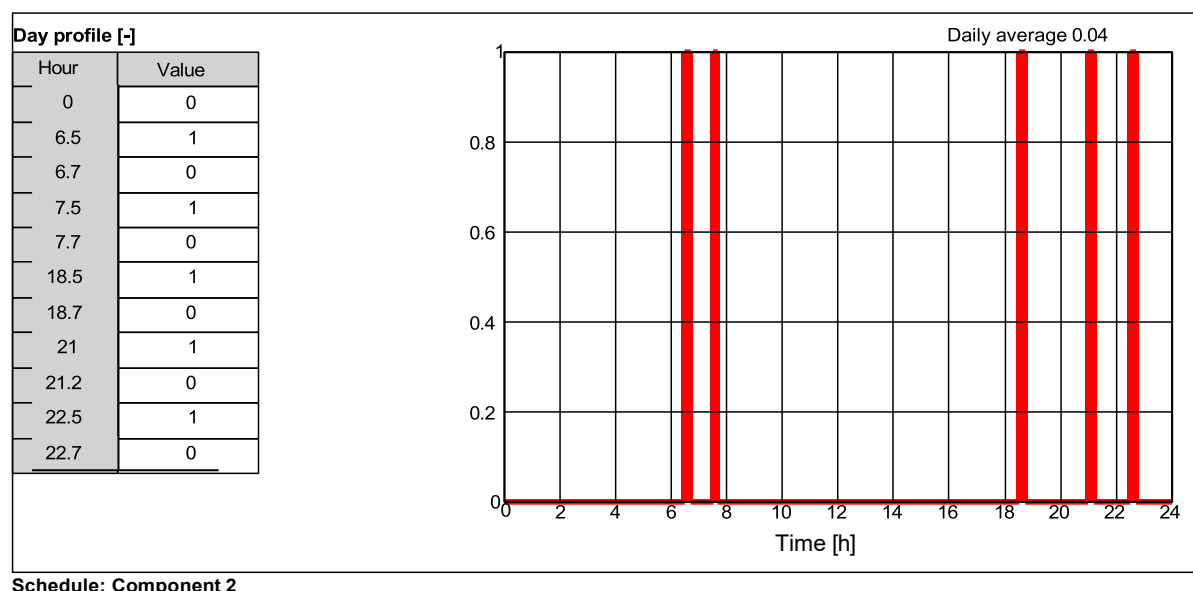


Figure 86. Córdoba ventilation profile Basis – Weekdays.

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Schedule: Component 2, exception 1

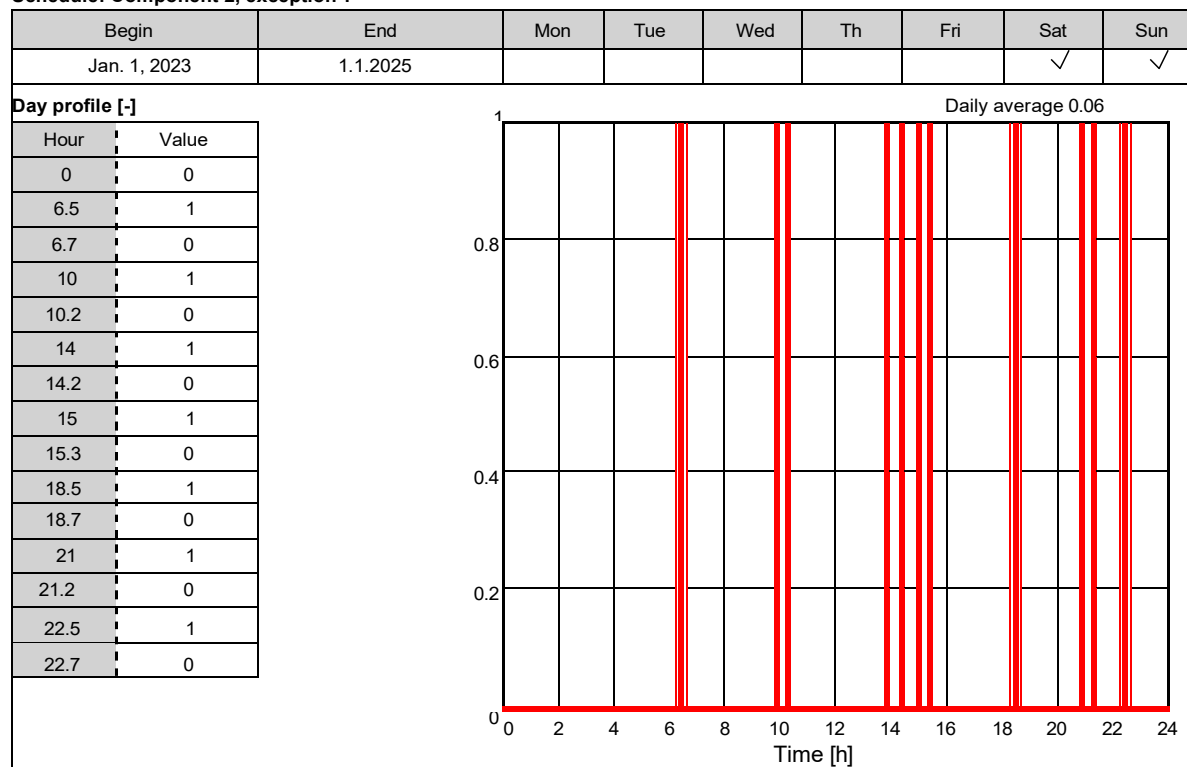


Figure 87. Ventilation profile Córdoba Basis – Weekend.

Schedule: Component 2, exception 2

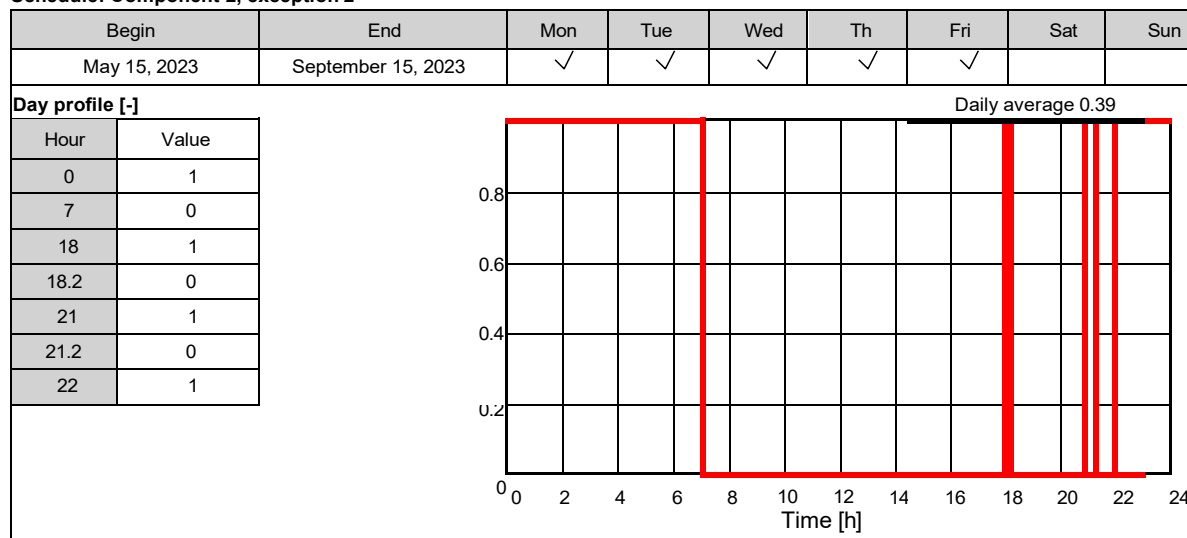


Figure 88. Ventilation profile Córdoba NV I – Weekdays.

D2.8 / Report on assessment of insulation systems for the envelope's retrofit including components' integration

Schedule: Component 2, exception 3

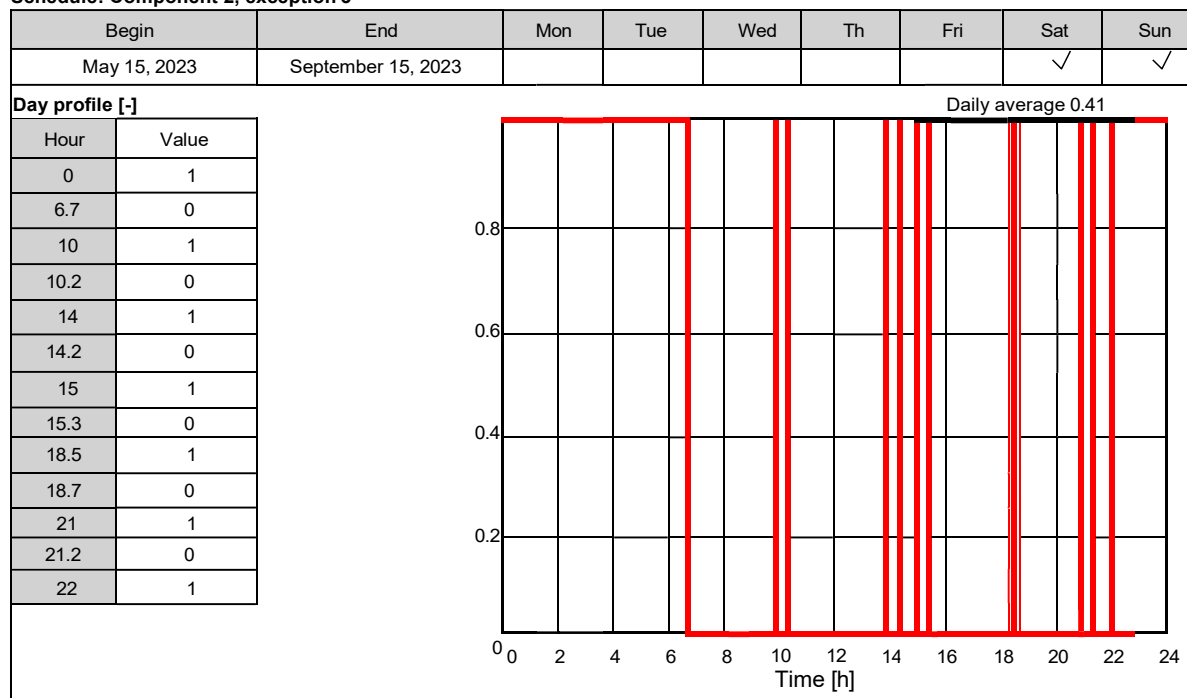


Figure 89. Ventilation profile Córdoba NV I - Weekend.

7.1.3.4. Shading profiles Córdoba

Closing factor, exception 1

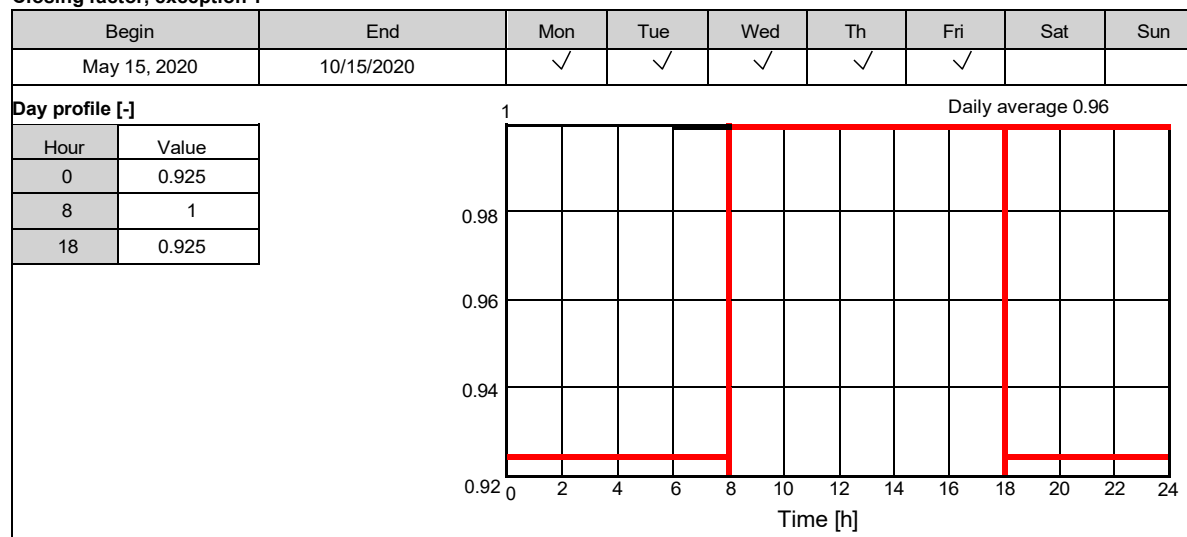


Figure 90. Shading profile Córdoba S I - Weekdays.

D2.8 / Report on assessment of insulation systems for the envelope's retrofit including components' integration

Closing factor, exception 2

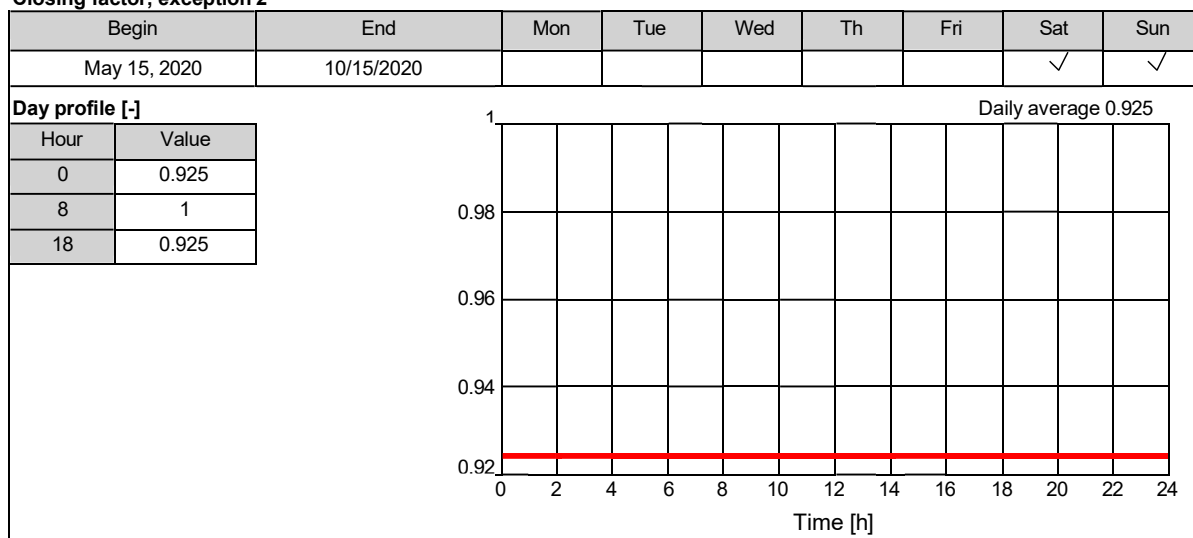


Figure 91. Shading profile Córdoba S I - Weekend.

Closing factor, exception 1

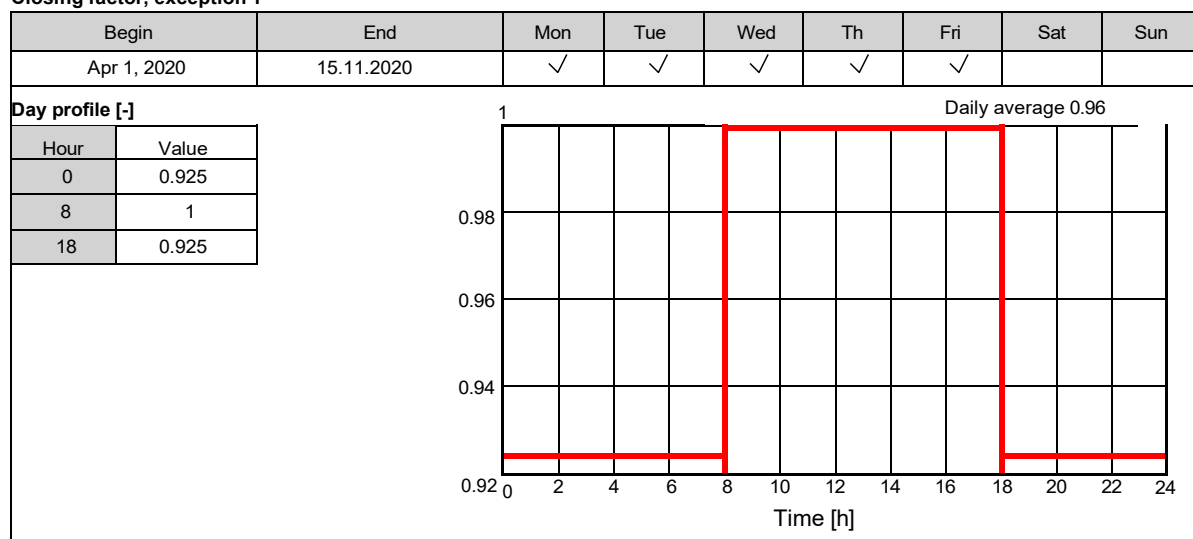


Figure 92. Shading profile Córdoba S II - Weekdays.

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Closing factor, exception 2

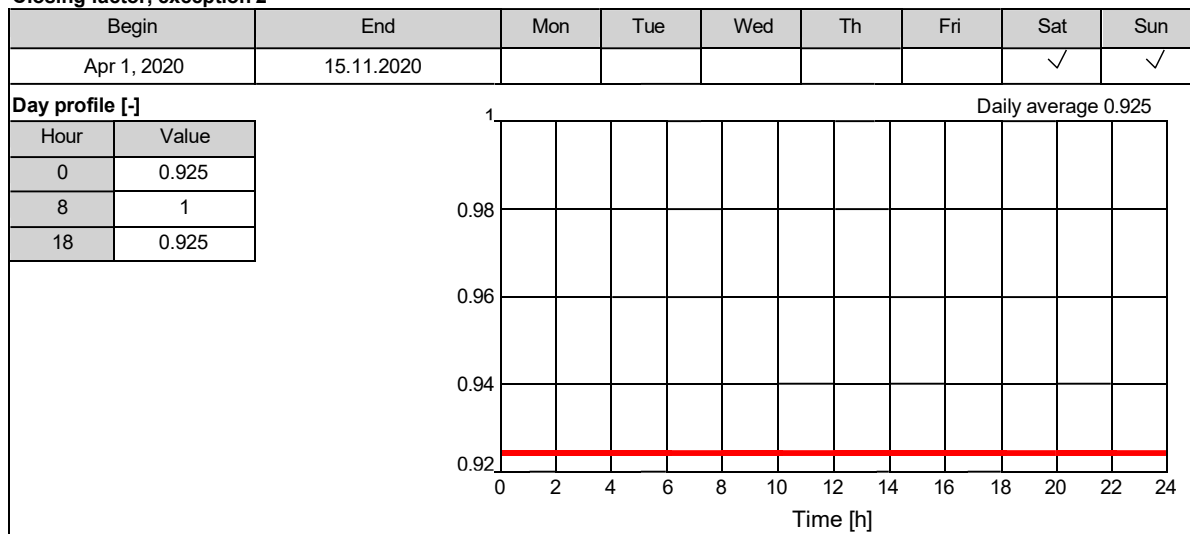


Figure 93. Shading profile Córdoba S II – Weekend.

7.1.4. Kamienica Krakow

7.1.4.1. Planning documents Kamienica

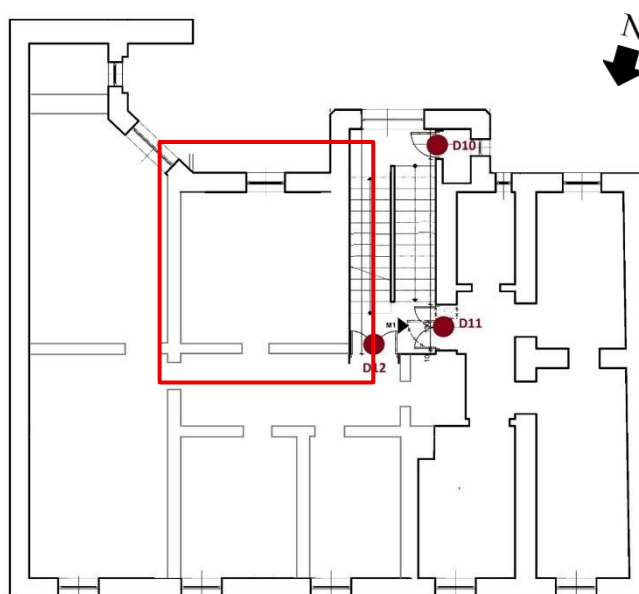


Figure 94. Floor plan of the first floor of Kamienica, without scale, living space marked in red. Source: Internal project illustration, 2024.

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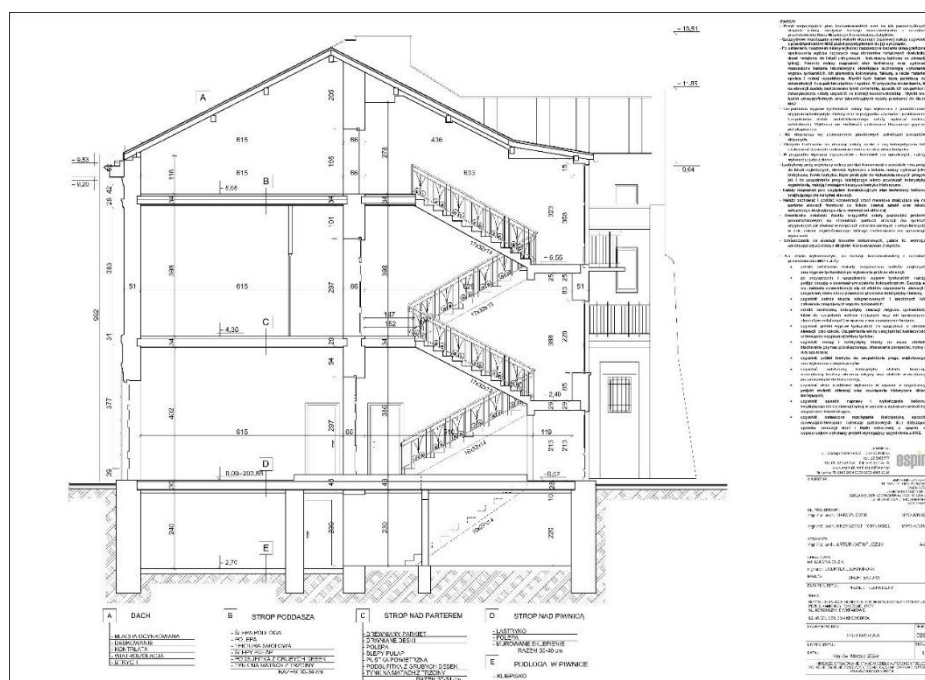


Figure 95. Section Kamienica, no scale, living space marked in red. Source: E-SPIN s.c. PRZĘKRÓJ A-A March 2024.

Ventilation and shading parameters Krakow

Window characteristics: Ventilation

Table 48. Component 5: Air flow model data.

Discharge coefficient (open) [-]	0.6
Width (openable part) [m]	1
Height (openable part) [m]	2
Flow exponent calculated [-]	
Flow exponent (closed) [-]	0.65
Flow coefficient calculated [dm ³ /(sm ² Pan)]	
Flow coefficient (closed) [dm ³ /(sm Pan)]	0.22

Table 49. Window characteristics: Shading.

Uw -mounted [W/m ² K]	3.1
Frame factor	0.6
Solar energy transmittance hemispherical	0.75
Long wave radiation emissivity (mean glazing/frame)	0.85

Shading element characteristics

Table 50. Solar protection (Id 1): Interior. Basic data.

Solar exposure for shading device [-]	0.61
Thermal resistance solar protection [m ² K/W]	0.025

Thermal resistance cavity [m²K/W]	0.2
Operation mode	Schedule

7.1.4.2. Ventilation profiles Krakow

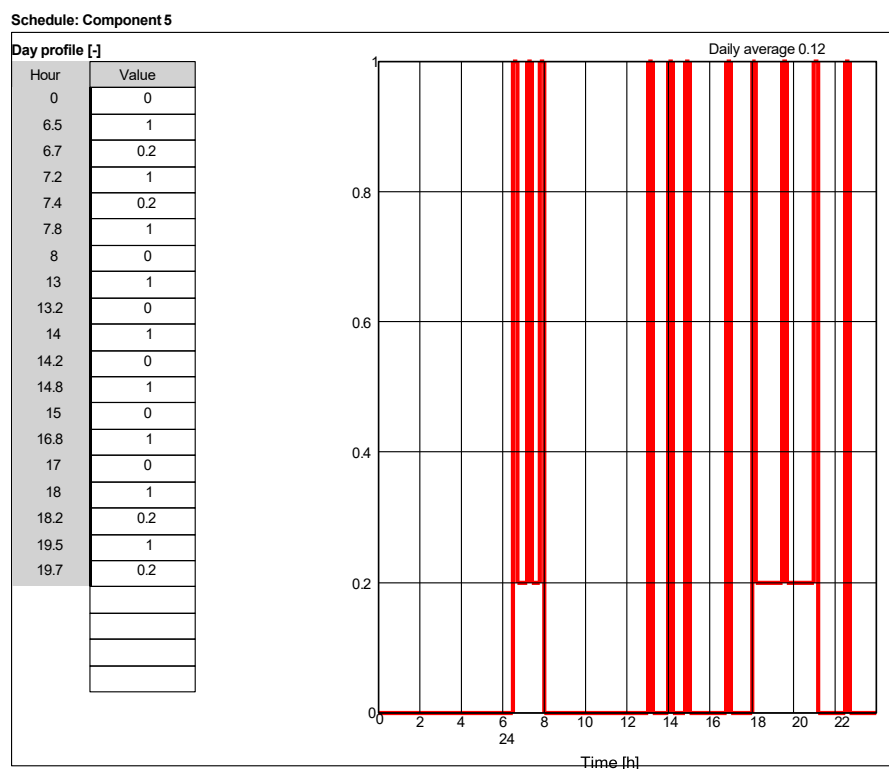


Figure 96. Ventilation profile Krakow Base – Weekdays.

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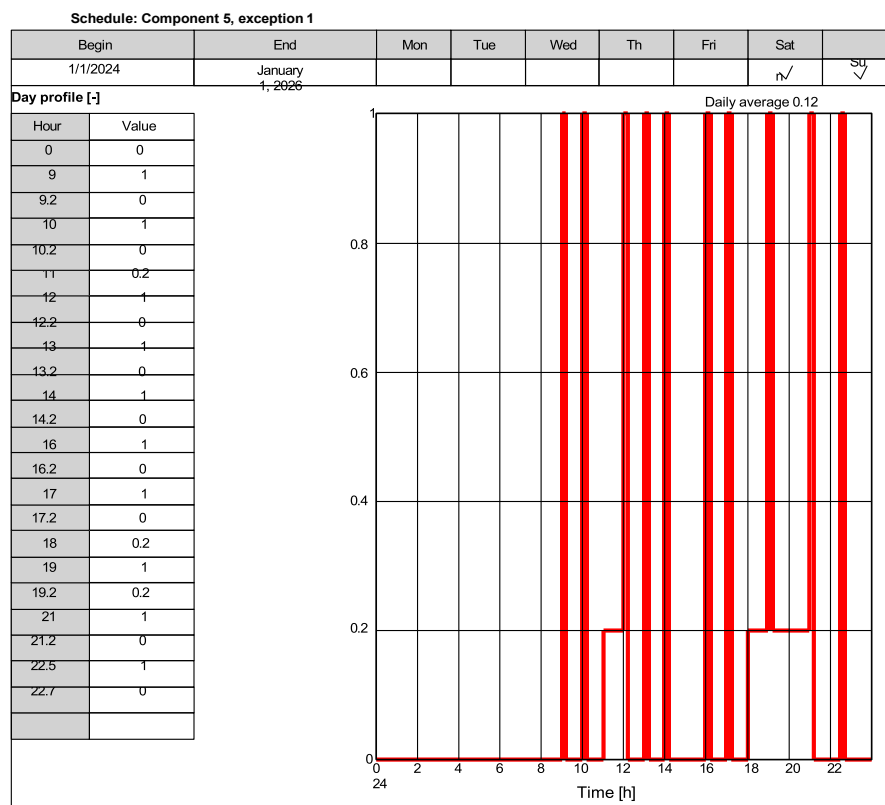


Figure 97. Ventilation profile Krakow Base – Weekend.

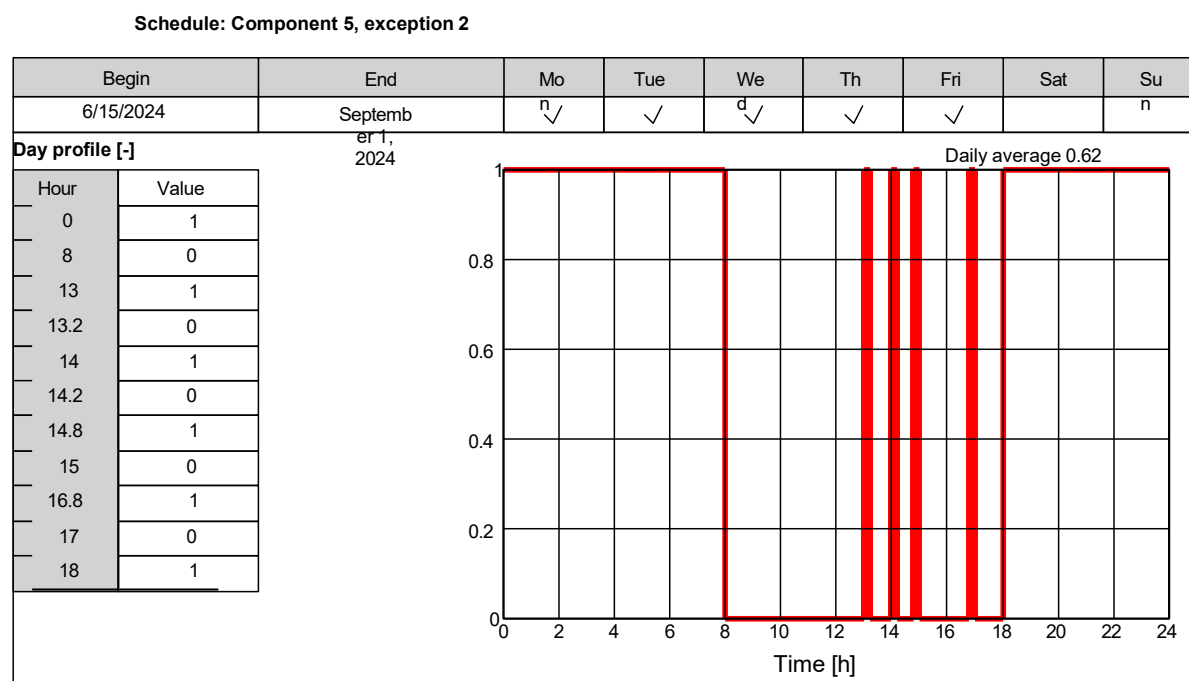


Figure 98. Ventilation profile Krakow NV I – Weekdays.

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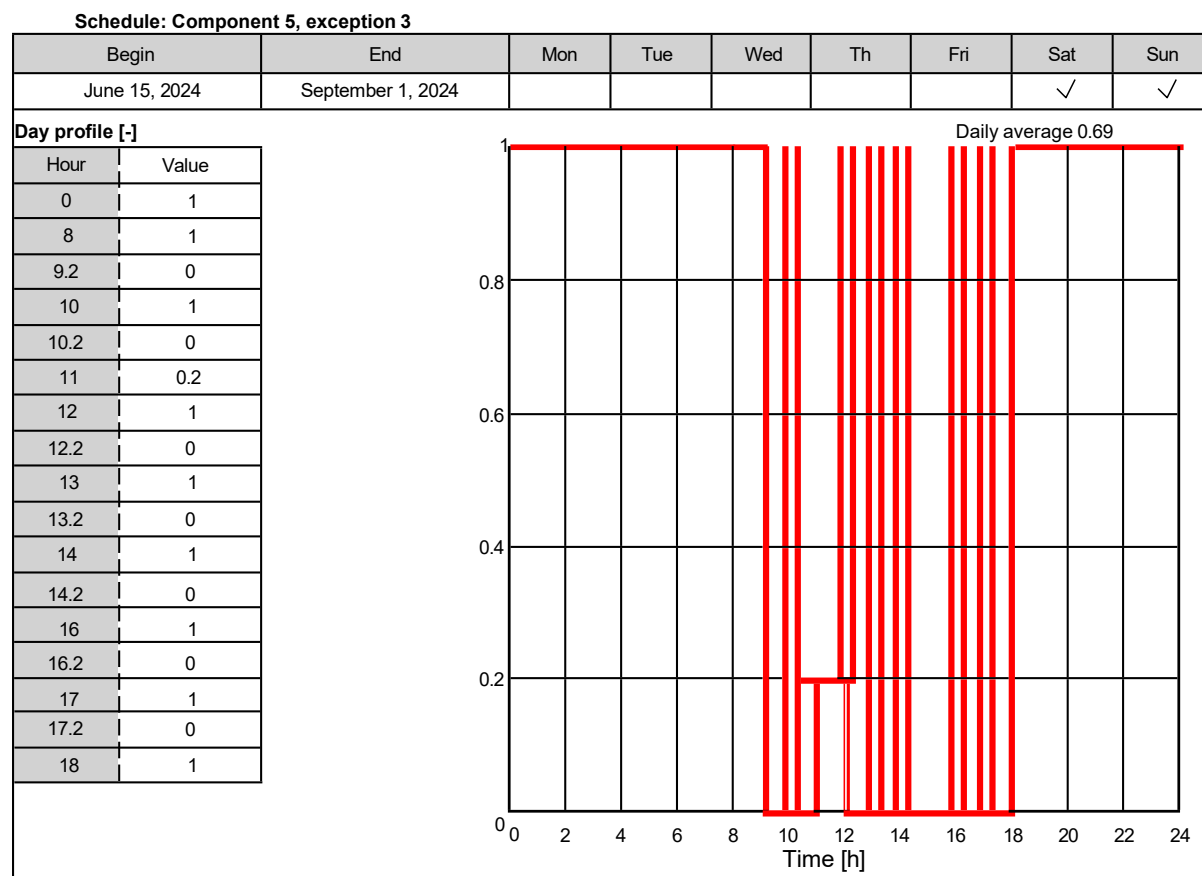


Figure 99. Ventilation profile Krakow NV I – Weekend.

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Schedule: Component 5, exception 2

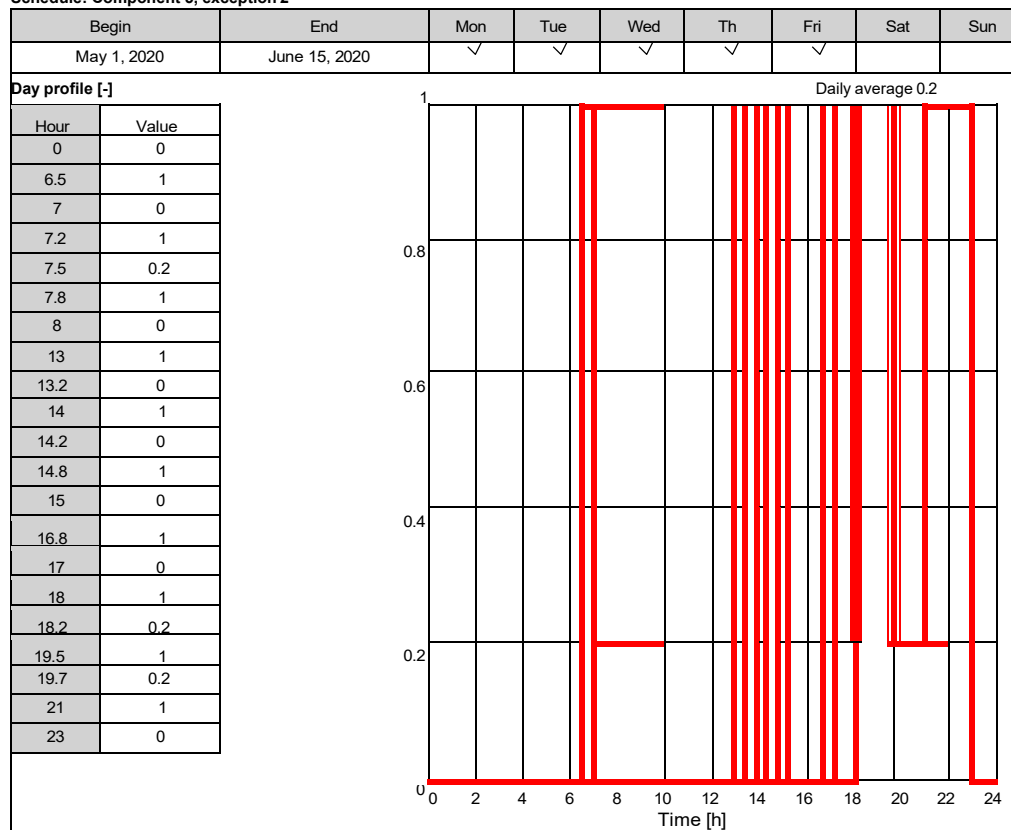


Figure 100. Ventilation profile Krakow NV II – Weekdays.

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Schedule: Component 5, exception 3

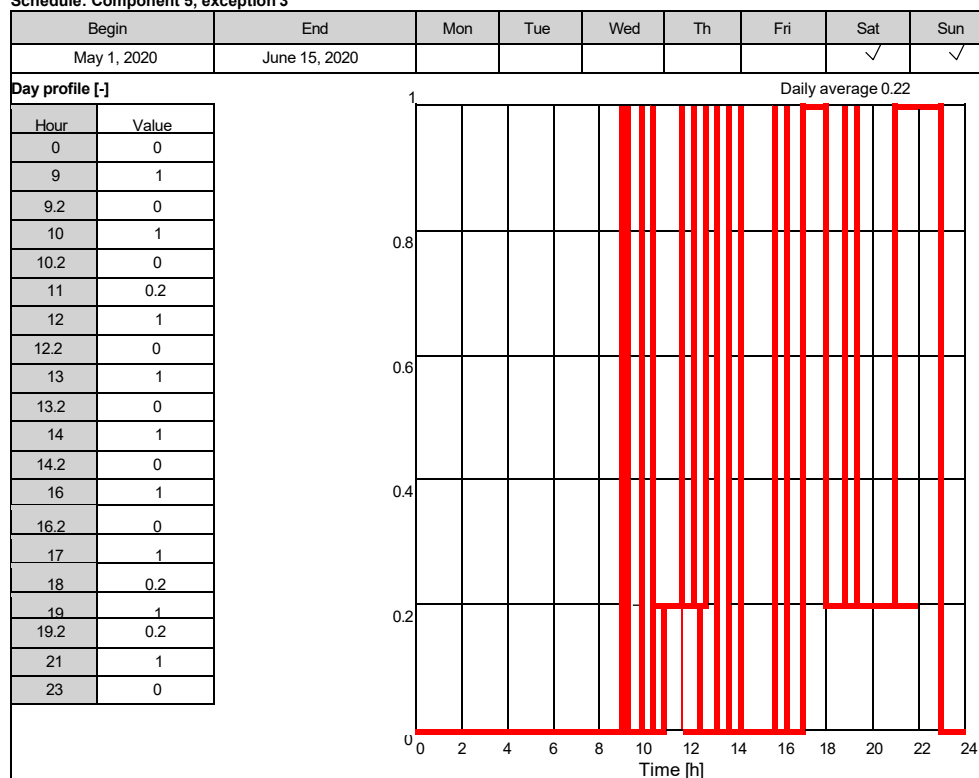


Figure 101. Ventilation profile Krakow NV II - Weekend.

7.1.4.3. Shading profiles Krakow

Closing factor, exception 1

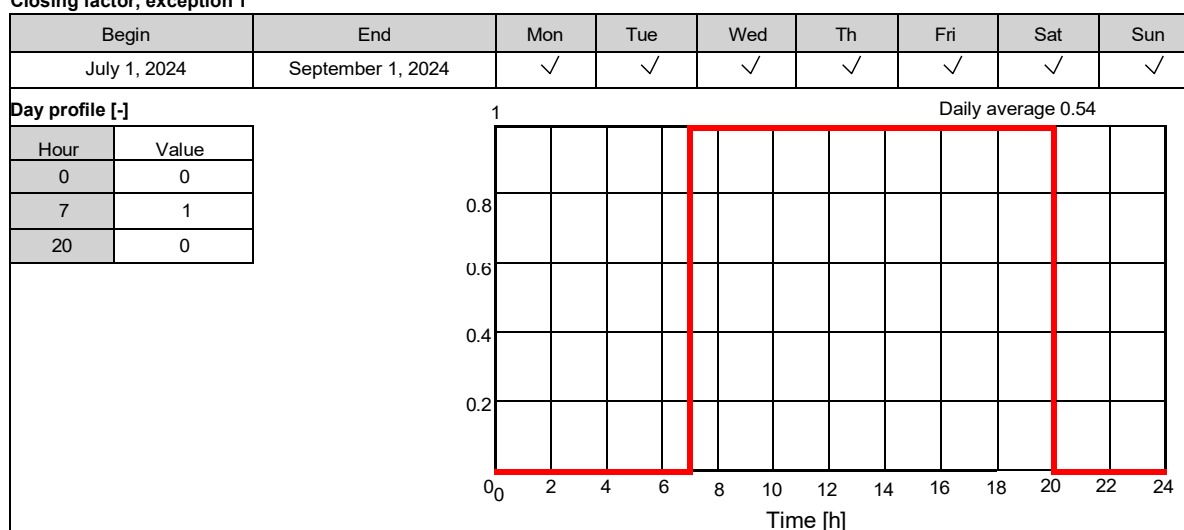


Figure 102. Shading profile Krakow S I - Entire week.

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Closing factor, exception 1

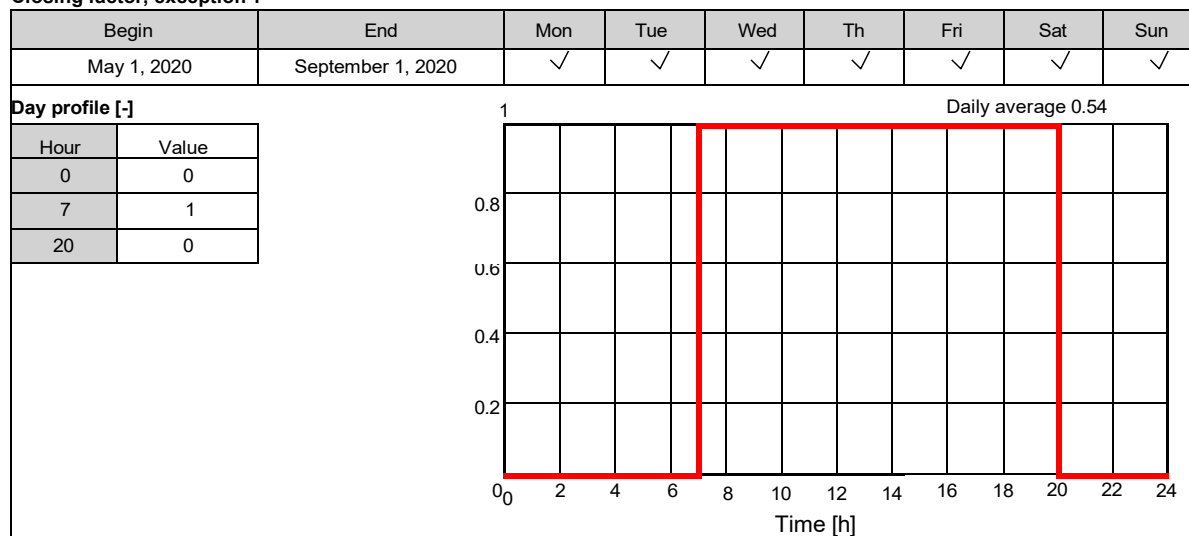


Figure 103. Shading profile Krakow S II – Entire week.



Tailored intervention solutions for future-proofing historic buildings

At FuturHist, we research and test energy-efficient retrofit interventions tailored to historic building typologies. We implement these solutions in real-life demonstration cases in Poland, Spain, Sweden and the UK. We focus on innovative solutions such as bio-based materials, internal insulation systems, window retrofits, HVAC, and RES integration.

DURATION OF THE PROJECT: JANUARY 2024 – DECEMBER 2027



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