Building envelope characteristics

Deliverable D2.1

Version N° 1.0

DOI: 10.5281/zenodo.15656117

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Funded by
the European Union

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Project information

Grant Agreement	n°101138672
Project Title	Future-proofing Heritage Townhouses by Optimising Comfort and Energy in Time and Space
Project Acronym	HeriTACE
Project Coordinator	Arnold Janssens, Ghent University
Project Duration	1 January 2024 - 31 December 2027 (48 months)

Deliverable information

Related Work Package	WP2: Energy efficient and durable building envelope solutions for heritage buildings
Related Task(s)	T2.1 Envelope characteristics
Lead Organisation	TALTECH
Contributing Partner(s)	TALTECH, SINTEF, UGent, EURAC, MKA
Due Date	M18
Submission Date	30/06/2025
Dissemination level	PU - Public

History

Date	Version	Submitted by	Reviewed by	Comments
30/06/2025	1.0	Paul Klõšeiko (TALTECH)	Elena Poma (EURAC)	Submitted

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Glossary

Acronym/abbreviation/term	Description
archetype	Here: a pattern or a type of building with common traits/configurations that represents a subset of buildings in the targeted neighbourhoods
EU	European Union
EPBD	Energy Performance of Buildings Directive (of the European Commission)
HeriTACE	Future-proofing HERItage Buildings by Optimising Comfort and Energy in Time and spACE
IAQ	Indoor air quality
HVAC	Heating, ventilation, air conditioning
R^2ES	Renewable and Residual Energy Sources
WP	Work package
WWII	World War II

Executive Summary

Project context

The deliverable "D2.1: Building envelope characteristics" is a report that documents the properties, current condition and damage mechanisms of the building envelope components: walls, roofs, ceiling and basement floors, windows and shading devices in Task 2.1 of the HeriTACE project.

The aim of this deliverable is to present the background information (envelope characteristics, condition, damage mechanisms) of the case study buildings which represent archetypes targeted in HeriTACE project (as described in further detail in deliverable D5.1) for both building energy simulations and informed interdisciplinary development of the retrofitting scenarios about the requirements, possibilities and constraints of the envelopes of the studied archetypes.

This deliverable should be considered in combination with description of the archetypes, case study buildings and case study neighbourhoods (deliverable D5.1), indoor air quality measurements (deliverable D3.2), R2ES situation (deliverable D4.1), heritage aspects (D5.2) and users/owners' perspectives (D5.3) to achieve a holistic overview of the existing conditions of the building archetypes targeted in HeriTACE. This background information is further analysed to define the baseline scenarios (summarized in deliverable D5.4) which describe the archetypical buildings as they were in a) before the introduction of EPBD (1990s-2000s state) and b) if they would be renovated today – they will be used as a reference to assess the effectiveness of the innovative retrofit scenarios developed in HeriTACE project.

Outcomes

The research was based on analysis of previous studies and project documentation, but also on in-situ measurements of airtightness, thermography and thermal transmittance. Condition of the envelopes were assessed visually and by non-destructive means. Thermal performance of inhomogeneous envelopes and details were modelled numerically.

The main country-specific findings and conclusions are:

Belgium

- A total of 15 cases was selected for the case study analysis (across different WP)
    - In 13 cases, valid air tightness measurements were carried out
    - In 7 cases, thermal transmittance measurements were carried out, mainly on facades (or party walls)
    - In 11 cases, a detailed analysis of the building envelope was made
- The different archetypes were all constructed in the same way, with the same materials. No notable difference regarding airtightness, thermal transmittance, condition, damage, … was noted.
- All cases were generally found to be in good condition.
    - The walls were typically well preserved, and structurally they were in excellent condition. Where damage was observed, it was most often limited to the

finishing layer, which tended to show signs of cracking, particularly on the rear façade.
    - Roofs were usually in good condition, provided they remained watertight. However, the roof supporting structures occasionally appeared to be under-dimensioned.
    - The majority of deterioration was observed in the wooden windows, where instances of wood rot were not uncommon.
- Typical for the Belgian archetypes are the solid masonry façade walls, party walls and internal (bearing and non-bearing) walls.
    - Front facades are characterized by their very high heritage value. Consequently, they were never energetic retrofitted, but often restored and well maintained. The measured and calculated thermal transmittance range between 0.86 and 1.38 W/m²K, which are quite low due to the large thickness of these walls. The thermal transmittance is also a lot lower than that of a party wall in these archetypes (U = 2.07... 2.47 W/m²K) or than the thermal transmittance of an insulated cavity wall, that is standard practice in houses of the late 20th century.
    - Back facades have limited heritage value and are sometimes retrofitted with external insulation. Party walls and the walls of the annex are typically thinner than the façade walls.
    - A range of pitched roofs have been encountered in the cases. From uninsulated roof structures to fully insulated and finished roofs. A lot of attic spaces are converted into bedrooms, apartments or office spaces. When the attic has become a livable space, the roof is often renovated, insulated and properly finished, so that it can be a decent space.
    - The window types observed across the cases exhibit significant variation. As original single glazing contributes to substantial heat loss and increases the risk of condensation, and the timber frames are frequently affected by wood rot, many original windows have been replaced. Windows in the rear façade are typically substituted with modern units that comply with the applicable standards at the time of replacement. In contrast, greater care is generally taken with those in the front façade due to its heritage value. In these instances, replacement windows are often modelled according to the original design, or the existing frames are retained and fitted with improved (thin) glazing (although this does not achieve the same thermal performance as entirely new windows). In some cases, the original windows are preserved and well maintained.
    - The front façade typically represents between 10 and 16% of the heat loss area, while other elements make up a larger part of the envelope, with the pitched roof (up to 25%), the floor boundary (up to 25%) and the windows (up to 21%) as the largest parts. Investing a lot of energy in retrofitting the front façade, which is often highly valuable and difficult to insulate, seems like a less interesting option.
    - A lot of construction details and connections seem to induce a risk for mould growth or surface condensation, although it is rarely encountered. The low moisture load in these buildings (as described in D3.2) in combination with a leaky envelope and window opening behaviour can be the reason why it is prevented so far. Making the envelope more airtight during retrofit or

introducing a higher moisture load (by intensifying the use of the building), can hold risk to mould growth, certainly when interior insulation is added.

- Airtightness measurements show a broad variety in the airtightness of the Belgian heritage townhouses. The q_{E50} value ranges from 4.81 m³/h·m² to 13.3 m³/h·m².
    - Heritage townhouses do not perform per se worse than non-heritage buildings. They do perform worse than the Flemish average for new buildings.
    - In instances where the roof had been recently insulated and fitted with a vapour barrier, airtightness was significantly improved compared to unrenovated buildings. However, this is not a guarantee for a good airtightness.

Norway

- In Norway, the primary focus of measurement efforts was on indoor air quality (as detailed in D3.2) and laboratory investigations into interior insulation solutions for plank walls (task T2.4 of the HeriTACE project). The envelope characteristics presented here summarize findings from previous studies.
- A defining feature of the building envelope of the Norwegian archetype, constructed with load-bearing timber logs or vertical planks, is that the exterior holds significant heritage value for townhouses intended for habitation. In many cases, replacing the old cladding is not feasible, especially if the wood remains in good condition. However, if there is considerable deterioration, modifications to the entire façade may be allowed. The visual characteristics of the windows are preserved. Upgrading the basement and roof/loft with thermal insulation is typically not constrained by stringent heritage regulations, allowing for the addition of insulation.
- The typical thermal properties of the Norwegian archetype indicate a U-value for the floor and ceiling structures ranging from 0.95 to 1.0 W/(m²·K) while wall structures exhibit a U-value of 0.8 W/ W/(m²·K) . The thermal performance of windows varies from 1.5 W/(m²·K) for coupled windows (featuring two separate sashes/glazing layers) to 1.0 W/(m²·K) for an outer single pane paired with an inner double-glazed insulating unit. Due to Norway's climatic conditions and indoor comfort needs, single glazing is rarely found in habitable heritage buildings.
- If exterior upgrades are allowed, it is feasible to add exterior insulation and a wind barrier, ensuring that the new cladding resembles the original. This would improve U-values and energy performance from the typical 0.8 to 0.3 W/(m²·K). Upgrading with interior insulation carries a higher risk of moisture issues and requires carefully considered solutions, demanding attention in future retrofit scenarios.
- The airtightness values of the Norwegian case studies have not been measured but are expected to be poor. Previous measurements of approximately 40 to 50-year-old Norwegian wooden houses suggest an airtightness of around 5.0 h^{-1} (n_{50}). It can be anticipated that heritage wooden buildings will have an airtightness range between 5 and 10 h^{-1}.
- Interventions, particularly involving interior insulation, can elevate the risk of moisture problems (such as mould and rot), especially as climate change leads to increased temperatures and humidity in the coming years.
- As noted in D3.2 regarding the measurement campaign for Bakklandet, the compact size, high user control, low occupant density, and behavioural adaptations (e.g.,

window airing, limited heating at night) contributed to unexpectedly robust indoor environmental quality performance including moisture loads. This is a favourable outcome concerning potential future insulation, particularly interior insulation. However, limited mechanical ventilation, inconsistent space conditioning, and dependence on user intervention may lead to inconsistencies, especially during atypical usage (e.g., tourist rentals).

Estonia

- Airtightness was measured in 4 buildings. In addition to single apartments, in Komeedi case, the whole building envelope was measured too.
- Thermal transmittance was measured in 4 buildings – mainly on walls, but in 1 case also on attic floor.
- The wooden apartment buildings are characterized by low airtightness. The measured q_{E50} levels are similar to previous studies ca 15 years ago, which suggests that interior insulation (that has now been more widely installed) has generally not improved it. However, 1 apartment with interior insulation had ca 2x higher airtightness than the median of previous measurements.
- Interior insulation was at least partly installed in all studied wooden buildings and at least in 1 apartment in 1 masonry building. Interior insulation of the wooden walls has been previously shown to be more suitable than on masonry walls, but can still be a risky solution, especially if indoor moisture load is high and the rainwater systems are faulty. As indoor air quality measurements given in D3.2 have shown, the indoor moisture load can be very high (up to Humidity class 4 according to EN ISO 13788 Annex A). Furthermore, interior insulation of masonry walls is riskier and requires case-specific solutions. If the risks have materialized or not, they were not studied here — the structures were not opened.
- Masonry walls studied here have 3-4x higher thermal transmittance ($U \approx 1–1.5$ $W/(m^2 \cdot K)$) than wooden ones. Besides higher energy losses it also means that along with high indoor humidity load also observed here, the interior surfaces can have suitable conditions for mould growth. The latter was observed in one of the case study apartments too. Moreover, as they form ca 40-50% of the envelope area of the building, such walls would greatly benefit from thermal upgrade.
- The measured thermal transmittance ($U \approx 1.45$ $W/(m^2 \cdot K)$) of a cavity masonry wall supposedly injected with foam insulation was similar to uninsulated masonry wall. This, along with modelling results, indicates that when the masonry is made of lime-sand brick and tie stones are used, the cavity insulation does not bring significant improvement to the thermal performance.
- The plinths of both wooden and Stalinist brick apartment buildings are made of limestone masonry with very high thermal transmittance ($U \approx 2.0–2.3$ $W/(m^2 \cdot K)$) and moisture issues (capillary rise, splashes from the street), which makes the basement conversion without major interventions difficult.
- A large share of original type windows has been replaced during the last 25 years by a varying mix of types (single frame, double frame), frame material (wood, PVC) and IGU (2-pane, 3-pane; different filler gases and spacers). Oldest of those have low thermal performance ($U_w \approx 2$ $W/(m^2 \cdot K)$) and usually do not fit in very well aesthetically – replacement of them could be justified on both thermal and heritage basis.

- Facades and plinths of ca 40-50% of the buildings in the neighbourhood are in a need of repairs within 5 years or sooner – this could be combined with energy renovation measures for a win-win situation.
- The damage to the facades is often due to infrequent or -adequate maintenance. Unmaintained rainwater systems have the highest impact on the rest of the building.

Italy

- In Italy four buildings, each representing one archetype have been selected as case studies: *Romano* for the Gothic Lot, *Montanara* for the Palazzetto, *Leonardo* for the Extended Building and *Vescovile* for the Courtyard building.
    - They have been documented in building identity cards – documenting besides general information and urban context, ownership and protection, architectural characteristic and technical installations, the single construction elements (roof | wall | floor | windows | interiors), for each of these describing the component, its state of conservation and the valuable elements. This information has been fed into the descriptions in the component sheets.
    - Thermal transmittance was measured in *Leonardo* and *Vescovile*, the two buildings, which were in use.
    - Air tightness of the whole building was measured at *Leonardo* and *Montanara*. *Vescovile* would have been too large, there has been measured the airtightness of one of the replica windows on the first floor.
- All case study buildings were found to be in overall good conditions. Main needs to intervene would usually be the plaster finishes and windows – which often has already been done.
- In terms of envelope characteristics, the four archetypes have considerable similarities which thus be presented here together:
- Masonry walls are made of raw bricks with plaster finish both inside and outside.
    - The thickness varies – for the Gothic Lot and Palazzetto between 44 to 46 cm on the front façade and 32 to 34 cm on the backyard, for the Extended Building between around 40 cm on the ground floor decreasing in upper floors, and for the much larger Courtyard building between 60 to 80 cm in the lower floors, also here decreasing with hight.
    - The measured U-value was both for wall similar with 0.85 W/m²K (Vescovile) and 0.81 W/m²K (Leonardo), even though the thicknesses of the walls differ considerable. This implies that the thermal conductivity of the used raw bricks does vary, and presumably for larger building and thicker walls more dense bricks were used. As typical U-values for the typology walls thus 0.8 - 0.9 W/m²K for the front/main façade walls was identified, and 1.0 - 1.2 W/m²K for the thinner walls of backyard/upper floors.
    - Where the plaster has been changed, attention should be given to the changed hygrothermal behaviour, shifted damage areas and potential material incompatibilities. That the original has already been lost does at the same time open up potential for replacement with thermally more performant plasters.
- The pitched roofs with wooden planking, joists and wooden beams with a circular section are often still the original ones with the ancient tiles as external cladding

- The U-value of ~ 2.3 W/m²K is in the case of the unused attic not relevant, as the attic floor will be the thermal envelope in those cases
  - If the typically as storage room used attic was transformed to living space, the roof is slightly insulated and shows a U-value of typically 0.55 W/m²K.
  - The insulation of the roof and use of the attic as living space is from conservation point of view seen as a viable option which can be implemented without too much interference on the heritage elements and has thus in various cases already been done, and will be considered as one of the use scenarios in HeriTACE
- Floors are typically composed of wooden floorboard resting on a framework of joists and main beams and do often have false ceiling made of reed and plaster. The cladding can be parquet, but also tiles, gres or simply screed in case of the attic floor.
  - The U-value ranges between 1.3 and 1.4 W/m²K with false ceiling, and is around 2.3 W/m²K if the woodwork is exposed.
  - The ceilings are often decorated, which will influence the options for internal insulation. For the attic floor insulation from top might just be preferred, is however not yet common practice.
- On the ground floor the wooden construction does rest on a masonry slab, often with a vault. This results in a U-value of around 0.8 to 0.9 W/m²K. Cellars are usually quite moist.
- Windows are originally two sash windows, with single glazing and horizontal bars – and U-values between 4.5 and 5 W/m²K. They have often already been replaced, since the sensibility and awareness for solutions which improve the windows thermal performance in a less invasive way (additional windows, replaced glazing in original frame, thin secondary glazing, …) is growing only in the last years and slowly. These replacement windows vary in their U-value form around 2.6 W/²K (double glazing, not yet IGU) to 1.5-1.8W/m²K. Whether no, part or all windows have been changed, and whether they were replaced with standard windows of that time or replica of the existing ones, depends on the protection status and the sensibility of the owner.
- Very characteristic for Italian townhouses are wooden shutters
  - Exterior shutters are found on practically all buildings. They reduce heat losses in winter (~30-50% better U-value in the case of single glazed windows, 10-25% if window is already well performing), but their main benefit is shading in summer while – in the case of the shutters with slats – allowing for daylight to enter and ventilation.
  - Interior shutters were found in three of the four case studies. They can be part of a wooden casing in the window reveal, but also just added directly on the window frame.
- From literature and the two measurements the air tightness is assumed to vary between 7.5 1/h for buildings with all original windows and 4.5 1/h if windows have already been replaced.
- Moisture safety evaluations will be done on the basis of dynamic simulations – also because a preliminary analysis of f_{Rsi} and climate shows, that in Mantova the warm season might give potentially critical situations and that however both approaches in EN 13788 have limitations in their models, with the continental model underestimating the interior moisture load, and the maritime model underestimating interior temperature in the not heated season.

Conclusions

There is distinction between front and back facades of the buildings in Belgium, Italy and Norway – front façades typically have high heritage value and past and future retrofit efforts could be targeted at the back façade, where more effective measures could be applied. Other less visible areas such as attic floors and basement ceilings have often already undergone such modifications.

The results highlight that isolated interventions are often not enough to overcome inherent shortcomings the historic building envelopes have (e.g. low airtightness of wooden walls, moisture and thermal issues with masonry walls).

Thermography and thermal modelling indicated hygric risks based on low temperature factors (f_{Rsi}) on existing Belgian, Estonian and Italian envelope details – this could be followed up using more detailed hygrothermal modelling which also takes hygrothermal buffering and actual climate conditions into account.

The need for retrofit solutions for masonry and timber walls in the Nordic regions is evident (both according to measurements, modelling and interviews with the inhabitants) and is something that tasks T2.3 and T2.4 have set out to develop. These measures could be essential for achieving the 60% energy reduction target that is set as an objective of the project.

The studied archetypes are rather leaky – especially the ones with wooden walls. So much so that the low airtightness has been the basis ventilation. However, good airtightness is required for heat recovery of modern air handling systems to be effective. At the same time, ventilation is required for mitigating hygric risks in envelope components if airtightness is improved. This is an example of how intertwined different building components are and how the retrofit scenarios need to be holistically designed and materialized.

Due to high occupancy, the indoor air humidity loads in Estonia are high enough to be risky for both wooden walls with interior insulation and masonry walls without insulation. While loads elsewhere were currently not as high, it might serve as a cautionary tale if townhouses are converted for multi-family use.

The baseline scenarios were compiled to describe the building components of Belgian, Norwegian, Estonian and Italian archetypes for building energy modelling. While done separately for each country, this resulted in surprisingly similar envelope component characteristics between the countries – despite being in different climatic zones. Pre EPBD scenarios (1990s–2000s) generally described the envelopes in their thermally unaltered state (beside occasional window upgrade). Masonry walls had thermal transmittance $U \approx 1$–2 W/(m²·K), wooden walls 0.5–1.2 W/(m²·K) and top and bottom boundaries 0.5–1 W/(m²·K). Windows were either single ($U_w \approx 6$ W/(m²·K)) or double glazed ($U_w \approx 3$ W/(m²·K)). In renovation scenarios (i.e. if retrofit was done today) the thermal transmittances of insulated walls, top and bottom boundaries were in the range of 0.2–0.4 W/(m²·K) and those of windows in the range of 0.85–1.5 W/(m²·K). Of course, the share of envelope where these measures can be applied is bound by specific local conditions.

1. Introduction

The ambitions of the European Union (EU) are substantial: to achieve climate neutrality by 2050. The European Green Deal and the New European Bauhaus aim to achieve a sustainable and inclusive society through transdisciplinary collaboration and innovation. The necessity and value of sustainable use and transformation of existing built environment has been emphasized in research for a long time (Fufa et al., 2021). However, one of the most significant challenges in this transition will be the renovation wave of our housing stock, which accounts for 27% of the final energy use of the EU (Eurostat, 2022). Historic cities in Europe present an additional challenge. It is evident that the historically valuable buildings in these cities must be preserved while respecting and considering the inherent heritage and societal values. However, it is unclear how we can balance the aspirations on heritage conservation on individual units with the overarching ambition for climate neutrality at the building stock level. More specifically, there is a need for a framework to assess these different aspects at building or neighbourhood level and offer insights and solutions to address this challenge.

The HeriTACE project investigates how we can future proof our heritage buildings in a manner that bridges the gap between heritage restrictions and environmental ambitions. The project focuses specifically on small to medium-sized heritage townhouses pre-dating 1945. Achieving the ambitious goal of climate-neutrality requires a transdisciplinary team to consider all aspects of renovation: heritage value, energy use, user comfort, functionality, cost-effectiveness, and waste management. Heritage restrictions often preclude generic solutions, necessitating innovative approaches to insulation, heating, ventilation, and heat/cold generation.

The aim of this deliverable is to gather background information (envelope characteristics, condition, damage mechanisms) for building energy simulations and inform tasks developing the retrofitting scenarios about the requirements, possibilities and constraints of the envelopes of the archetypical buildings forming the case study neighbourhoods targeted within this project.

This deliverable should be considered in combination with the description of the building archetypes, case study buildings and case study neighbourhoods (deliverable D5.1), indoor air quality measurements (deliverable D3.2), R2ES situation (deliverable D4.1), heritage aspects (D5.2) and users/owners' perspectives (D5.3) to achieve a holistic overview of the existing conditions and baseline scenarios (summarized in D5.4) for the building archetypes targeted in HeriTACE. These results will be used in combination with energy and space conditioning scenarios for building energy modelling in tasks T3.2.2 and T3.5.

The results are presented in this deliverable on several levels:

- Description of the main damage mechanisms affecting the envelopes of targeted buildings.
- Country-specific sections contain:
    - A brief introduction to the targeted building archetypes and the scope of studies.
    - Description and characteristics of individual envelope components.
    - Overview of the technical state of the envelopes, specific aspects of airtightness testing and assessment of thermal bridges.

- Summarized main characteristics of the envelopes on case study building level.
- The archetype building envelope scenarios for two time points: a) before the introduction of EPBD (1990s-2000s state) and b) if they would be renovated today.

2. Methods

To achieve an overview of characteristics and condition of the targeted envelopes, in-situ studies were performed to augment the literature and numerical analysis. The methods of the in-situ studies (envelope condition, airtightness, thermography and thermal transmittance) are described in the following subsections and the targeted buildings/archetypes under the subsequent country-specific sections.

2.1 Envelope condition assessment

The visual assessment of the condition of the buildings was based on EN 16096. The buildings were visited by experts of the consortium and parts of the envelope were assessed by non-destructive means separately. Photographs were taken to document the situation. The findings were classified according to condition (Table 2-1), urgency (Table 2-2) and overall recommendation classes (Table 2-3). An example of the condition classes of the paint layer is given on Figure 2-1.

Table 2-1: Classification of component condition.

Condition class	Symptoms
CC 0	No symptoms
CC 1	Minor symptoms
CC 2	Moderately strong symptoms
CC 3	Major symptoms

Table 2-2: Classification of urgency of amelioration works.

Urgency class	Urgency
UC 0	Long term (ca 10 years)
UC 1	Intermediate term (ca 5 years)
UC 2	Short term (ca 2 years)
UC 3	Urgent and immediate

Table 2-3: Overall classification of recommendations

Recommendation class	Possible measures
RC 0	No measures
RC 1	Maintenance/Preventive conservation
RC 2	Moderate repair and/or further investigation
RC 3	Major intervention based on diagnosis

CC1: minor symptoms — CC2: moderately strong symptoms — CC3: major symptoms

Figure 2-1: An example of condition classification of exterior paint.

The results were compiled by case study building to separate spreadsheets detailing the condition and properties of the envelope components. Summarized versions of these sheets are given under the chapters of respective countries. There they also form the basis for the envelope component sheets.

2.2 Airtightness measurement

The airtightness of building envelope was measured according to EN ISO 9972. The test device was installed in the opening of the apartment's exterior door or building's exterior door. The device consisted of an adjustable frame, an airtight fabric panel, a fan, and associated measurement and control equipment. The fan generated a pressure difference between the indoor and outdoor environments. During the test, the airflow required to maintain the specified pressure difference was measured. This airflow, which passed through the fan, was equal to the amount of air leaking into the apartment through the building envelope and cracks.

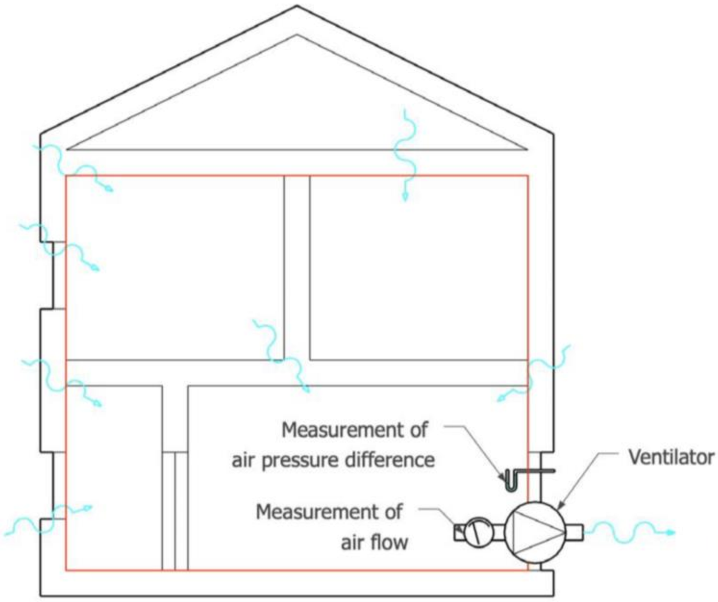
Air leakage was measured under both depressurisation and pressurisation conditions, in increments of ~10 Pa, within the range of ±10 to ±80 Pa. From the trend line of airflow versus pressure for both depressurisation and pressurisation measurements, the leakage airflow at 50 Pa was determined and averaged. Before and after the test, the natural pressure difference between indoors and outdoors as well as the indoor and outdoor air temperatures were recorded, and the results were corrected accordingly.

To ensure that only the leakage through the building envelope was measured, all externally closable openings (windows and doors) were kept closed in their normal position, and air inlets and ventilation ducts were sealed with tape. Internal doors were left open, and it was verified that all plumbing traps contained water.

The airtightness of the building envelope is characterized by the air leakage rate at 50 Pa, q_{50} (in $m^3/(h \cdot m^2)$), which indicates the airflow rate (m^3/h) through 1 m^2 of envelope area at a pressure difference of 50 Pa. Since airtightness cannot be measured separately for each component of the envelope under real conditions, the test measured the total air leakage of the apartment or of the building, expressed as an average leakage over all envelope surfaces.

Additionally, airtightness was characterized using the air change rate at 50 Pa, n_{50} (in 1/h), which expresses how many times the air volume of the apartment or building is replaced per hour under a 50 Pa pressure difference. Both q_{E50} and n_{50} are derived from the same measurement method. When expressed as q_{E50}, the measured leakage airflow at 50 Pa is divided by the total internal surface area of the apartment or building envelope (including floors and walls). When expressed as n_{50}, the same airflow is divided by the internal volume of the apartment or building.

The measurement can also be further augmented to find the air leakage areas by using thermography, smoke or sensing air flows using e.g. hands.



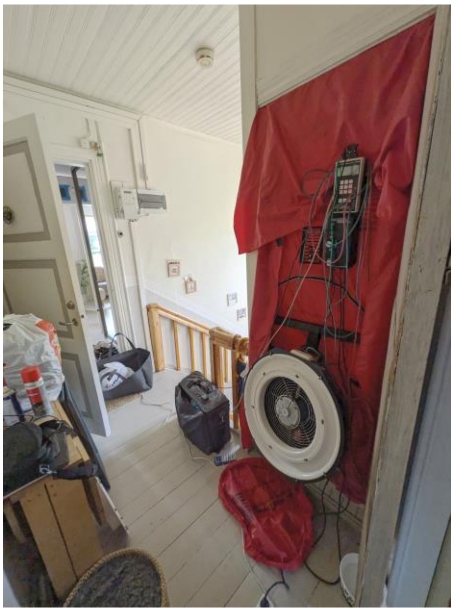


Figure 2-2: Measurement of building envelope airtightness using pressurization and depressurization tests according to EN ISO 9972 (left, schematic by Hallik 2022), measurement device in use (right, photo by Paul Klõšeiko).

2.3 Thermal transmittance

2.3.1 Measurement of thermal transmittance (heat flow meter method)

The thermal transmittance (U-value) of the envelope is measured by recording the heat flux and temperature on both sides of the element under consideration and dividing the heat flux by temperature difference. While this is straightforward under steady state conditions, the envelope of a real building is bound by constantly changing temperature, thermal radiation, etc. Furthermore, thermal mass of the component buffers the effects of these factors – all in all, instantaneous measurement values do not usually reflect the true properties of the component. ISO 9869-1:2014 gives guidelines to overcome this. The recommended approach is sufficiently long measurement period (typically a minimum of 72h) with stable conditions and minimum effect of solar radiation. After averaging over the reliable measurement period and verifying the stability, the thermal transmittance of the component can be estimated.

The devices used for measurement in this study are presented in Table 2-4. The heat flux sensors were mounted on the interior surface of the studied component with tape; thermal paste was used as couplant. Temperature sensors measured the air temperature close to the interior and exterior surfaces. If a thermally inhomogeneous component (e.g. interior insulation between studs) was measured, several heat flux sensors were used (on studs and on insulation section) and measurement results were used to calibrate a numerical thermal model from which the final thermal transmittance was taken.

Table 2-4: Devices used for thermal transmittance measurement.

	Heat flux sensors	Temperature sensors	Data acquisition
Belgium	GreenTEG gSKIN® Heat Flux Sensor	GreenTEG gSKIN® DLOG Data Logger with 2 temperature sensors	
Estonia	Hukseflux HFP01	Pt1000	Grant Squirrel SQ2020 1F8
Italy	Ahlborn Almemo Heat flow plate FQA018C (120x120[mm]) and FQA019C (250x250[mm])	Ahlborn Almemo Thermocouples Cu-CuNi Type T	Ahlborn Datalogger Almemo 2590-and 2690

2.3.2 Calculated thermal transmittance

Calculation of the thermal transmittance is based on the presumption that thermal transfer inside the building envelope components (beside windows) can be characterized by thermal conductivity of the materials and that the radiative and convective heat exchange inside the material can be accounted for by that measured parameter. Then, the thermal transmission inside the structure can be calculated based on the Fourier's law:

$$q = -\lambda \nabla T$$

Where:

q – heat flux density, W/m²

λ – thermal conductivity of the material, W/(m·K)

∇T – temperature gradient, K/m

EN ISO 6946 gives the general methodology for calculating the thermal transmittance of 1-dimensional structures and simplified approaches to account for some special effects (air cavities, inhomogeneous structures that comply with certain conditions, etc). Presuming that the properties remain constant throughout the thickness of material layer, the structure is divided into homogenous elements (layers) and for every layer the thermal resistance is found:

$$R = d/\lambda$$

Where:

R – thermal resistance of a layer, m²·K/W

d – thickness of the layer, m

The thermal transmittance is then found:

$$U = \frac{1}{R_{si} + R_1 + R_2 + \cdots + R_n + R_{se}}$$

Where:

R_{si} – thermal resistance of the interior surface, m²·K/W

R_1, R_2,…, R_n – thermal resistance of every layer, m²·K/W

R_{se} – thermal resistance of the exterior surface, m²·K/W

For more complex structures (e.g. envelope details, structures where inhomogeneity is caused by thermally significantly different materials) the numerical approach according to EN ISO 10211:2017 is used. Instead of analytically solving the equations, the structure is divided into a mesh, where temperature and heat flux is iteratively calculated for every element of the mesh until a certain degree of accuracy is reached. These models are also used to find the temperature factors and linear thermal transmittances of the envelope details.

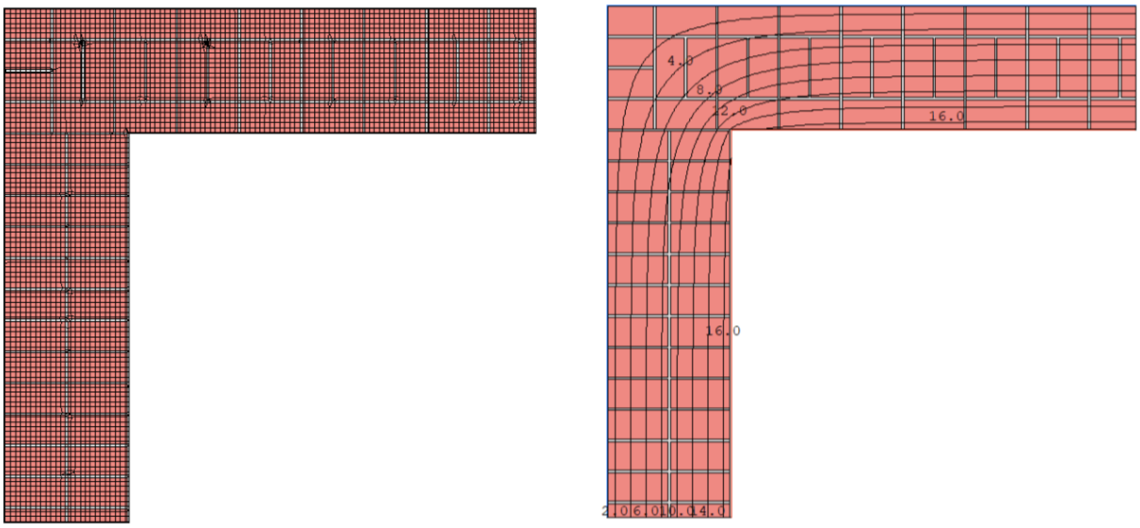


Figure 2-3: An example of numerical thermal modelling of a corner detail in LBNL Therm 7.8: numerical mesh (left) and results presented as isotherms (right).

3. Damage mechanisms

This section lists the prevalent damage mechanisms that were detected during the envelope condition assessment of the case study buildings and neighbourhoods. The subsections describe the nature of the phenomena, their causes and general methods to avoid and ameliorate the situation. The more specific circumstances and envelope components they occur on are described under subsequent sections of Belgium, Norway, Estonia and Italy.

3.1 Frost

Frost damage is a well-known issue affecting porous external façade materials such as natural stone, lime and cement mortars, and facade plasters. It results from the expansion of volume during the phase transition of water to ice. This damage mechanism has been recognized for decades, particularly in relation to natural stone (Schaffer, 1932). The process begins when moisture penetrates the material (often due to wind-driven rain) and subsequently freezes. As water turns into ice, it expands and creates internal stress in the material. Over time, with repeated freeze-thaw cycles, this can lead to cracking, flaking, or delamination of the material.

Figure 3-1: Left: frost damage in the plinth area of a brick wall. The bricks lack adequate frost resistance, making them unsuitable for use in plinth areas exposed to freeze–thaw cycles in cold climates (photo: Targo Kalamees). Right: damaged water flashing on top of plinth has led to frost damage of underlying lime-sand bricks and plaster below (photo: Paul Klõšeiko).

Frost damage mechanisms must be taken into account, particularly in regions with cold winters and fluctuating temperatures around freezing. The risk increases with a higher degree of saturation and lower temperatures (Feng et al., 2019). Freeze damage requires special attention during renovation works. For instance, in older buildings, internal heat loss through the walls was inadvertently warming also the facade. After retrofitting with internal insulation, the heat flux through the wall is reduced, resulting in colder exterior surfaces and a potentially higher risk of frost damage.

To limit frost damage, three main strategies can be applied. First, exposure to wind-driven rain can be minimized by incorporating longer roof overhangs and installing effective rainwater management systems etc. The second option is to improve the material properties on the external surface. This could be done by applying hydrophobic agents or paint to the facade surface. The third option is to improve the material itself. For example, the addition of pozzolanic materials to lime mortars has been shown to enhance frost resistance (Janotová et al., 2023).

Ongoing maintenance also plays a key role in the prevention of freezing damage. Small cracks should be sealed promptly to prevent further water ingress, and rainwater systems should be cleaned regularly to avoid overflow or water spilling onto the facade.

3.2 Salt efflorescence

Salt efflorescence is a deterioration phenomenon that affects natural stone as well as masonry walls and facades. It manifests as crystalline deposition on the surface of walls, typically white in colour. This occurs when water containing dissolved salts migrates through the material and evaporates at the surface, leaving the salt behind. Over time, repeated crystallisation of these salts can lead to both visual staining and physical degradation of the stone.

Figure 3-2: salt efflorescence appearing on damp areas of a masonry wall finished with cement-lime plaster after renovation (left). The moisture source was precipitation that infiltrated the masonry cavities during the renovation process. Drying was accelerated using localised heating to halt further salt migration (right). Photos by Martin Talvik.

The underlying mechanism begins with moisture ingress, often caused by precipitation, rising damp from the ground, or condensation. Water dissolves salts either naturally present in the material or introduced from external sources. As the solution moves towards the surface and evaporates, the salts crystallise. For massive masonry walls, a general rule of thumb is that in cold climates, salt efflorescence is more likely to occur on the internal surface of the wall, while in hot climates, it tends to appear on the external side.

Although efflorescence is most commonly associated with porous stones, it is not exclusive to them. Even granite walls can display surface deposits when salts migrate through adjacent, more absorbent components like mortar joints or cracks in the stone itself. In such cases, more localised crystallisation is typically observed along mortar lines.

Effective mitigation of salt efflorescence hinges on moisture control. Buildings should be equipped with proper rainwater management systems and drainage. For underground structures, waterproofing membranes are essential. In the case of historic mass walls, horizontal damp-proofing can be introduced during renovation by either removing and reinstating sections of the wall or by injecting waterproofing agents into the wall at plinth level.

During the first years after renovation, salts may migrate to the surface even if the source problem has been resolved. The process should then be waited out while cleaning the salts regularly. Internal paints with high water vapour diffusion resistance should be avoided on historic walls, as they trap moisture and worsen the issue.

The methodology for predicting salt crystallisation through testing and modelling remains an evolving field of research (Lubelli et al., 2018). Nonetheless, there is widespread agreement that salt-induced deterioration must be considered during the design and renovation of buildings.

3.3 Mould growth

Mould growth is a common moisture-related problem in historic Norwegian wooden buildings, particularly affecting interiors during periods of high humidity. It typically appears on organic surfaces such as wooden walls, ceilings, or furnishings, as well as on finishes like paint or wallpaper. Mould spores are always present in the air but require specific conditions to grow: RH above 75–80% for extended periods, surface temperatures above the dew point, and a suitable organic material. In older wooden buildings, poor ventilation, leaking roofs, or inappropriate insulation and air-tightening measures often contribute to moisture accumulation and mould growth. The consequences range from superficial staining and odours to degradation of materials and health issues for occupants. Mould is particularly problematic in under-ventilated attics or behind retrofitted insulation layers. A typical cause is insufficient drying of the building envelope before applying interior insulation, which traps moisture and allows mould to grow unseen behind the surface, potentially requiring costly remediation and material replacement. Another typical example is mould growth on the underside of roof boards in unheated attics, caused by warm, humid indoor air leaking into the attic during winter. When the moist air condenses on cold wooden surfaces, it creates ideal conditions for mould to develop, especially if ventilation is insufficient. Over time, this can lead to persistent odour problems and discolouration, and may require cleaning or even replacement of affected materials. (SINTEF 701.401, 2005)

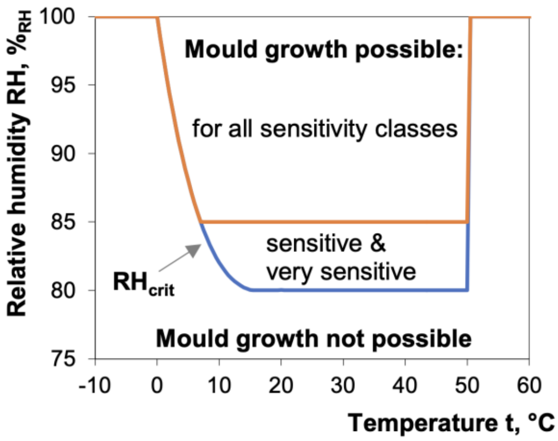


Figure 3-3: Left: favourable conditions for mould growth based on Viitanen et al. (2011). Right: mould growth on interior surface (a window-wall-ceiling-partition wall intersection of a masonry wall; schematic & photo: Paul Klõšeiko).

3.4 Wood rot

Wood rot, or fungal decay, is a serious deterioration mechanism in historic Norwegian timber buildings. It primarily affects structural and load-bearing wooden elements exposed to prolonged moisture, especially in ground-contact zones, around windows, and in poorly maintained roof or gutter areas. The decay fungi responsible for wood rot require wood moisture content typically above 20–25%, oxygen, and moderate temperatures. If these conditions persist, the fungi can digest cellulose and lignin, leading to significant loss of strength. Wood rot is far more destructive than mould and can compromise the safety and usability of heritage structures. To prevent wood rot, proper drainage, ventilation, and maintenance of exterior elements are critical. Preserving traditional construction details, such as raised foundations and wide roof overhangs, also helps limit water ingress. A common cause is splashwater or capillary moisture at the base of exterior walls, where lack of proper drainage or failure of protective cladding leads to hidden decay in sill beams or floor structures—damage that often remains unnoticed until it becomes structurally critical.

Figure 3-4: Left: rot damage at the notch joints in a log wall (photo: Sverre Holøs, SINTEF 720.082, 2007). Right: rot damage of logs behind ventilated cladding, caused by faulty flashings (photo: Paul Klõšeiko).

3.5 Rust/corrosion

Corrosion is a deterioration mechanism that can be present in metal components in heritage buildings. Examples of such metal elements are the ornamented structures of the balcony, often made out of cast iron or wrought iron, steel beams in vaults (and in some cases also wall anchors).

Corrosion is an electrochemical reaction between a metal, oxygen and water (in all its forms). The metal oxidates under the influence of oxygen and forms a new material layer, a metal hydroxide, also called rust. Moisture is needed for the transport of electrons and ions that take place during the oxidation reaction. The forming of this new rest product rust, causes an increase in the volume that increases the pressure on the surrounding materials. This can cause cracking and spalling in these materials, which influence the structural strength. At the same time, the corrosion reaction reduces the amount of metal in the original material, which can also impact the structural stability of the metal elements.

Corrosion is always induced by the presence of moisture. These metal elements can easily be in contact with moisture, as rain, condensation or capillary rise are frequently present in these heritage buildings. Certain salts, present in the building materials or in the surroundings (certainly in maritime or urban areas) can accelerate the corrosion process.

In the heritage context, special attention to the corrosion risk is needed, because these metal elements are most of the time very typical and valuable for the architectural style. Additionally, repairing them without endangering the stability or impacting the authenticity is very difficult. Consequently, prevention is an important strategy, by controlling presence the moisture, inspection and maintenance and the application of reversible protection coatings.

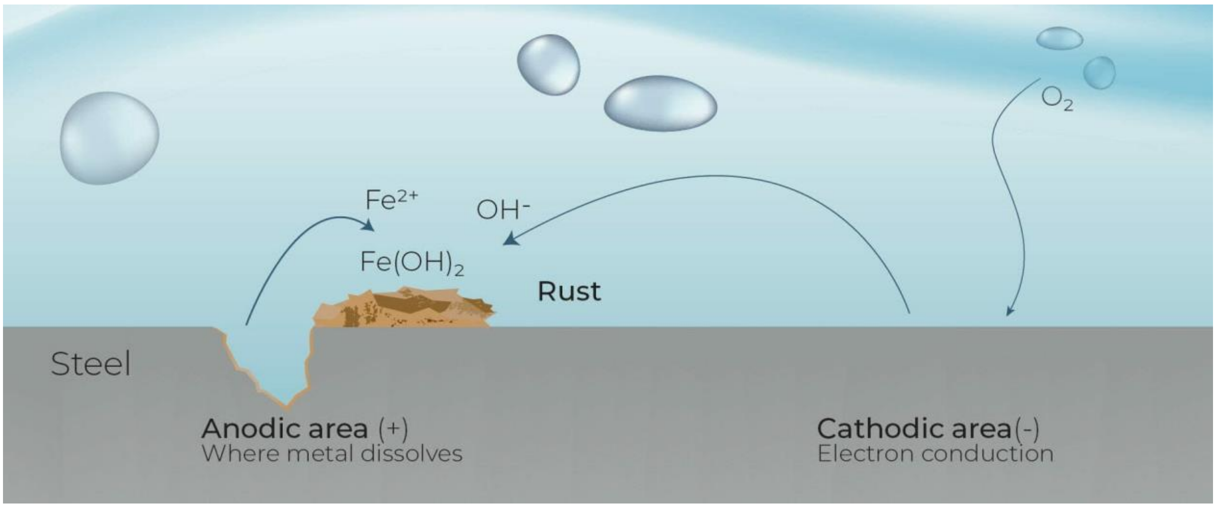


Figure 3-5: Illustration of the corrosion mechanism (Cathwell, 2023).

3.6 Ambient strain

3.6.1 Shrinkage-swelling

Hygroscopic materials such as wood absorb and release moisture depending on the surrounding relative humidity. Associated with this change in moisture content is also a change in size: they swell with increasing moisture content and shrink when it decreases.

For wood the amount of shrinking and swelling depends also on the direction of the grain: Tangential shrinkage (along the growth rings) is the greatest, followed by radial shrinkage (across the growth rings), with longitudinal shrinkage (along the grain) being minimal. This can affect the structural integrity of wooden components, particularly where different pieces are joined, and in can lead to deformations, e.g. of window frames, which will be difficult to close and leave gaps for infiltration of air.

Furthermore, especially with massive wooden elements, a fast change of the moisture will lead to fast drying – and shrinkage – of the outermost layers, while the inner parts will still be moist and swollen. This results in cracks in the outermost layer.

Similar, if the wood is decorated, the paint layer, gesso, putty or whatever will not swell and shrink to the same extent as the wood underneath. This causes those layers to be continuously compressed and stretched until they finally crack and flake. Through this crack, humidity can reach more easily the wood and a vicious cycle has started.

3.6.2 UV damage

Ultraviolet (UV) radiation causes degradation of various building materials through a process called photo-oxidation, where the photons with high energy intensity act on the bonding – leading to specific damage patterns in different materials. Most susceptible are organic materials like wood and plastic/polymers.

In wood the photo-oxidation process induced by the UV light breaks down the lignin, a key component for its strength and stability. This leads to discolouring, the surface fading and turning grey, but also to increased roughness of the surface, which means that the wood will be more susceptible to moisture absorption. Furthermore, the loss of strength can also lead to cracking, warping and easier failing under stress.

UV exposure does also cause paints and coatings to fade, crack and lose their protective properties. This can lead to the deterioration of the underlying materials (which is prevented by regular re-painting).

Plastics too become brittle, crack, and lose their colour with UV radiation. This is particularly true for polymers which are commonly used in roofing membranes, window frames, and other building components – which might not have been part of a historic building from the beginning but have been added over time.

Masonry and stucco themselves are rather unaffected by UV radiation, but they can contain polymers which themselves can degrade with UV.

Figure 3-6: Sealant is damaged by UV radiation and differential deformations (left). Shrinkage and swelling of the wooden window frame has contributed to degradation of the paint layer (right). Photos: Paul Klõšeiko.

3.7 Soiling of facades

3.7.1 Algae growth

Algae and cyanobacteria are micro-organisms able to create a biofouling film covering building surfaces. All materials that do absorb and store water are concerned, since free water availability is besides temperature, the main factor favouring algae growth. The main causes for wetting of facades are (i) wind driven rain, (ii) leaks for water drainage systems and (iii) dew water.

With (i) wind driven rain actually two factors play together: the water and the biological contaminants brought to the surface with the wind. Furthermore, roughness of the surface comes in here as it favours the adhesion of organic materials and affects the flow of water on the surface. Finally, also a slight inclination of the wall can notably increase the surface exposed to water. Spatially limited causes as cracks in the surface allowing for more water to be absorbed locally or leaks (ii) might form the starting point, run-off water can then however advance the spread of algae to further areas not already contaminated.

Figure 3-7: Examples of algae growth on external walls: (left two) façades exposed to wind driven rain; (right two) fed by drain water from windows overhangs
(Blumberga and de Place Hansen, 2020 and https://www.ribuild.eu/algae-growth)

The above mentioned third source of moisture, (iii) dew water forming on a wall when in a bright night long wave radiation from the wall to the clear sky causes the temperature to drop below air temperature is less frequent in historic buildings, which are typically characterised by high thermal mass so that the temperature does not decrease too much. It is more typical for facades with light weight exterior insulation, where actually patterns due to difference in surface temperature may occur.

Since the time of wetness is important, shaded facades are more at risk for fast algae growth, while sun radiation leads to evaporation and drying and thus less favourable conditions. However, drying of facades during the day might not be enough, since algae can survive dry periods and restart their growth when enough water is available.

In addition to unsightly discoloration and aesthetic deterioration, algae can even compromise the durability of materials: While they don't structurally damage buildings directly, they do favour the growth of mould, lichens, fungi and other microorganisms and lead to mechanical stress, loosen material grains especially on stone surfaces.

Remedial actions can be both mechanical (removing stains and patina from contaminated elements either by hand or with tools) or physical treating the surface with ultraviolet (UV) radiation. Biocides are also often used in practice, either as a main or accompanying measure, but do have severe drawbacks in terms of leaking out and accumulating in soil and water.

3.7.2 Accumulation of dust

As regards the accumulation of dust, three aspects play together: (i) Which and how many particles are there? (ii) How easily are they deposited on the surface? And finally (iii) how well do they stick or formulate the other way round how difficult is resuspension?

As regards (i), the amount of particulate matter in the air, there is reason for hope. While already in 2007 Grossi and Brimblecombe argued that there was a shift from high levels of sulphate deposition from coal and oil burning to blackening process dominated by diesel soot and nitrogen from vehicular sources, climate mitigation measures will help also in this regard: reducing energy need in buildings and shifting it to not-fossil as well as reducing traffic and bringing it to electric will reduce soot and other particulate matter in the air – in cities and hopefully also beyond.

As regards (ii) the deposition of particles on surfaces again several factors play a role: on the one hand side in areas where there is a turbulent air flow near the surface, more particles will deposit – leading e.g. to pattern behind corners, but also due to microturbulences next to cracks. Thermophoresis will drive particles towards a surface which is colder than the air. And, especially for larger particles, gravity plays an important role: already slightly inclined surfaces are well exposed to dust accumulation.

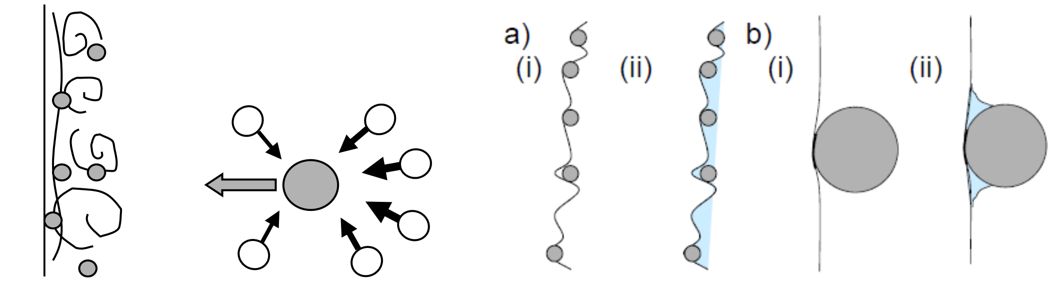
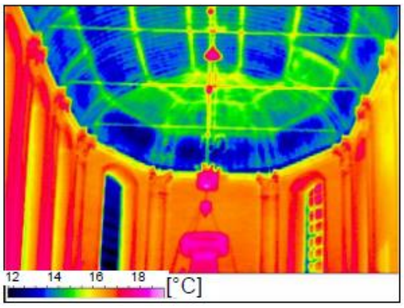


Figure 3-8: deposition and adherence mechanisms.

Finally, as regards (iii) resuspension of particles: small particles will adhere well to rough surfaces, larger particles adhere better to smooth surfaces (especially if they are slightly compressed upon impact or indent the substrate e.g., wax, so that the contact area becomes larger and the van der Waals forces become stronger). And in both cases, even a minimal film of water on the surface causes the particles to be partially enveloped and held particularly efficiently due to the adhesion and surface tension of the water. This leads to soiling pattern depending on the surface temperature (and related condensation) – which might make substructures visible.



St. Gerlachus in Houthem, in [Schellen 2002]

Figure 3-9: More soiling on colder surface makes the otherwise hidden substructure visible

4. Belgium

Authors: Luca Maton (UGent), Veerle Vercauteren (GENT), Wolf Bracke (UGent), Nathan Van Den Bossche (UGent), Arnold Janssens (UGent)

In Belgium the typology of the heritage masonry terraced townhouses, built between 1800 and 1918, is studied. During this period of industrialisation, historical cities in Belgium and other major EU cities, experienced a colossal growth and the bourgeois society emerged. The townhouses reflect the evolving social landscape of this bourgeois society. They were shaped by the desires for individuality and social status, leading to distinct architectural forms, especially in their facades, which became key to personal expression and were thus highly ornamented. Other common features among all the typologies include vertical organization and a clear hierarchy of spaces, arranged as an enfilade perpendicular to the street and on top of each other. The **middle-class townhouse** is most prevalent in all

Belgian historical cities and certainly in Ghent. Wealthier homes, the **private mansions**, present an excess of rooms, more elaborate spatial divisions and more decorated facades and interiors. **Multi-family townhouses**, although less prevalent in Ghent, are common in bigger cities like Antwerp and Brussels, where they maintained the hierarchical structure of middle-class living but with a horizontal organization, reflecting a shift from verticality to internal differentiation. In contrast, **modest houses** represented a simplified version of middle-class townhouses, with fewer rooms and less complexity, tailored for the upper working class. The neighbourhood, archetype and case study building selection is further detailed in 'D5.1 Case-study selection at building and neighbourhood levels.

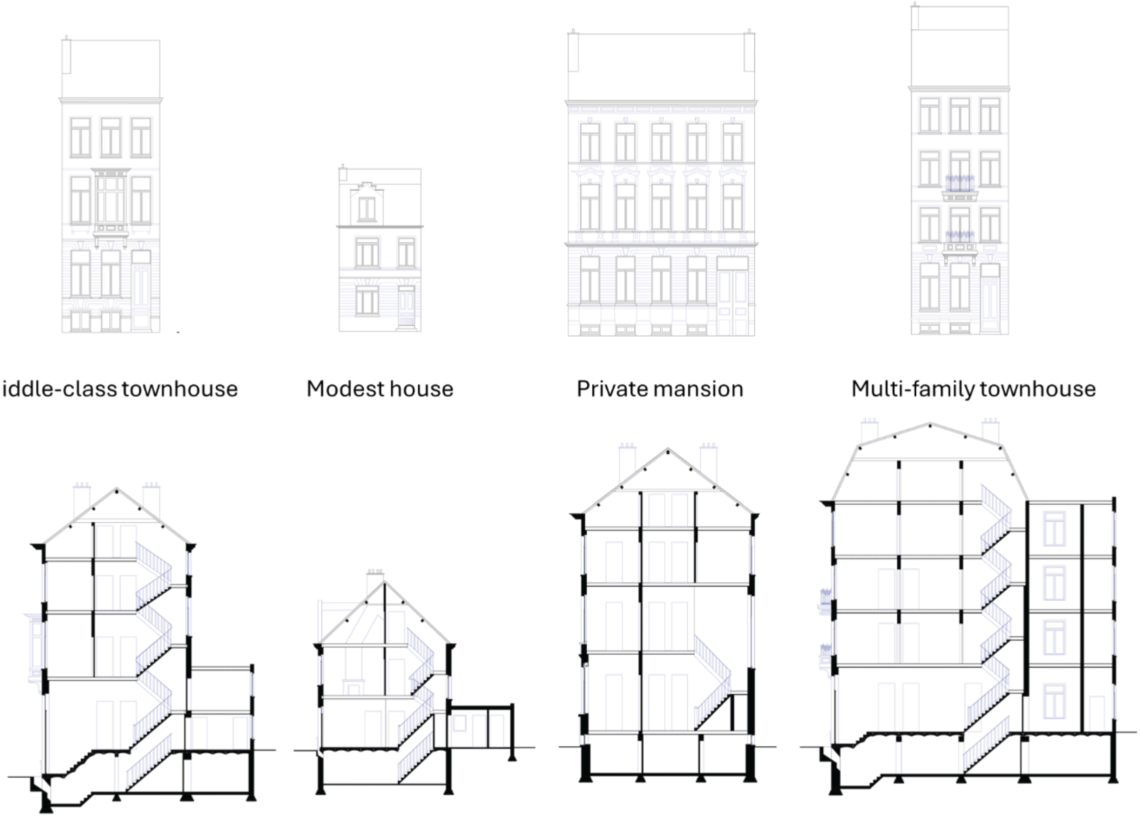


Figure 4-1: Overview of the Belgian townhouse archetypes by facade and section.

In Belgium, 14 case studies were examined in the city centre of Ghent during January and February 2025. This investigation was conducted as part of the current task T2.1, alongside related tasks focusing on the case studies in other WP, namely T3.1, T4.1 and T5.1. The aim was to include a representative sample of the various building archetypes. Ultimately, nine of the case studies concern middle-class townhouses (as this in in practice also the most prevalent archetype), three are classified as private mansions, and two represent modest houses. The multi-family townhouse was not included, as this archetype is relatively uncommon in Ghent. However, its building envelope characteristics are largely comparable to those of the middle-class townhouse.

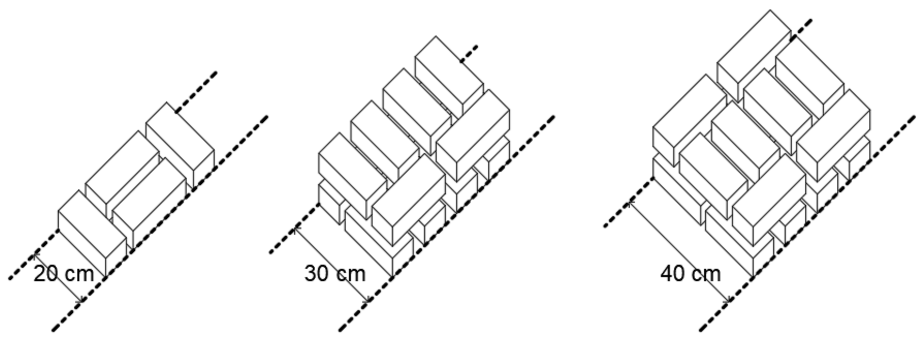
A range of investigations was carried out across the different case studies. In nearly all cases, a technical inventory was compiled, documenting the typical building envelope elements, their surface areas, and construction build-ups. In addition, a heritage expert assessed the technical condition of the elements. In situ measurements of thermal resistance were conducted in as many dwellings as time and equipment availability allowed, with particular attention given to measuring the front façade, and where possible, an additional rear façade or party wall. Finally, air tightness measurements were performed on all 14 case study buildings using the fan pressurization method.

4.1 Envelope characteristics

4.1.1 Walls

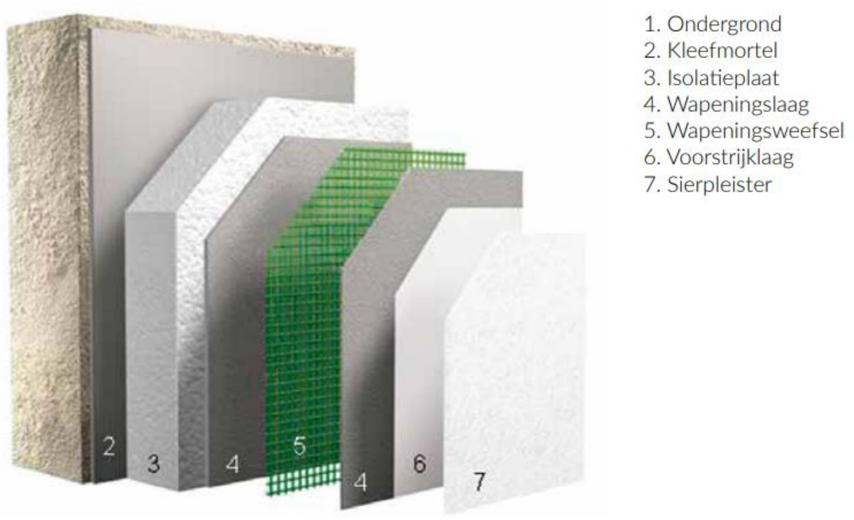
4.1.1.1 Massive masonry walls

Description	Belgian 19th century townhouses were constructed using solid masonry walls. This was the case for the front façade, the back façade, the internal walls, the party walls and the walls of the annex. The thickness of these walls was dependant on the function of the walls (whether it is a bearing wall or not), the façade construction (solid or with a facing stone), the location in the building (front façade, back façade or annex), the location in the façade (when the façade is tapering upwards) and the archetype. For the middle-class townhouse, the multi-family townhouse and the private mansion, the front façade consists of a double brick *masonry* wall on the ground floor, that narrows to a one a half brick wall on the higher floors. The back façade is a one and a half brick masonry wall and the façade of the annex (only for the middle-class townhouse) a one brick masonry wall. The facades of the modest house are all one and a half brick masonry walls, while the annex is again a one brick masonry wall. Interior load-bearing walls could be one brick or one and a half brick masonry walls, while non-load-bearing walls could be thinner, only a half brick wall. As the party walls could be load-bearing or non-load-bearing walls, they could be a one brick or half brick masonry wall as well. During the 19th century, the masonry walls were built using local bricks, predominantly hand-moulded bricks (*handvormsteen)* and extruded bricks (*strengpersteen)* that were the result of mechanized industrial processes (Calle, 2020). Lime mortar was used as masonry and joint mortar until it was gradually replaced by a mix of lime and cement at the end of the 19th century and then by a pure cement mortar during the 20th century (Le Noir, 2017). The brick façades were finished on the inside with a layer of lime plaster. The exterior was also often finished with a painted, smooth lime plaster, applied in several layers and provided with decorative forms such as profiled frames or imitation bands. Around the turn of the century and at the beginning of the 20th century, a plaster was sometimes applied that imitated sand-lime brick or bluestone due to its colour, composition and imitation joints. This could be used for an entire façade or for façade components. In the same period, it was customary to provide a façade with a facing in decorative bricks, whether or not in different colours. The most lavish facades were often finished with a parament and details in natural stone. In this construction period, a façade was always provided with a natural stone plinth, which could extend to the windowsills of the ground floor. This plinth often consisted of a carved bluestone slab that was attached to the brick. At the beginning of the 20th century, plinths were also frequently made of quarry stone with irregular shapes. Window sills, continuous drip sills or constructive elements such as balcony floors or consoles were also always made of natural stone.

<table>
<tr><td>Typical condition</td><td>Typically RC0: good, may need maintenance in 10 years.
Front facades are generally in good condition, largely because they are highly visible from the street and therefore receive regular maintenance and are often recently renovated. In contrast, rear facades and annexes typically receive much less attention, which can result in poorer overall condition. Structurally, however, all these walls remain sound, due in part to the durable nature of the solid masonry construction.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Common degradation mechanisms affecting solid brick masonry walls include salt efflorescence originating from the bricks, as well as flaking of plaster and/or paint layers on facades due to cyclical expansion and contraction, and solar exposure. In addition, plastered finishes may become dirty as a result of urban pollution.
Mould growth and condensation on the interior surface are relatively rare, primarily due to the thickness of the solid masonry, which buffers temperature fluctuations from the outside. Furthermore, the lime plaster layer contributes additional moisture buffering capacity, contributing to the mitigation of mould growth. Damage as a consequence of freeze-thaw cycles is not observed but will be an important concern when insulating these masonry walls from the interior side.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th colspan="2">Plaster finish</th><th colspan="2">Masonry finish</th><th colspan="2">Plinth</th></tr>
<tr><td>Material</td><td>Thickness [m]</td><td>Material</td><td>Thicknes s [m]</td><td>Material</td><td>Thicknes s [m]</td></tr>
<tr><td>Interior</td><td></td><td>Interior</td><td></td><td>Interior</td><td></td></tr>
<tr><td>Lime plaster</td><td>0.02</td><td>Lime plaster</td><td>0.02</td><td>Lime plaster</td><td>0.02</td></tr>
<tr><td>Masonry + Lime mortar</td><td>0.155… 0.355</td><td>Masonry + Lime mortar</td><td>0.28... 0.38</td><td>Masonry + Lime mortar</td><td>0.28... 0.38</td></tr>
<tr><td>Lime plaster</td><td>0.025</td><td>Exterior</td><td></td><td>Natural stone</td><td>0.05..0.1</td></tr>
<tr><td>Exterior</td><td></td><td></td><td></td><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.2...0.4</td><td></td><td>0.3...0.4</td><td></td><td>0.35...0.5</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>- Front facade: 0.86…1.38 (based on measurements carried out according to ISO 9869)
- Back facade: 1.20 … 1.74 (based on measurements carried out according to ISO 9869)
- Annex façade: 1.20 … 1.89 (based on calculations)</td></tr>
</table>

	- Party wall: 2.07..2.47 (based on measurements carried out according to ISO 9869)

4.1.1.2 Massive masonry walls with exterior insulation

<table>
<tr><td>Description</td><td>A significant part of the back walls of the townhouses is already insulated. The one and a half brick solid masonry wall is insulated using ETICS exterior insulation. EPS insulation material with a thickness between 8 cm and 16 cm (in these cases) is fixed onto the bricks and the wall is finished with a modern plaster, commonly a cement plaster.</td></tr>
<tr><td>Typical condition</td><td>Typically, RC0: good, may need maintenance in 10 years. Because of the recent renovation, these back facades are generally in good condition.</td></tr>
<tr><td>Typical damage mechanisms</td><td>The same damage mechanisms as in the non-insulated masonry walls can be observed. Additionally, the cement plaster is more sensitive for damage (cracking, spalling, …) because of their lower flexibility and lower moisture permeability than lime plasters.</td></tr>
<tr><td>Illustration</td><td>

(Xthermo.be, 2020)</td></tr>
<tr><td>Structure</td><td><table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Lime plaster</td><td>0.02</td></tr>
<tr><td>Masonry
+ Lime mortar</td><td>0.155…0.255</td></tr>
<tr><td>EPS insulation</td><td>0.08…0.16</td></tr>
<tr><td>Cement plaster</td><td>0.01</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.275...0.455</td></tr>
</table></td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>0.37…0.52
Based on measurements carried out according to ISO 9869 and calculations)</td></tr>
</table>

4.1.1.3 Bay windows

A typical feature of Belgian heritage townhouses are the bay windows in the front façade, which were often added as a renovation around the turn of the 19th century. They are mostly present in the middle-class townhouses, but also the private mansion and the multi-family townhouse can be equipped with a bay window. A slab out of natural stone, that is anchored in the façade, supports the wall and roof structure of the bay window. Apart from the large, glazed parts, they consist mainly of wooden panelling and a timber frame. At the most luxurious homes, the bay window was executed in natural stone.

Figure 4-2: Bay windows in the city of Ghent (DSAM, 2025a): a bay window in natural stone on the left and a wooden example on the right.

4.1.2 Top boundary

4.1.2.1 Pitched roof

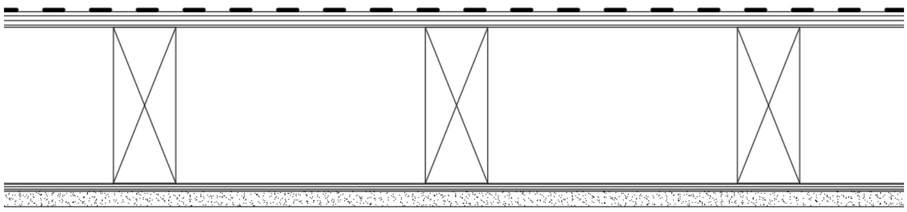
Description	The top boundary of the main volume of all the archetypes is a traditional wooden purlin-supported pitched roof. Apart from the wooden beams of (some of) the floor grating, the purlins were the only structural elements embedded within the party walls. Consequently, the potential length limitations of these beams also determined the width of the dwellings. Only in the wider buildings, such as the private mansions or sometimes the middle-class townhouses, additional trusses are present. The purlins were substantial timber beams, the dimensions of which could vary considerably, but could also be determined by using semi-empirical tables, that took the span and the roof covering into account (Morin, 1853, as cited in Vandenabeele, 2018). In the case studies, beams were encountered with widths ranging from 6.5 cm to 9 cm and heights from 16 cm to 26 cm. Rafters were mounted onto the purlins, and these were covered with a continuous layer of horizontal timber boards in case there was a slate roofing. These boards served as a sub-roof—although they were not truly wind- or waterproof. In older buildings, hardwood (e.g. oak) was used as construction material until a shortage of this type of wood occurred in the beginning of the 19th century. The wood used in the roof structure in the

	considered archetypes is mainly softwood from the Northern countries (e.g. Nordic pine) (Vandenabeele, 2018). The roof is commonly finished with ceramic roof tiles or natural slates, placed on a wooden substructure.
Typical condition	Typically, RC0-RC1: good. Roofs are either in good condition and may need attention in 10 years (often because they are already renovated throughout their existence) or may need maintenance on the intermediate term, because of the deflection of the purlins.
Typical damage mechanisms	Due to the timber structure of the roof, there is an inherent vulnerability to wood rot, although no such deterioration was observed in the examined cases. However, if the roof covering becomes damaged and allows water infiltration, moisture can penetrate the wooden purlins and rafters, potentially initiating the wood rot process. Additionally, the load-bearing purlins may exhibit significant deflection. In many cases, undersized purlins have undergone excessive bending as a result of the load of the roof and fluctuating indoor humidity levels. This is a particularly important consideration when planning to add insulation or roof windows, as these will further increase the structural load.
Illustration	 (DSAM, 2025b)

<table>
<tr><td>Structure</td><td>
<table>
<tr><th></th><th></th></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Purlins</td><td>0.18 x 0.08</td></tr>
<tr><td>Rafters</td><td>0.06 x 0.06</td></tr>
<tr><td>Wooden boarding</td><td>0.02</td></tr>
<tr><td>Ceramic roof tiles</td><td>0.02</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.28 (including wooden structure)</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>2…2.8 (based on calculations)</td></tr>
</table>

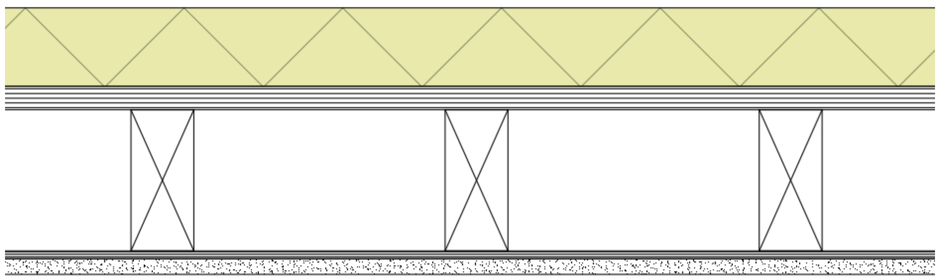
4.1.2.2 Flat roof

Description	The top boundary of the annex was originally always a pitched roof but is often already transformed into a flat roof. In the case of a flat roof, the construction is similar to that of wooden floors (see 4.1.3.2). Wooden beams form the structural part of the flat roof, typically with a height of around 20 cm. Wooden boarding is used as a carrier for the roof finish and is placed under a small grade. The Watertightness of the roof is provided by the zinc roof finish (original situation) or with a bituminous roofing (recent renovation). The interior side of the flat roof is finished with a lime plaster on a base of wooden slats or with a plasterboard (in recent renovations).
Typical condition	Typically RC0: good, may need attention in 10 years.
Typical damage mechanisms	Flat roofs, like pitched roofs, are susceptible to wood rot due to their timber construction. When the waterproofing layer—whether zinc or bituminous—is compromised, water can infiltrate the roof structure, potentially causing damage to wooden boards or beams. Moisture penetrating into the plaster layer can also lead to mould growth. In addition, corrosion may occur in zinc roofing, particularly on the underside, where insufficient ventilation can lead to moisture accumulation and accelerate the corrosion process. However, none of these damage mechanisms were observed in the case study buildings

<table>
<tr><td>Illustration</td><td></td></tr>
<tr><td>Structure</td><td>
<table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Lime plaster</td><td>0.02</td></tr>
<tr><td>Wooden slats</td><td>0.01</td></tr>
<tr><td>Wooden beams + air cavity</td><td>0.2</td></tr>
<tr><td>Wooden boarding</td><td>0.02</td></tr>
<tr><td>Zinc/bituminous finish</td><td>0.008</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.258</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>1.8 … 2 (based on calculations)</td></tr>
</table>

4.1.2.3 Attic floor with insulation

Description	An easy way to insulate the top boundary of these archetypes is insulating the floor of the attic. The attic is often not in use and quite spacious, which makes insulation the roof itself less interesting. Insulation panels or insulation mats are placed on the wooden flooring of the attic, without much further fixation or sealing of the insulation layer, which could cause a worse performing insulation layer.
Typical condition	Typically, RC1: good, may need maintenance on the intermediate term. Usually in good condition now, but the simple setup is sensitive for wear and damage
Typical damage mechanisms	No significant building physics-related damage mechanisms are associated with this construction setup. The primary risks are limited to mechanical damage, which may result from people walking on it or the movement of objects across the surface.

<table>
<tr><td>Illustration</td><td></td></tr>
<tr><td>Structure</td><td>
<table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Lime plaster</td><td>0.02</td></tr>
<tr><td>Wooden slats</td><td>0.01</td></tr>
<tr><td>Wooden beams + air cavity</td><td>0.18</td></tr>
<tr><td>Wooden flooring</td><td>0.03</td></tr>
<tr><td>Insulation material</td><td>0.08…0.16</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.32...0.4</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>0.2…0.3 (based on calculations)</td></tr>
</table>

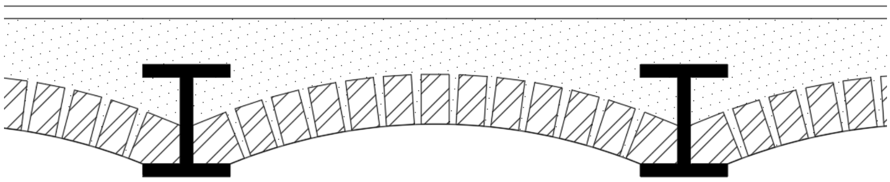
4.1.2.4 *Insulated pitched and flat roof*

In the various case studies, pitched roofs (and flat roofs as well) had often already been insulated during the course of their existence. As insulating a pitched roof is a relatively straightforward and frequently cost-effective method of improving the energy efficiency of a dwelling, it is more commonly encountered than the insulation of façades or floors. In earlier renovation works, carried out prior to the implementation of EPBD requirements, only minimal insulation thicknesses can be expected which was also observed in several of the case studies. In more recent renovations, EPBD requirements are taken into account, and roofs are required to achieve a maximum U-value of 0.24 W/m²K, a standard that can be readily met by fully filling the roof structure. For pitched roofs, insulation material—often in the form of flexible mats—is placed between the rafters and purlins and finished with plasterboard. In the case of flat roofs, insulation may be installed either between the wooden beams on the interior side or applied on the exterior side.

4.1.3 Floors

4.1.3.1 *Vaulted floors*

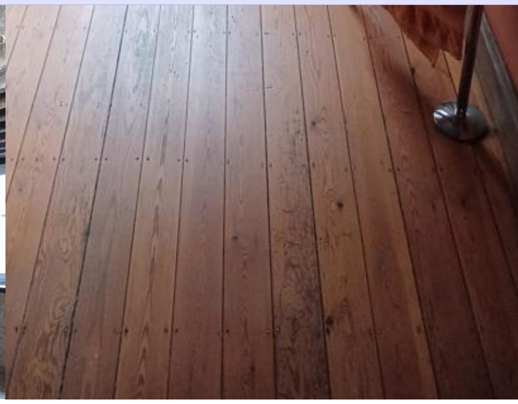
Description	The floors in the hallway of the ground floor were always provided with hard finishing materials, such as natural stone, ceramic or cement tiles, which are placed in a sand bed. These tiles were cheap, easy to keep clean and could be provided with colourful patterns. Where these hard finishing materials were applied, floors were originally supported by

<table>
<tr><td></td><td>trough vaults (troggewelven) (Ledent, 2012) that are placed on steel profiles. Sand is used to fill up the vaults. Until today, these are almost always still present under the hallway or under the coach entry of a private mansion.</td></tr>
<tr><td>Typical condition</td><td>Typically, RC0: good, may need maintenance in 10 years.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Because the trough vaults are exposed to the basement environment, that is often moist and cold, salt efflorescence of the brickwork and corrosion of the steel beams can be expected. However, in all the case study buildings, the vaulted floors had no damage.</td></tr>
<tr><td>Illustration</td><td>

(DSAM, 2025c)</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Cement tiles</td><td>0.02</td></tr>
<tr><td>Sand bed</td><td>0.09-0.17</td></tr>
<tr><td>Masonry</td><td>0.08</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.19-0.27</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>1.23 (based on calculations).</td></tr>
</table>

4.1.3.2 Wooden floors

Description	All floors within these archetypes – except for the basement floor and the hallway or coach entry floor (as previously described) – consist of wooden floors, comprising wooden beams and wooden parquet or

<table>
<tr><td></td><td>planks. Due to fire safety regulations in some Belgian cities, the timber floor structure could not be anchored into the party walls. As a result, the structural load of the floors was typically borne from façade to façade (and supported by any intermediate internal walls) (Burniat, 2012). In other cities, like Ghent for example, the load-bearing beams can be embedded in the party walls. Consequently, the direction of the beams could change from floor to floor. The timber beams generally had a height of approximately 18 cm, although this dimension varied depending on the span of the floor. These beams, like those used in the roof structures, were predominantly made of softwood. Fixed to this structural framework, the flooring itself consisted of wooden parquet or solid wooden planks typically ranging in thickness from 2.5 to 3.4 cm (Cloquet, 1898). These planks – commonly made from oak (parquet) or spruce (planks) – could be laid in various patterns, depending on the intended finish of the interior space.
The underside of these timber floors was often finished with a lime plaster layer applied to a structure made of wooden slats.</td></tr>
<tr><td>Typical condition</td><td>Typically RC0: good, may need maintenance in 10 years.</td></tr>
<tr><td>Typical damage mechanisms</td><td>In the case study buildings, wooden floors were rarely subject to damage. While the timber structure is inherently susceptible to wood rot, it is extremely rare for moisture levels to become high enough to initiate such deterioration. Additionally, cracks in the plaster layer of the ceiling are sometimes observed, likely resulting from the shrinking and swelling of the underlying timber structure due to humidity fluctuations. Finally, wooden parquet flooring may show signs of wear and abrasion over time.</td></tr>
<tr><td>Illustration</td><td> 
(DSAM, 2025d</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Wooden flooring</td><td>0.03</td></tr>
<tr><td>Wooden beams + air cavity</td><td>0.18</td></tr>
<tr><td>Wooden slats</td><td>0.01</td></tr>
<tr><td>Lime plaster</td><td>0.02</td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.24</td></tr>
</table>
</td></tr>
</table>

Thermal transmittance U, W/(m²·K)	1.21 (based on calculations) Measurements resulted in fluctuating U-values between 0.09 and 0.4. The results were not in accordance with ISO 9869 because of too high fluctuations.

4.1.3.3 Basement floors

<table>
<tr><td>Description</td><td>The basement floor is usually not (thoroughly) renovated, and thus also not insulated. It consists of cement or ceramic tiles in a sand bed. In some cases – usually a case in a very authentic condition - the floor consists of masonry bricks in a sand bed.</td></tr>
<tr><td>Typical condition</td><td>RC 1: Some basement floors may need maintenance on the intermediate term</td></tr>
<tr><td>Typical damage mechanisms</td><td>The most commonly observed damage to basement floors involves moisture-related deterioration due to the humid conditions typical of basements, as well as the sagging or displacement of floor tiles, which is attributed to the instability of the underlying sand layer.</td></tr>
<tr><td>Illustration</td><td>
(DSAM,2025e)</td></tr>
<tr><td>Structure</td><td><table>
<tr><td></td><td></td></tr>
<tr><td>Material</td><td>Thickness [m]</td></tr>
<tr><td>Interior</td><td></td></tr>
<tr><td>Ceramic/cement tiles</td><td>0.02</td></tr>
<tr><td>Sand bed</td><td></td></tr>
<tr><td>Exterior</td><td></td></tr>
<tr><td>TOTAL</td><td>0.02 ...</td></tr>
</table></td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>0.29 … 0.6 (based on calculations)
Thermal transmittance is very depended on the floor geometry and depth of the basement floor (and less on the materials used)</td></tr>
</table>

4.1.3.4 Slab on ground

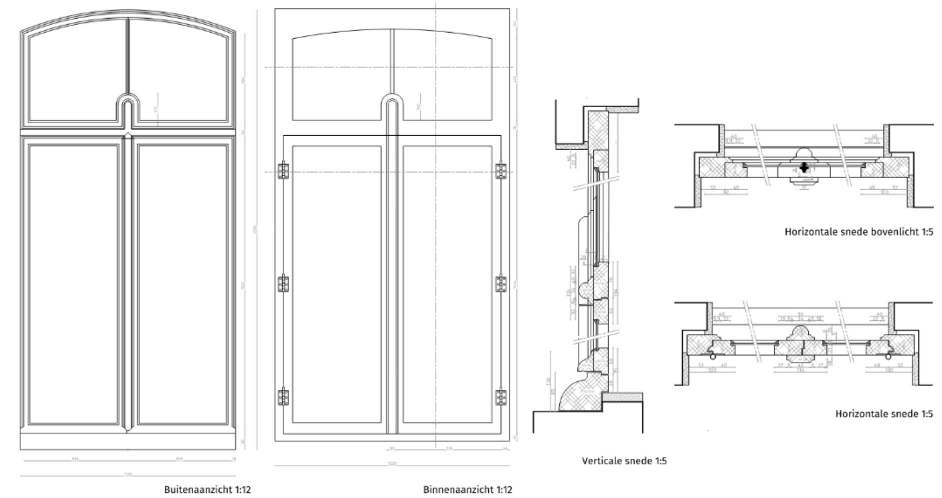
In some cases there are also floors directly on the soil, e.g. under annexes where there is no cellar, under newer extensions, under verandas, … They can be uninsulated or insulated, depending on when they are constructed or renovated. Most of the time, these floors are also constructed with ceramic tiles on a sand bed. When there has been a recent renovation, this construction is replaced by an traditional floor build-up: concrete floor structure –

insulation – screed – tiles. The U-value calculated from the case study buildings vary between 1.2 W/m²K (unrenovated) and 0.14 (renovated).

4.1.4 Windows

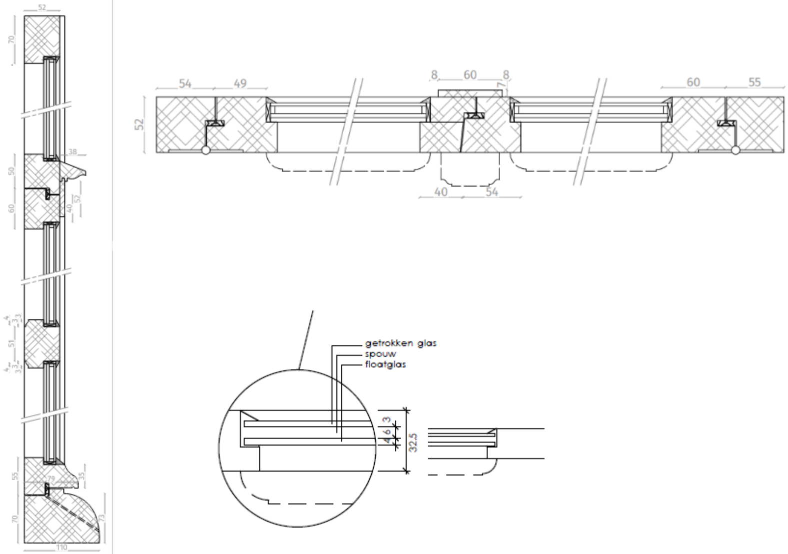
4.1.4.1 Original single glazed wooden windows

Description	In most of the case study buildings, some original single-glazed wooden windows are still present. This includes not only the transom windows above the front doors – which are almost always original – but also the cellar windows and even the windows in the front façade. These elements have often been preserved due to their heritage value and distinctive aesthetic qualities. Various types of windows were common in 19th- and early 20th- century architecture, including guillotine windows and windows with a fixed transom and two casement sashes. These were all characterized by wooden frames, typically quite slender (around 4,5 cm thick), and featured distinctive window divisions. A typical configuration included two vertically operable sections with a fixed horizontal transom above. Originally the glass panels were divided using wooden or iron rods but often the original windowpanes and the rods were already replaced by large glass panels (without rods). The glazing consisted of a single pane of glass, usually about 3 or 4 mm thick, made from materials such as drawn glass (*getrokken glas*) or mouth-blown glass (*mondgeblazen glas*), both of which contribute to the characteristic visual appearance of historic windows. These windows were also fitted with ornamented ironmongery (*raambeslag*) in the interior, which is considered of high historical and aesthetic value.
Typical condition	RC 0 – RC 3: the windows that are maintained are generally in a very good condition, where no measures are needed. However, a lot of original windows are also in bad condition, where the wood is damaged and the frames are crooked. In those cases, urgent major interventions are needed.
Typical damage mechanisms	Windows are typically among the most vulnerable building components in historic constructions. The thin wooden frames are particularly susceptible to wood rot and mould growth, especially at the lower sections where moisture tends to accumulate due to condensation on the single glazing. These slender frames are highly sensitive to external environmental conditions, such as freezing temperatures and fluctuating humidity levels. Consequently, the timber undergoes repeated cycles of swelling and shrinking, which can lead to cracking, warping, and general structural distortion over time.

Illustration	 (DSAM, 2017)
Thermal transmittance U, W/(m²·K)	Single glazing: Ug = 5.8 W/m²K Window: U = 4 W/m²K…5 W/m²K (based on calculations, depending on window geometry)

4.1.4.2 Updated original windows with thin double glazing

Description	To make the original windows more energy efficient while preserving the original elements and look, the original single glazing is replaced by new thin double glazing that is integrated in the original wooden windows. Because of the limited thickness of the window frames, the new glazing should be much thinner than contemporary glazing, that is typically 23 mm thick. The thin double glazing can be as thin as 7 mm, consisting of two single glass panes and a gas filled cavity, to improve the thermal properties. The outer glass panel can be provided in drawn or imitation mouth-blown glass so that it gets the look of historical glazing. Also vacuum glazing can be integrated into the existing original frames but were not observed in the cases.
Typical condition	RC 0 : good, may need attention in 10 years. As these interventions are usually recent and only carried out in well-maintained or repaired frames, the condition of these windows is good.
Typical damage mechanisms	In general, damage mechanisms that are applicable for the original windows are also applicable here, because the original wooden frame is retained. Of course, the condensation on the glass should be mitigated because the thermal transmittance of the thin double glazing is a lot lower.

Illustration	 (DSAM, 2024)
Thermal transmittance U, W/(m²·K)	Thin double glazing: Ug = 1.8 W/m²K… 3.6 W/m²K Window: U = 2.1 W/m²K…3.5 W/m²K (based on calculations, depending on window geometry)

4.1.4.3 New (harmonized) wooden windows with double glazing

Description	The windows can be replaced by contemporary wooden windows that harmonize with the original material, window layout and details. The windows are thus completely new, but with a similar appearance and the same material as the original ones. The new windows have high energy performance, with better insulating windows frames and high-performance glazing.
Typical condition	RC 0: good, may need attention in 10 years. These interventions are usually recent, consequently, the condition of the windows is good.
Typical damage mechanisms	In general, the damage mechanisms that are applicable for the original windows are also applicable here, but to a lesser extent. The thicker window frames and lower thermal transmittance of the glazing should help mitigate the consequences of the external conditions and humidity variations. Additionally, condensation is ruled out.
Illustration	 (DSAM, 2025f)

Thermal transmittance U, W/(m²·K)	(High performance) double glazing: Ug = 1.0 W/m²K… 2.8 W/m²K Window: U = 1.6 W/m²K…2.6 W/m²K (based on calculations, depending on window geometry)

4.1.4.4 Skylights

In rear extensions featuring a veranda, a skylight is often incorporated to maximise natural daylight. Traditionally, these skylights were decorative in nature, comprising an inner layer of single glazing made from ornamented stained glass, and an outer layer – also single glazed – that formed the actual skylight. In contemporary extensions or during renovation works, this configuration is typically replaced. The external structure now usually consists of a double-walled dome made of acrylic or polycarbonate, while the internal finish is generally more simplified, often realised as a flat pane of glass or polycarbonate without ornamental detailing.

4.2 Airtightness

In 15 case study buildings, airtightness measurements were conducted using the pressurization method in accordance with the EN ISO 9972 standard. In two cases–HOOG and KUIPER–no valid airtightness test could be completed, as the equipment was unable to achieve the required pressure differentials. In the remaining 13 cases, airtightness tests were successfully conducted following the EN ISO 9972 preparation Method 1. In all cases, the basement was excluded from the tested volume by closing off the access door. In certain cases – KEIZER, CITADEL, and MEERS – the attic was also excluded from the test volume (also by closing the attic door). An overview of the measurement results is presented in Figure 4-3. More details about the measurements can be found in Macharis (2025).

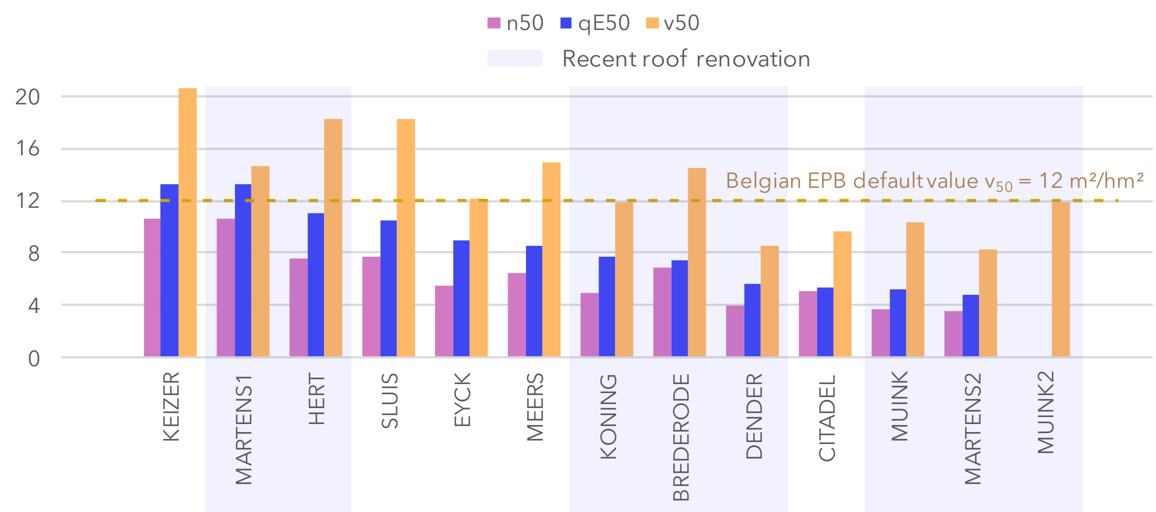


Figure 4-3: Overview of the airtightness measurements carried out in 13 Belgian cases.

As can be observed, the airtightness values vary significantly. KEIZER recorded a q_{E50}-value of 13.3 m³/h·m², whereas MARTENS2 achieved a considerably lower value of 4.81 m³/h·m² – more than 2.5 times lower. In the case of KEIZER, the townhouse remained largely in its original condition, with only minor renovations carried out in the second half of the 20th century. The roof was poorly insulated, with no attention to airtightness – visible gaps even allowed daylight to penetrate. In contrast, MARTENS2 underwent a thorough renovation within the last five years, including a complete roof replacement with airtightness measures, as well as new windows. Brush seals were also installed in the window sashes and the front door.

The average q_{E50}-value of the measured cases is 8.48 m³/hm² and the average n_{50}-value is 6.4 /h. Research by Laverge et al. (2014) indicated an average n_{50}-value of 6.4 as well for newly built dwellings between 2006 and 2010, proving that these historic buildings not necessarily perform much worse than more recent building. However, the Belgian SENVIVV research on airtightness of residential buildings (built at the end of the 20th century, before EPBD-regulations) reported an average n_{50}-value for terraced dwellings of 5.3 /h, which is lower than the measured values in our cases (of which some are renovated) (Bossaer et al., 1998). When only the cases are considered where no recent renovation took place, the average n_{50}-value increases to 7.1 /h, with outliers up to 10.65 /h. Evidently, deriving a fixed value for heritage buildings is difficult, as also stated by Martín-Garín et al. (2020). The latter tested heritage dwellings in Spain, for which the n_{50}-value fluctuated between 3.87 /h and 18.26 /h.

Across all case studies, the roof and windows consistently emerged as the primary sources of air leakage, based on in-situ observations. This corresponds with the findings of the SENVIVV research, that indicate that 30-40% of the air leakage can be attributed to the attic. In instances where the roof had been recently insulated and fitted with a vapour barrier, airtightness was significantly improved compared to unrenovated buildings. However, this is not a guarantee for a good airtightness, as demonstrated by MARTENS1 and HERT. In these cases, other leakage paths also played a major role; notably, both buildings still featured original window frames. Finally, the attention for airtightness during renovation will determine the airtightness of the building in the end.

In addition to the quantities defined in EN ISO 9972 – the air change rate at 50 Pa pressure difference (n_{50}) and the specific leakage rate at 50 Pa (qE_{50}) – Belgian national regulations also employ an alternative approach to express the specific envelope leakage rate, i.e. the v_{50}-value. While the qE_{50}-value is calculated using the envelope area (A_E), which includes all loss surfaces based on internal dimensions – covering surfaces exposed to the exterior, the ground, and adjacent buildings – the v_{50}-value in Belgium is based on the test area (A_{Test}). This area is calculated using external dimensions and includes only surfaces in contact with the unheated external environment. As such, party walls are excluded from A_{Test}, marking a significant distinction from A_E.

Belgian EPB legislation does not impose a mandatory airtightness requirement. However, in the absence of an airtightness test, a conservative default v_{50}-value of 12 m³/h·m² is adopted (derived from the SENVIVV-study). As can be observed in Figure 4-3, also the v_{50}-value varies significantly between all cases, following a slightly different trend than the n_{50}- and q_{E50}-value. When the party walls have a large share of the total envelope, the v_{50}-value is closer to the q_{E50}-value. 6 cases have a v_{50}-value that is higher than the default EPB-value, and 3 others are closely to this default value. Again here, a recent renovation of the roof, with attention for airtightness, is an indication of better airtightness, although not a guarantee. The lowest measured v_{50}-value is 8.23 m³/hm² (MARTENS2), which is still a lot higher than the average value of all the EPB declarations of 3 m³/hm² in 2022 for newly built dwellings and renovations (Flemish Energy and Climate Agency, n.d.).

4.3 Moisture safety on interior surface (temperature factors)

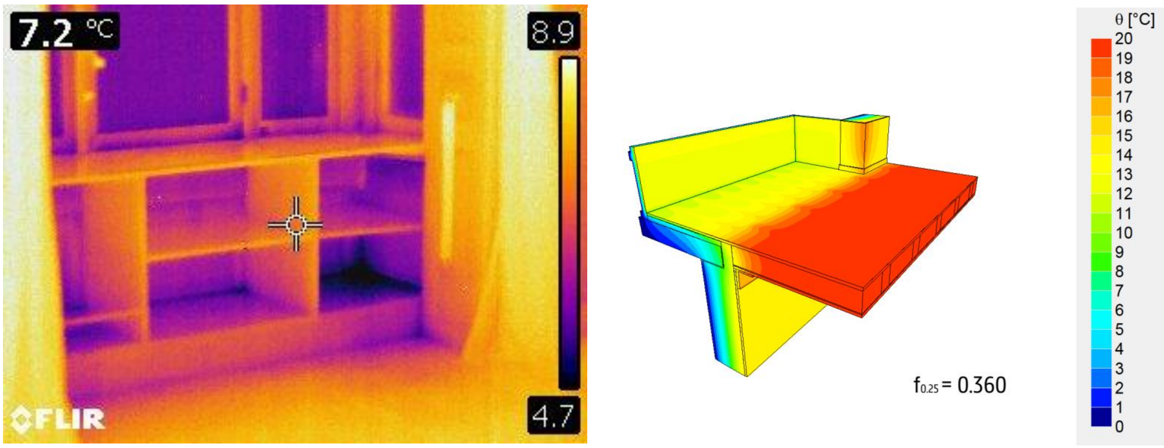


Figure 4-4: Thermographic image (left) and isotherms (right) of the lower part of a bay window.

Based on thermographic research in the different cases, some critical points at the interior side of the front façade are identified. A more thorough investigation of the temperature factors of the interior surfaces is done on the archetype level, in this case the middle-class townhouse. Alongside the section of the front facade, 6 construction junctions are analysed, as indicated on Figure 4-5. Those construction junctions are modelled in the thermal analysis software TRISCO 3D to calculate the interior surface temperatures and corresponding temperature factors. These temperature factors are calculated using an interior surface resistance of 0.25 m²K/W, taking into account a safer, more conservative condition to assess the moisture safety on the interior surfaces. Table 4-1 provides an overview of those junctions, a brief description and the corresponding temperature factor (and where the most critical point is located).

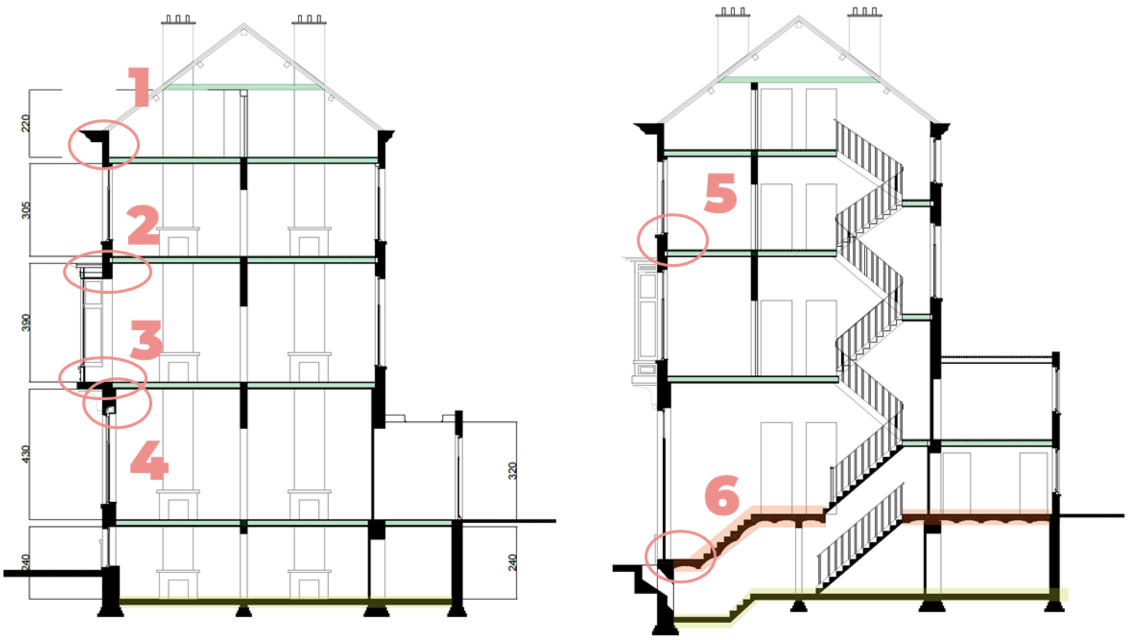


Figure 4-5: Indication of the different critical junctions that were analysed.

Table 4-1: Overview of the calculated temperature factors for the different identified junctions

Building junction	Description	Temperature factor
1	Interface between the uninsulated pitched roof and the uninsulated front facade (including the connection with the party wall, which is also not insulated).	$f_{0.25}$ = 0.27 (roof)
2	Interface between the upper part of the bay window, consisting of a wooden roof structure, and the front façade (and the wooden internal floor).	$f_{0.25}$ = 0.32 (lintel above the window)
3	Interface between the lower part of the bay window (stone slab with wooden flooring) and the uninsulated front façade (and the wooden internal floor).	$f_{0.25}$ = 0.36 (lower corner wooden floor bay window)
4	Interface between the wooden windows on the ground floor (where a roller blind casement is present) with the uninsulated front façade.	$f_{0.25}$ = 0.54 (corner of window reveal)
5	Interface between a wooden window, the uninsulated front façade and the wooden internal floor.	$f_{0.25}$ = 0.54 (window reveal)
6	Interface between the uninsulated front façade, the vaulted floor, the wooden floor and the internal wall.	$f_{0.25}$ = 0.73 (connection floor-facade)

As can be seen in Table 4-1, the temperature factors are quite low, ranging from 0.274 to 0.542, with a maximum value of 0.734. Buildwise, the Belgian research institute for the construction industry, proposes a temperature factor of 0.7 as a minimum to prevent surface condensation and mould growth (Buildwise , 1984). The values found in these historic buildings are clearly a lot lower than this limit, although little to no mould growth has been found in the case study buildings. The intensive windows opening and the low airtightness of the building envelope could be an explanation for the absence of mould growth, although the surface temperature is low.

4.4 Technical condition of archetype envelope

In general, the building envelope of the examined case studies is in good condition. The owners of these buildings clearly take proper care of their homes, ensuring regular maintenance and timely repairs when needed. However, it is important to note that this does not provide a complete overview of all buildings within the archetypes studied. It is evident that in other examples, significant damage may be present, ranging from localized defects to entire facades, roofs, floors, or windows being in poor condition. Such deterioration is often observed in buildings that have been vacant for extended periods, where maintenance has been neglected for years. In these cases, it could be advantageous to combine the repair or replacement of building elements with energy-efficient renovation strategies.

It is clear that the presence of damage does not correlate with specific building archetypes. This is logical, as the construction techniques are largely consistent across all four archetypes, which means that potential damage mechanisms are similar and can occur in any of them. Below is a summary of the most common and noteworthy conditions observed in the building envelope components.

The walls of the various archetypes are generally in very good condition, especially the front façades. Damage is more often observed in the plaster layers, both on the interior and exterior. The most frequent issues are cracking and soiling of plaster. Mould growth on the interior surface is rare but possible in exceptional cases. Salt efflorescence on the brickwork is also not uncommon, which can negatively impact the aesthetic appearance of the façade. Structurally, however, the masonry walls are almost always in perfect condition.

Roofs are usually also in good condition, although the absence of proper underlayment can lead to water infiltration. This moisture can affect the timber roof structure, potentially leading to wood rot. Critical zones include the junction between the roof and façade and the cornice, which, being a wooden component, is often the first to deteriorate. Furthermore, the wooden purlins are frequently undersized, and excessive deflection is a common issue in older buildings.

Windows are often the most vulnerable element of the building envelope. Especially in cases where the original single-glazed wooden windows are still in place, there is a high risk of damage if they have not been adequately maintained. The timber window frames are frequently affected by wood rot, particularly due to water accumulation. Condensation on the single glazing is also common. Given their slender construction, these frames are highly sensitive to external climatic conditions, resulting in swelling and shrinking. Over time, this can cause deformation of the window frame, leading to difficulties in closing and sealing the windows properly.

4.5 Archetype envelope characteristics

4.5.1 Summary of envelope characteristics of case study buildings

Table 4-2: Middle-class townhouse: envelope characteristics of case study buildings

Blue hatched = measured

Country	Belgium		**Building code**	MEERS	HERT	EYCK	KONING
Archetype	Middle-class townh.		**Heated area, m²**	239.67	327.79	331.12	225.98
Town	Ghent		**Heated Volume, m³**	657.99	922.74	1178.66	638.429
			Envelope area, m²	307.48	438.52	651.87	332.8977
Exterior wall	**Front Façade**		U, W/(m²·K)	1.12	1.77	0.86	1.38 / 0.47
			Share of envelope, %	14%	13%	11%	12%
			Technical state	RC 1	R 0	RC 0	RC 0
	Back Façade		U, W/(m²·K)	0.37	0.52	1.56	1.38 / 1.74
			Share of envelope, %	9.9%	8.1%	6.9%	19%
			Technical state	RC 0	RC 0	RC 1	RC 0
	Annex Façade		U, W/(m²·K)	0	0.38	0.57	0
			Share of envelope, %	0	5%	8%	0
			Technical state	0	RC 0	RC 0	0
Top boundary	**Pitched Roof**		U, W/(m²·K)	0.46	0.26	0.26 / 2.69	0.39
			Share of envelope, %	22.4%	21.7%	1.8% / 0%	25.9%
			Technical state	RC 0	RC 0	RC 1	RC 0
	Flat roof		U, W/(m²·K)	0	0.24	0	0.29
			Share of envelope, %	0	6.6%	0	3.4%
			Technical state	0	RC 0	0	RC 0
	Attic floor as top boundary		U, W/(m²·K)	0	0	0.22	0
			Share of envelope, %	0	0	8.2%	0
			Technical state	0	0	RC 1	0
Floors	**Basement floor**		U, W/(m²·K)	0.34	0.54	0.30	0.60
			Share of envelope, %	25.3%	0.0%	0.0%	0.0%
			Technical state	RC 0	RC 1	RC 0	RC 0
	Basement vaulted ceiling		U, W/(m²·K)	n/a	1.30	n/a	n/a
			Share of envelope, %	0.0%	5.3%	6.3%	11.9%
			Technical state	RC 0	RC 0	RC 0	RC 0
	Basement wooden ceiling		U, W/(m²·K)	n/a	2.49	0.86	0
			Share of envelope, %	0.0%	5.7%	8.5%	0
			Technical state	RC 0	RC 0	RC 0	0
	Slab on ground		U, W/(m²·K)	0	0.20	0	0.33
			Share of envelope, %	0	7.0%	0	2.8%
			Technical state	0	RC 0	0	RC 0
Windows	**Original window (original frame + single glazing)**		U_{window}, W/(m²·K)	4.11	4.42	4.68	0
			U_{glass}, W/(m²·K)	5.8	5.8	5.8	0
			g-value, -	0.8	0.8	0.8	0
			Share of envelope, %	2.7%	4.1%	0.3%	0
			q_{E50}, m³/(h·m²)	n/a	n/a	n/a	0
			Technical state	RC 3	RC 0	RC 0	0
	Upgraded original window (harmonized window/thin glazing in original frame)		U_{window}, W/(m²·K)	1.90	0	1.60	2.10
			U_{glass}, W/(m²·K)	1.3	0	1.1	1.8
			g-value, -	0.61	0	0.63	0.56
			Share of envelope, %	1.8%	0	4.2%	4.4%
			q_{E50}, m³/(h·m²)	n/a	0	n/a	n/a
			Technical state	RC 1	0	RC 0	RC 0
	New windows (new frame + new glazing)		U_{window}, W/(m²·K)	1.85	2.79	1.72	1.97
			U_{glass}, W/(m²·K)	1.1	2.8	1.3	1.6
			g-value, -	0.63	0.7	0.43	0.77
			Share of envelope, %	1.1%	1.3%	3.8%	3.5%
			q_{E50}, m³/(h·m²)	n/a	n/a	n/a	n/a
			Technical state	RC 0	RC 0	RC 0	RC 0
	Other		U_{window}, W/(m²·K)	4.39	2.79	0	4.49
			U_{glass}, W/(m²·K)	5.8	2.8	0	5.8
			g-value, -	0.8	0.7	0	0.8
			Share of envelope, %	2.9%	2.1%	0	3.4%
			q_{E50}, m³/(h·m²)	n/a	n/a	0	n/a
			Technical state	RC 1	RC 0	0	RC 0
Air tightness	**Envelope average**		q_{E50}, m³/(h·m²)	8.520	11.083	6.349	7.690

Blue hatched = measured							
Country	Belgium		**Building code**	CITADEL	KEIZER	MARTENS2	MUINK2
Archetype	Middle-class townh.		**Heated area, m²**	226.94	254.66	341.604	282.35
Town	Ghent		**Heated Volume, m³**	693.7451	825.2114	1143.8241	816.9934
			Envelope area, m²	489.8393	396.2255	530.8235	348.0922
Exterior wall	**Front Façade**		U, W/(m²·K)	1.27	1.32	1.18	1.28
			Share of envelope, %	n/a	n/a	n/a	n/a
			Technical state	RC 0	RC 0	RC 0	RC 0
	Back Façade		U, W/(m²·K)	1.27	1.31	1.47	0.32
			Share of envelope, %	n/a	n/a	n/a	n/a
			Technical state	RC 1	RC 1	RC 0	RC 0
	Annex Façade		U, W/(m²·K)	1.73	1.89 / 0.37	0.40	0
			Share of envelope, %	n/a	n/a	n/a	0
			Technical state	RC 2	RC 1	RC 0	0
Top boundary	**Pitched Roof**		U, W/(m²·K)	2.15	0.47	0.29	0.18
			Share of envelope, %	n/a	21.0%	17%	22%
			Technical state	RC 0	RC 1	RC 0	RC 0
	Flat roof		U, W/(m²·K)	1.84	1.91	0	0.17
			Share of envelope, %	n/a	2.2%	0	3.4%
			Technical state	RC 0	RC 0	0	RC 0
	Attic floor as top boundary		U, W/(m²·K)	0	0	0	0
			Share of envelope, %	0	0	0	0
			Technical state	0	0	0	0
Floors	**Basement floor**		U, W/(m²·K)	0.39	0.34	0.30	0.36
			Share of envelope, %	0.0%	0.0%	0.0%	20.7%
			Technical state	RC 0	RC 0	RC 0	RC 0
	Basement vaulted ceiling		U, W/(m²·K)	n/a	n/a	0.40	n/a
			Share of envelope, %	5.8%	5.3%	9.5%	0.0%
			Technical state	RC 0	RC 0	RC 0	RC 0
	Basement wooden ceiling		U, W/(m²·K)	0	1.19	0.40	0.22
			Share of envelope, %	0	11.1%	9.5%	0.0%
			Technical state	0	RC 0	RC 0	RC 0
	Slab on ground		U, W/(m²·K)	0.30	n/a	0.27	0
			Share of envelope, %	11.5%	5.4%	4.6%	0
			Technical state	RC 0	RC 0	RC 0	0
Windows	**Original window (original frame + single glazing)**		U_{window}, W/(m²·K)	4.28	n/a	0	0
			U_{glass}, W/(m²·K)	5.8	5.8	0	0
			g-value, -	0.8	0.8	0	0
			Share of envelope, %	n/a	n/a	0	0
			q_{E50}, m³/(h·m²)	n/a	n/a	0	0
			Technical state	RC 0	RC 2	0	0
	Upgraded original window (harmonized window/thin glazing in original frame)		U_{window}, W/(m²·K)	0	n/a	2.23	1.56
			U_{glass}, W/(m²·K)	0	1.3	2	1
			g-value, -	0	0.63	0.6	0.5
			Share of envelope, %	0	n/a	n/a	n/a
			q_{E50}, m³/(h·m²)	0	n/a	n/a	n/a
			Technical state	0	RC 2	RC 0	RC 0
	New windows (new frame + new glazing)		U_{window}, W/(m²·K)	n/a	n/a	1.55	1.43
			U_{glass}, W/(m²·K)	1.2	1.5	1.1	1
			g-value, -	0.61	0.43	0.6	0.5
			Share of envelope, %	n/a	n/a	n/a	n/a
			q_{E50}, m³/(h·m²)	n/a	n/a	n/a	n/a
			Technical state	RC 0	RC 0	RC 0	RC 0
	Other		U_{window}, W/(m²·K)	n/a	n/a	0	2.78
			U_{glass}, W/(m²·K)	2.7	2.8	0	2.8
			g-value, -	0.7	0.7	0	0.7
			Share of envelope, %	n/a	n/a	0	n/a
			q_{E50}, m³/(h·m²)	n/a	n/a	0	n/a
			Technical state	RC 0	RC 0	0	RC 0
Air tightness	**Envelope average**		q_{E50}, m³/(h·m²)	5.374	13.296	4.817	v50 = 11.9

Table 4-3: Modest house and private mansion: envelope characteristics of case study buildings

Blue hatched = measured						
Country	Belgium	**Building code**	MARTENS1		HOOG	MUINK
Archetype	Modest house	**Heated area, m²**	202.70	Private mansion	538.82	385.15
Town	Ghent	**Heated Volume, m³**	556.46		2088.36	1314.1745
		Envelope area, m²	442.78		924.27	592.0848
Exterior wall	**Front Façade**	U, W/(m²·K)	1.20		1.03	1.41
		Share of envelope, %	11%		16%	n/a
		Technical state	RC 0		RC 1	RC 0
	Back Façade	U, W/(m²·K)	1.20		1.17	1.41
		Share of envelope, %	4%		17%	n/a
		Technical state	RC 0		RC 1	RC 0
	Annex Façade	U, W/(m²·K)	1.2		0	0
		Share of envelope, %	8%		0	0
		Technical state	RC 0		0	0
Top boundary	**Pitched Roof**	U, W/(m²·K)	0.20		2.70	0.19
		Share of envelope, %	16.4%		0.0%	n/a
		Technical state	RC 0		RC 1	RC 0
	Flat roof	U, W/(m²·K)	0.31		0	0.41
		Share of envelope, %	2.9%		0	4.9%
		Technical state	RC 0		0	RC 0
	Attic floor as top boundary	U, W/(m²·K)	0		0.28	0
		Share of envelope, %	0		18.0%	0
		Technical state	0		RC 1	0
Floors	**Basement floor**	U, W/(m²·K)	0.52		0.49	0.48 / 0.41
		Share of envelope, %	0.0%		8.5%	0.0%
		Technical state	RC 2		RC 1	RC 0
	Basement vaulted ceiling	U, W/(m²·K)	n/a		n/a	n/a
		Share of envelope, %	4.1%		0.0%	0.0%
		Technical state	RC 0		RC 0	RC 0
	Basement wooden ceiling	U, W/(m²·K)	0		n/a	0.35
		Share of envelope, %	0		0.0%	14.2%
		Technical state	0		RC 0	RC 0
	Slab on ground	U, W/(m²·K)	0.14		0.13	0
		Share of envelope, %	7.6%		6.3%	0
		Technical state	RC 0		RC 0	0
Windows	**Original window (original frame + single glazing)**	U_{window}, W/(m²·K)	4.82		4.80	0
		U_{glass}, W/(m²·K)	5.8		5.8	0
		g-value, -	0.8		0.8	0
		Share of envelope, %	1.6%		1.7%	0
		q_{E50}, m³/(h·m²)	n/a		n/a	0
		Technical state	RC 1		RC 2	0
	Upgraded original window (harmonized window/thin glazing in original frame)	U_{window}, W/(m²·K)	1.84		2.62	1.65
		U_{glass}, W/(m²·K)	1.4		2.8	1.1
		g-value, -	0.77		0.77	0.6
		Share of envelope, %	2.5%		6.1%	n/a
		q_{E50}, m³/(h·m²)	n/a		n/a	n/a
		Technical state	RC 0		RC 0	RC 0
	New windows (new frame + new glazing)	U_{window}, W/(m²·K)	2.64		1.49	0
		U_{glass}, W/(m²·K)	2.8		1.1	0
		g-value, -	0.77		0.4	0
		Share of envelope, %	2.0%		0.6%	0
		q_{E50}, m³/(h·m²)	n/a		n/a	0
		Technical state	RC 0		RC 0	0
	Other	U_{window}, W/(m²·K)	0		1.52	0
		U_{glass}, W/(m²·K)	0		1	0
		g-value, -	0		0.48	0
		Share of envelope, %	0		1.0%	0
		q_{E50}, m³/(h·m²)	0		n/a	0
		Technical state	0		RC 0	0
Air tightness	**Envelope average**	q_{E50}, m³/(h·m²)	13.286		not possible to measure	5.226

4.5.2 Baseline definition

Finally, based on the observations made in the case-study buildings and taking into account literature, expertise and experience of Ghent University, the city of Ghent and SWECO on renovation of heritage buildings, for each Belgian townhouse archetype as described in 'D5.1 Case-study selection at building and neighbourhood levels', section 1.3, a pre-renovation and renovation baseline for the building envelope is derived. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these types of buildings as if they would be renovated today. In this report, only the baseline scenarios regarding the building envelope are described. The complete baseline scenarios (including heritage value, space conditioning, energy systems and use scenarios) are described in 'D5.4 Baseline scenarios.

4.5.2.1 Pre-renovation baseline

Three building envelope pre-renovation baselines are considered, BS1_PB: Low insulated building with all original windows', 'BS2_PB: Low insulated building with only original windows in the front facade' and 'BS3_PB: Low insulated building with all double-glazed windows. The only difference is the type of windows that are present. In the following paragraphs, a detailed analysis and substantiation of the baseline decisions is presented by building components. Some of these specifications will be dependent on the archetype, some are applicable to all archetypes.

4.5.2.1.1 Walls

In all scenarios, the walls are solid masonry walls finished with a 20 mm thick lime plaster on the interior side and a 25 mm thick lime plaster on the exterior side. To derive the parameters for the thermal transmittance of these walls, literature is consulted on the one hand, and an analysis of the cases is made on the other hand.

According to Calle (2020), the average density of a extruded brick is 1670 kg/m³, which is almost twice the density of contemporary construction brick. The following relation between the bulk density (ρ) and the thermal conductivity (λ) of historic bricks is given by Roels et al. (2023):

$$\ln(\lambda) = 0.0011377 * \rho - 2.5959733$$

For a bulk density of 1670 kg/m³, a corresponding lambda value of 0.5 W/mK for the bricks can be expected. Taking into account the lime mortar joints (λ = 0.7 W/mK), the equivalent thermal conductivity of a masonry wall is 0.56 W/mK, based on literature.

Table 4-4 gives a summary of all the U-value measurements that are carried out in the case study buildings. For each case, the thermal transmittance of the wall, the thickness of the total wall and the thickness of the masonry part are given. Additionally, the thermal conductivity of the masonry part is calculated (excluding the plaster finish). The measurement of HERT is clearly an outlier, which is explained by the measurements period which was too short according to ISO 9869. When excluding this value, an average thermal conductivity of 0.58 W/mK is obtained, which corresponds very well to the value found in literature.

Table 4-4: Overview of the thermal transmittance, thickness and thermal conductivity of the facades of the cases.

Case	MEERS	HERT	EYCK Front	EYCK Back	KONING Front	KONING Back	MARTENS	HOOG	
Measured U-value [W/m²K]	1.12	1.77*	0.86	1.56	1.38	1.74	1.18*	1.2	
Total thickness [m]	0.4	0.4	0.35	0.45	0.38	0.26	0.4	0.32	
Thickness masonry [m]	0.355	0.38	0.33	0.43	0.335	0.215	0.38	0.3	**Average (excluding HERT)**
Thermal conductivity masonry [W/mK]	0.53	1.04	0.78	0.45	0.66	0.6	0.58	0.47	**0.576**

*Not in accordance with EN ISO 9869

Both values are close to each other, so a thermal conductivity of 0.58 W/mK for the brick-mortar composition is assumed to be on the safe side. As described in 4.1.1.1, the different walls have different thicknesses. In the middle-class townhouse, the private mansion and the multi-family townhouse, the front façade is 40 cm thick on the ground floor and 30 cm on the other floors, while in the case of the modest house, the front façade is everywhere 30 cm thick. The back façade of all archetypes has a thickness of 30 cm and the walls of the annex are 20 cm thick. The corresponding thermal transmittance can be found in Table 4-5.

Table 4-5 : Overview of the thermal transmittance of the walls for the pre-renovation baseline.

Wall type	Front façade	Front façade	Back façade	Annex
Thickness [m]	0.4	0.3	0.3	0.2
U-value [W/m²K]	1.20	1.52	1.52	2.05

4.5.2.1.2 Top boundary

For the three building envelope scenarios and the four archetypes, the approach for the pitched roof and the flat roof is the same. The original, uninsulated roof is assumed to be changed in the pre-renovation baseline: a minimal thickness of insulation is placed between the rafters of the pitched roof or on the exterior side of the flat roof (if present), as would be done before any EPBD regulations. According to the calculation methods of the Flemish energy performance certificate, buildings renovated between 1986-1992 had 60 mm of insulation installed in the pitched roof (Flemish Energy and Climate Agency, 2022). For the flat roof, the same insulation thickness is assumed. This results in a thermal transmittance for the pitched roof of 0.71 W/m²K and 0.54 W/m²K for the flat roof.

4.5.2.1.3 Floors

The floors are still the original floors and are not changed throughout the different building envelope scenarios or archetypes. The basement floor consists of ceramic or cement tiles in a sand bed, with a thermal resistance around 0.23 m²K/W. The thermal transmittance depends on the geometry of the floor. The floors of the hallway, finished with cement tiles, are still the original vaulted floors, with a thermal transmittance of 1.22 W/m²K. The wooden floors, that are present in all the other rooms are also still the original ones, with the same thermal transmittance of 1.22 W/m²K.

4.5.2.1.4 Windows

The primary distinction between the three pre-renovation building envelope baselines lies in the treatment of the windows. As observed in the case studies, some buildings—particularly those with historically or architecturally significant façades—still retain their original windows, while others have undergone partial or complete window replacement, either in the past or more recently. In all cases, the windows in the rear façade have been replaced with double-glazed units, with the exception of those deemed valuable or exceptional. This necessitates a clear distinction between the windows in the front and rear façades. Table 4-6 provides an overview of the thermal transmittance of the windows across the different building envelope scenarios.

Table 4-6: Overview of the windows scenarios in the pre-renovation baselines.

Building envelope baseline scenario	BS1_PB	BS2_PB	BS3_PB
Front façade windows			
Description	Original wooden windows with single glazing	Original wooden windows with single glazing	Contemporary windows (wood-PVC-alu) with double glazing
Ug-value [W/m²K]	5.8	5.8	2.8
Uf-value [W/m²K]	2	2	1.8-2.5
Back façade windows			
Decription	Original wooden windows with single glazing	Contemporary windows (wood-PVC-alu) with double glazing	Contemporary windows (wood-PVC-alu) with double glazing
Ug-value [W/m²K]	5.8	2.8	2.8
Uf-value [W/m²K]	2	1.8-2.5	1.8-2.5

4.5.2.1.5 Airtightness

As outlined in section 4.2, it is difficult to draw strong conclusions from the airtightness measurements of historic townhouses. Nevertheless, certain assumptions must be made regarding the airtightness of the various archetypes in their pre-renovation state. The (pitched) roofs are treated similarly across all building envelope scenarios, with little specific consideration given to airtightness. Both the results of airtightness tests and the literature indicate that, along with the windows, these roofs constitute the primary sources of air leakage. In scenario BS3_PB, all windows have already been replaced, yet no specific measures have been taken to improve airtightness. For this condition, the default value from the Flemish EPBD framework is adopted, namely a v_{50}-value of 12 m³/hm². This building envelope scenario aligns closely with the expected performance of an average (non-heritage) dwelling prior to the introduction of EPBD requirements, as the default value is based on this condition.

However, measurements indicate that many dwellings exhibit v_{50}-values significantly higher than 12 m³/hm². These are primarily homes where original windows are still present, suggesting that further differentiation should be made based on the renovation status of these windows. Scenario BS2_PB represents a baseline where the windows in the front façade retain their original frames and glazing. A lower level of airtightness can therefore be expected here compared to a situation where all windows have been replaced; accordingly, a v_{50}-value of 14 m^3/hm^2 is assumed. In BS1_PB, where all the windows are still original, it may be assumed that airtightness is even worse, and thus a v_{50}-value of 16 m^3/hm^2 is adopted.

<table>
<tr><th colspan="5">**Pre-renovation:** Building envelope scenario</th></tr>
<tr><th colspan="2">Scenario</th><th>BS1_PB</th><th>BS2_PB</th><th>BS3_PB</th></tr>
<tr><td rowspan="3">Walls</td><td>Front facade</td><td colspan="3">Solid masonry walls with interior lime plaster and exterior lime plaster.
MCT, PM, MFT → thickness 40cm ground floor (U=1.2W/m²K), 30 cm other floors
MH → thickness 30 cm (U=1.52 W/m²K)</td></tr>
<tr><td>Back facade</td><td colspan="3">Solid masonry walls with interior lime plaster and exterior lime plaster
MCT, MH, PM, MFT → thickness 30 cm (U=1.52 W/m²K)</td></tr>
<tr><td>Annex facade</td><td colspan="3">Solid masonry walls with interior lime plaster and exterior lime plaster
MCT, MH, PM, MFT → thickness 20 cm (U=2.05 W/m²K)</td></tr>
<tr><td rowspan="2">Top boundary</td><td>Pitched roof</td><td colspan="3">Traditional wooden purlin-supported roof with ceramic roof tiles
6 cm mineral wool insulation between the rafters (U = 0.71 W/m²K)</td></tr>
<tr><td>Flat roof</td><td colspan="3">Wooden beam structure finished with lime plaster ceiling and bituminous roofing
6 cm mineral wool as exterior insulation (U = 0.56 W/m²K)</td></tr>
<tr><td rowspan="2">Floors</td><td>Basement floor</td><td colspan="3">Ceramic/cement tiles in sand bed (R = 0.23 m²K/W)</td></tr>
<tr><td>Basement ceiling</td><td colspan="3">Cement tile flooring on vaults (U = 1.22 W/m²K)
Wooden floor structure with wooden flooring (U= 1.22 W/m²K)</td></tr>
<tr><td rowspan="2">Windows</td><td>Front windows</td><td>Original wooden frame
Single glazing
(Ug = 5.8 W/m²K)</td><td>Original wooden frame
Single glazing
(Ug = 5.8 W/m²K)</td><td>Double glazed windows
(Ug = 2.8 W/m²K)</td></tr>
<tr><td>Back windows</td><td>Original wooden frame
Single glazing
(Ug = 5.8 W/m²K)</td><td>Double glazed windows
(Ug = 2.8 W/m²K)</td><td>Double glazed windows
(Ug = 2.8 W/m²K)</td></tr>
<tr><td colspan="2">Airtightness</td><td>v50 = 16 m³/hm²</td><td>v50 = 14 m³/hm²</td><td>v50 = 12 m³/hm²</td></tr>
</table>

Figure 4-6: Overview of the three building envelope scenarios for the Belgian pre-renovation baseline.

4.5.2.2 Renovation baseline

Most of the cases have some construction elements that are already renovated and can serve as a reference to determine the renovation baselines. For these renovation baseline, three building envelope scenarios are identified, 'BS1_RB: Insulated building with thin double front window glazing, without front façade insulation', 'BS2_RB: Insulated building with high performance (harmonized) front windows , without front façade insulation' and 'BS3_RB: Insulated building with high performance (harmonized) front windows , with interior front façade insulation', which are again applicable for the different archetypes. The insulation level that is applied to the different elements is based on the Belgian EPB insulation requirements where needed. This usually corresponds to a maximum thermal transmittance of 0.24 W/m²K for opaque construction elements. Where no requirements apply (e.g. due to the heritage status of the building), the insulation level is based on the requirements to receive renovation subsidies (Flanders, 2025), so not perse on the maximum U-value requirements.

4.5.2.2.1 Walls

The different walls are treated differently in the different building envelope scenario. Firstly, the back façade and the annex facades are assumed to be insulated in all the scenarios using exterior insulation (ETICS), finished with a gypsum plaster. Both facades are insulated until a thermal transmittance of 0.24 W/m²K is reached. On achieving this, the insulation layer has a higher thermal resistance than 3 m²K/W, which is the limit to receive subsidies.

The front facade is treated differently: in BS1_RB and BS1_RB, the front façade is not insulated because of the high heritage value of both the interior and exterior side. The thermal transmittance remains 1.2 W/m²K for the ground floor and 1.52 W/m²K for the other floors. In BS3_RB, the front façade is assumed to be insulated from the interior side. The subsidy requirement is an insulation package with a thermal resistance bigger than 2 m²K/W. This results in a thermal transmittance of 0.35 W/m²K for the ground floor and 0.37 W/m²K for the other floors. Additional attention is needed for the thermal bridges that are created using interior insulation.

4.5.2.2.2 Top boundary

The pitched roof and flat roof are renovated in the same way for the different baseline scenarios and archetypes. For the pitched roof, additional insulation is placed between the purlins, so that the total insulation package has a thermal resistance of 4.5 m²K/W (to receive subsidies). The resulting thermal transmittance of the pitched roof is 0.22 W/m²K. For the flat roof, the insulation is added on the exterior side, replacing the old insulation layer. This results in a thermal transmittance of 0.19 W/m²K.

4.5.2.2.3 Floors

The floors of the ground floor (basement ceiling) are insulated in the same way in the three building envelope scenarios and in all the archetypes. Insulation is placed from the bottom side against the vaulted ceiling and between the wooden beam structure of the wooden floors. Belgian EPB requirements demand a maximum thermal transmittance of 0.24 W/m²K for floors. This results in an insulation layer with a thermal resistance that is higher than 2 m²K/W, which is required for receiving subsidies.

4.5.2.2.4 Windows

As can be seen in most cases, the windows in the back facade are replaced with new windows with high performance glazing, mostly with PVC frames. Also, for the three building envelope renovation baselines, the windows in the back façade are considered new windows with high performance glazing, with a thermal transmittance for the glazing of 1.0 W/m²K. The frames of those windows can be any material: PVC, wood or aluminium.

The windows in the front façade are treated differently. Also, here the heritage value of the windows and the building will determine which measure is taken. In BS1_RB the windows of the front façade are preserved as much as possible. The original wooden frames are restored and equipped with thin double glazing, so that they fit in the section of the existing frame. The thermal transmittance of the glazing is in accordance with the observations in the cases, assumed 1.8 W/m²K. For BS2_RB and BS3_RB the windows in the front façade are supposed to be new ones, but in harmony with the original material and esthetics. The new windows are thus wooden windows that are made according to the original window model, where modern high-performance glazing can be introduced. The thermal transmittance of the glazing can be the same as modern ones, 1.0 W/m²K. In Table 4-7, an overview of the different windows in the different building envelope renovation baselines is shown.

Table 4-7: Overview of the windows scenarios in the Belgian renovation baselines.

Building envelope baseline scenario	BS1_PB	BS2_PB	BS3_PB
Front façade windows			
Description	Original wooden frames with thin double glazing	New harmonizing windows with high performance glazing	New harmonizing windows with high performance glazing
Ug-value [W/m²K]	1.8	1.0	1.0
Uf-value [W/m²K]	2	1.8	1.8
Back façade windows			
Description	Contemporary windows (wood-PVC-alu) with high performance double glazing		
Ug-value [W/m²K]	1.0		
Uf-value [W/m²K]	1.8-2.5		

4.5.2.2.5 Airtightness

Firstly, it is again difficult to determine the airtightness for the different renovation baselines, as the results from the measurements are characterised by a large spread.

It can be assumed that, in general, airtightness improves following thorough energy renovation compared to the pre-renovation condition, even in historic townhouses. Consequently, the v_{50}-value is expected to be lower than that of the pre-renovation baseline. However, this level of airtightness will not match that of new-build dwellings or standard home renovations, which, according to Flemish data, typically achieve values for the specific envelope leakage rate around 3 m³/hm² (Flemish Energy and Climate Agency, n.d.). Research into post-renovation airtightness demonstrates that achieving such low values is challenging. Lambie and Saelens (2021) concluded that while renovating dwellings can lead to improved airtightness—up to a v_{50}-value of 5.5 m³/hm²—this requires significant interventions. Nevertheless, when examining the airtightness measurement results of the most extensively renovated cases—MUINK, DENDER, and MARTENS2—it appears that only v_{50}-values between 8 and 9 m³/hm² are attainable.

In BS2_RB and BS3_RB, a comprehensive renovation is assumed, involving complete roof insulation including the application of a vapour barrier, as well as the replacement of all windows throughout the dwelling. In this context, the best possible airtightness can be expected, bearing in mind that these remain large, historic properties. A v_{50}-value of 6 m³/hm² is therefore adopted in these renovation baselines, consistent with the value assumed by Decorte (2024) for deep energy renovations of Flemish homes. For BS1_RB, where the roof is thoroughly renovated but the window in the front façade is not replaced (only the glazing is upgraded), a v_{50}-value of 8 m³/hm² is assumed.

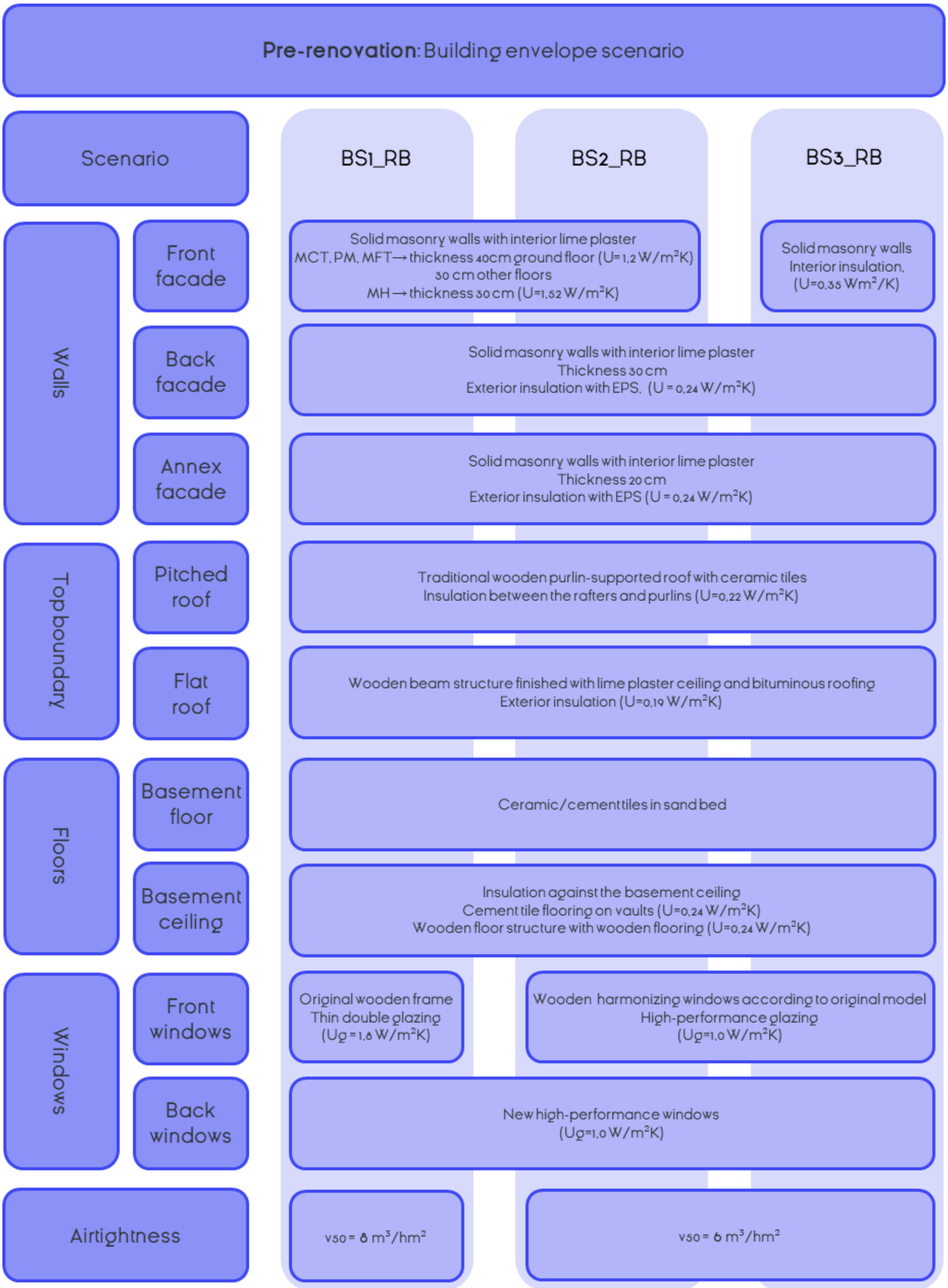


Figure 4-7: Overview of the three building envelope scenarios for the Belgian renovation baseline.

5. Norway

The studied archetype is the **townhouse with courtyard**, which is characteristic of the "Bakklandet" neighbourhood of Trondheim. It is based on a timber/wood log construction. Traditional log buildings in Norway hold significant cultural value. Adapting these structures for modern comfort without compromising their heritage value, is challenging. Introducing new materials for insulation must be done carefully to avoid damaging the buildings. The primary structure is made of massive wood, featuring either a wood log system or a system composed by vertical wooden planks within a timber frame. The prevailing construction is wood log system in the front buildings (towards the street), and either wood log or timber frame in the outbuildings (wing- and back yard buildings). The neighbourhood, archetype and case study building selection is further detailed in deliverable D5.1.

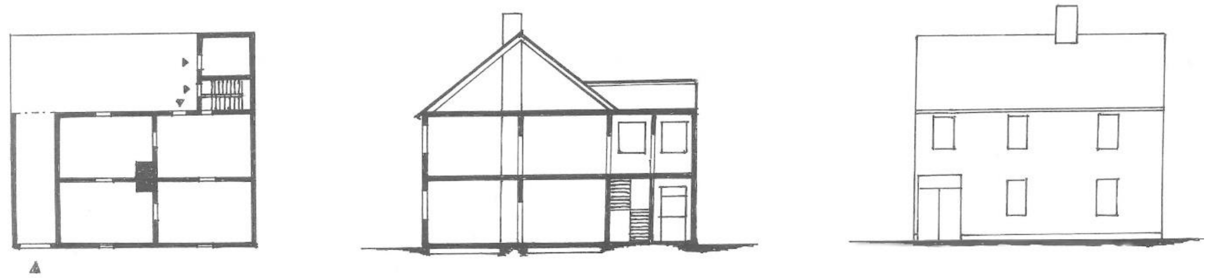
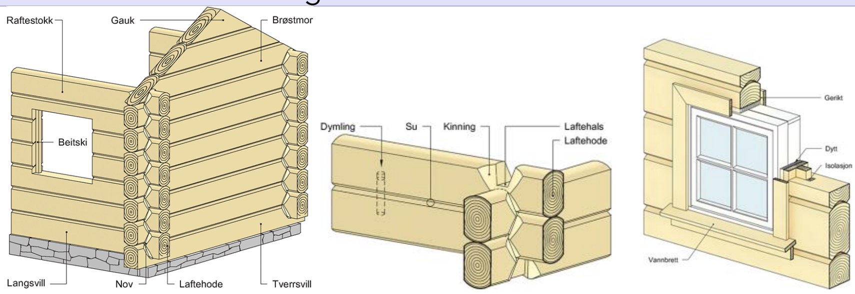


Figure 5-1: Overview of the Norwegian townhouse with courtyard archetype by plan, section, and facade (NO).

In Norway, the primary focus of measurement efforts was on indoor air quality (as detailed in D3.2) and laboratory investigations into interior insulation solutions for plank walls (task T2.4 of the HeriTACE project). The envelope characteristics presented here have been assessed and summarized by use of findings from previous Norwegian studies on heritage buildings very much resembles the ones found in "Bakklandet".

5.1 Envelope characteristics

5.1.1 Exterior walls – Solid log structures

<table>
<tr><td>Description</td><td>Solid log structures were widely used as exterior walls from the late 18th century and well into the 19th century.</td></tr>
<tr><td>Typical condition</td><td>The walls are often found to be structurally intact due to the high quality of original materials and craftsmanship. These walls were typically constructed with solid logs with or without exterior barrier layer/ exterior or interior wooden claddings. While many retain their structural integrity, they often show signs of aging such as surface wear, deformations, or weathering. Original architectural details—such as trims, corner boards, or profiled cladding—are frequently preserved but may be brittle or degraded due to prolonged exposure to moisture and UV radiation.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Common deterioration in these wall constructions includes moisture-induced decay such as rot in the lower sections of the wall, particularly near ground level, beneath windows, and in areas with poor drainage. Cracking, settlement, and warping may also occur due to foundation shifts, thermal movements, or frost action. Biological growth, such as algae and fungi, is frequently found in shaded or poorly ventilated areas. Insect damage, such as from wood-boring beetles, can be present in untreated or previously damp timber. In addition, paint degradation and the delamination of protective coatings are common and contribute to accelerated weathering of the wood underneath.</td></tr>
<tr><td>Illustration</td><td>

(SINTEF 723.304, 2017)</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material</th><th>Thickness [mm]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Wooden log structure</td><td>76,2</td><td>0.12 - 0.13</td><td>450 - 500</td></tr>
<tr><td>TOTAL</td><td>152.3-189.8</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>The typical value of log walls is (SINTEF 471.431, 2013):
50 mm (2"): 2,0 W/(m²·K), 100 mm (4"): 1,2 W/(m²·K), 150 mm (6"): 0,84 W/(m²·K), 200 mm (8"): 0,65 W/(m²·K), 250 mm (10"): 0,54 W/(m²·K)</td></tr>
</table>

5.1.2 Exterior walls – Vertical plank framing

Description

Traditional Norwegian exterior walls evolved from solid log construction, which was widely used from the late 18th century and well into the 19th century. In 1850–1900, timber frame structures with infill panels became common, especially for smaller residential buildings. From around 1850, lighter frame constructions with various types of infill began to replace the heavy log structures. One such system was "vertical plank framing", where vertical planks served as both the load-bearing element and enclosure; this technique became common around 1910 and was used until the 1950s.

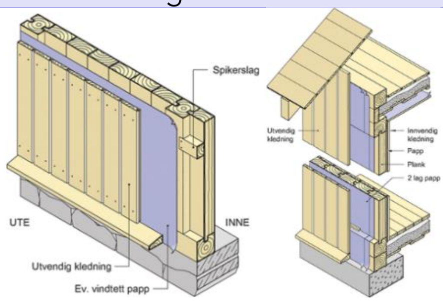
Typical condition

Exterior walls in heritage wooden buildings are often found to be structurally intact due to the high quality of original materials and craftsmanship. While many retain their structural integrity, they often show signs of aging such as surface wear, deformations, or weathering. Original architectural details—such as trims, corner boards, or profiled cladding—are frequently preserved but may be brittle or degraded due to prolonged exposure to moisture and UV radiation.

Typical damage mechanisms

Common deterioration includes moisture-induced decay such as rot in the lower sections of the wall, particularly near ground level, beneath windows, and in areas with poor drainage. Cracking, settlement, and warping may also occur due to foundation shifts, thermal movements, or frost action. Biological growth is frequently found in shaded or poorly ventilated areas. Insect damage can be present in untreated or previously damp timber. In addition, paint degradation and the delamination of protective coatings are common.

Illustration



(SINTEF 723.305, 2017)

Structure

Material	Thickness [mm]	Thermal conductivity [W/(m·K)]	Density [kg/m³]
Interior wooden cladding	19-32	0.12 - 0.13	450 - 500
Barrier layer (One or two layers of wool or cellulose paper (impregnated))	-	-	-
Wooden planks (softwood)	76	0.12 - 0.13	450 - 500
Barrier layer (Two layers of impregnated building paper (sheathing paper)	-	-	-
Air layer (unventilated)	39-50		
Exterior wooden cladding	19-32	0.12 - 0.13	450 - 500
TOTAL	150 -190		

Thermal transmittance U, W/(m²·K)

The typical value is approximately **0,80 W/(m²K)**

5.1.3 Top boundary - Ceiling towards cold attic / Intermediate floors

Description

Ceilings towards cold attics and intermediate floors in heritage wooden buildings were typically constructed with large timber joists, covered with wooden boards above and below (commonly referred to as *stubbeloft* in Norwegian). The cavity between the joists was filled with clay or other mineral soil materials without organic content, serving as thermal and acoustic insulation as well as fire protection. From around the mid-19th century, this construction became widespread due to increased regulatory requirements and higher comfort expectations. The floorboards, often made of spruce or pine, varied in width depending on the construction period. Joist dimensions typically ranged from 18–20 cm in width and 23–25 cm in height, with joist spacing between 0.8 and 1.0 metres. [1]

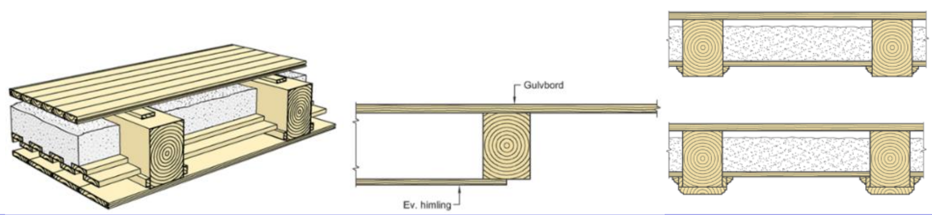
Typical condition

Ceilings and intermediate floors in older wooden buildings are often well-preserved, particularly when protected from moisture ingress and structural overloading. The timber elements generally exhibit high material quality, and the original clay infill is frequently still present. Hand-planed or early machine-planed floorboards are commonly intact, although wear is often visible. In well-maintained buildings, these constructions provide good acoustic and thermal performance, although they may not meet modern standards.

Typical damage mechanisms

Damage to intermediate floors and ceilings is most often related to moisture exposure, such as leakage from above or condensation issues in unventilated cold attics. Rot and fungal growth may affect joists and boards, especially around penetrations or where ventilation is poor. Sagging due to long-term deflection, insect damage (e.g., from woodworm or beetles), and brittle or compacted clay fill are also typical issues. In some cases, floorboards may have loosened or split due to drying shrinkage or mechanical stress. Cracking in plastered ceilings beneath may indicate structural movement or fatigue in the timber frame.

Illustration



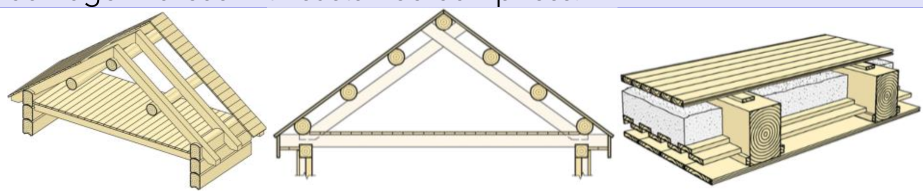
Structure

Material	Thickness [m]	Thermal conductivity [W/(m·K)]	Density [kg/m³]
Exterior wooden board	50.8 (2”)	0.12-0.13	450 - 500
Air layer			
Clay layer	50 – 150[1]		1200 – 1800
Interior wooden board	50.8 (2”)	0.12-0.13	450 - 500
TOTAL	152-252		

Thermal transmittance U, W/(m²·K)

The indicative U-value of these constructions is approximately **0.95-1.0 W/(m²K),** depending on fill depth and material.

5.1.4 Pitched roofs with cold attics

Description	Roofs in traditional wooden buildings were typically constructed as pitched timber structures. For buildings of standard width and roof pitches of 25–30° or more, the uppermost floor would have a horizontal ceiling below a relatively spacious unheated attic (referred to as *kaldt loft* or *mørkeloft* in Norwegian). In urban apartment buildings, the attic space was often expanded using a knee wall (*knevegg*) and tie beam, allowing the area to be used for storage or drying clothes. The floor of the attic, and thus the ceiling above the heated space, was generally constructed in the same manner as intermediate floors, with timber joists and a *stubbeloft* layer filled with mineral soil materials for thermal and acoustic insulation. [1]
Typical condition	Floors beneath cold attics (ceilings) are often found in good structural condition, especially when protected from roof leaks and condensation. The original timber joists and clay infill typically remain intact and functional. The unheated attic space contributes to the longevity of the construction by buffering temperature extremes and reducing moisture fluctuations. Floorboards laid over the attic joists are often preserved and may still be used for access or light storage. Where ventilation has been sufficient, the condition of both timber and infill materials tends to be stable.
Typical damage mechanisms	Common types of deterioration in roof-ceiling assemblies include moisture damage caused by roof leakage, poor ventilation, or condensation within the cold attic. This can lead to rot in joists and degradation of the clay infill. Mould and fungal growth may occur on the underside of attic boards or within the insulation cavity if humidity levels remain high. Air leakage from the heated space below can exacerbate condensation issues and lead to ice damming in cold climates. Other typical issues include sagging ceilings due to long-term deflection, cracking in plaster finishes, and localized insect damage in areas with sustained dampness.
Illustration	

Structure

Material	Thickness [mm]	Thermal conductivity [W/(m·K)]	Density [kg/m³]
Exterior wooden board	50.8 (2″)	0.12-0.13	450-500
Air layer			
Clay layer	50 – 150		1200 – 1800
Interior wooden board	50.8 (2″)		450-500
TOTAL	152-252		

Thermal transmittance U, W/(m²·K)	The indicative U-value of the ceiling structure is **0.95-1.0 W/(m²K),** without considering the R-value of the cold attic and roof structure. (SINTEF 725.012, 2016) (SINTEF 722.310, 2017)

5.1.5 Floors - slab on ground, above basements or above crawlspaces

Description

In traditional wooden buildings constructed before around 1850, floors were typically built above shallow foundations. For lightweight structures, the foundation wall was often laid directly on levelled stones or constructed as a dry-stone perimeter enclosing a compacted fill of available materials. Wooden floor joists were commonly embedded directly in this fill, either loosely supported within the sill frame or partially buried. This technique aimed to minimise air infiltration and cold draughts by maintaining the soil close to the underside of the floorboards. Monumental structures had continuous deep stone foundations. Typical floor constructions had little or no insulation, and thermal performance depended largely on the ground conditions and fill materials.

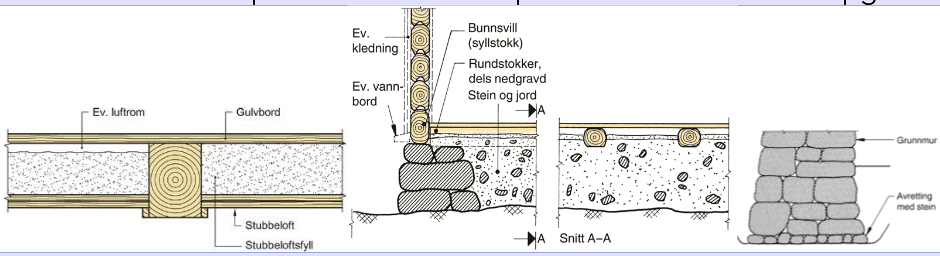
Typical condition

Ground-floor constructions in historic timber buildings can often be found largely intact, particularly when protected from prolonged exposure to soil moisture. In many cases, the original wooden joists and boards are preserved. Dry fill and close ground contact helped reduce draughts but also limited ventilation. Where good drainage and sufficient sub-floor ventilation are present, wooden components tend to remain in relatively stable condition.

Typical damage mechanisms

The most common forms of deterioration in traditional ground-floor assemblies stem from moisture ingress from the surrounding soil. Joists and sill beams may be subject to rot or insect attack, particularly where the timber is in direct contact with damp fill or unventilated cavities. Fungal decay and settlement are frequent in floors with inadequate drainage or no capillary break. Over time, structural sagging, woodworm damage, and air leakage due to shrinkage and joint opening may also occur. In some cases, complete floor replacement may have been carried out due to persistent moisture problems or functional upgrades.

Illustration



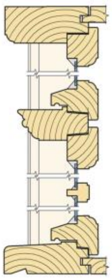
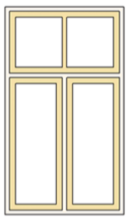
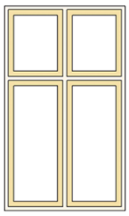
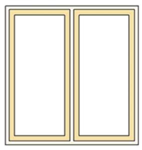
Structure

Material	Thickness [mm]	Thermal conductivity [W/(m·K)]	Density [kg/m³]
Interior wooden board	50.8 (2”)	0.12-0.13	450-500
Clay layer	50 – 150		1200 – 1800
Air layer			
Exterior wooden board	50.8 (2”)	0.12-0.13	450-500
TOTAL	152-252		

Thermal transmittance U, W/(m²·K)

The indicative U-value of the floor structure is **0,95–1,0 W/(m²K).** This does not include the R-value of the ground/crawlspace/basement.

5.1.6 Windows - Cross-post and T-post

Description	Cross-post and T-post windows became widespread during the latter half of the 19th century, in parallel with the rise of the Swiss chalet style. Often referred to as "Swiss-style windows", these designs were not limited to that architectural tradition. Windows from this period typically featured more robust frames and lintels, especially around the central mullion, which was sometimes omitted altogether. The increasing availability of industrially produced ironmongery gradually replaced earlier hand-forged fittings, reflecting broader developments in building technology. Cross-post windows generally have four sashes, while T-post windows typically have three sashes in the lower part, enhancing light and ventilation.
Typical condition	If well maintained, original cross-post and T-post windows are often well preserved in historic buildings due to the quality of the timber and craftsmanship used in their construction. Where they have been maintained or protected from excessive moisture, these windows retain their original profiles, joinery, and fittings. Paint layers may show evidence of repeated maintenance over time, including changes in colour or paint systems. In some cases, the original glazing – typically thin, hand-blown or early machine-made glass – is still intact. The windows often continue to function as intended, especially where overhauls or partial restorations have been carried out.
Typical damage mechanisms	Common forms of deterioration in these historic window types include rot at the lower rails and sills due to water ingress, particularly in poorly maintained or exposed facades. The central post or mullion may show signs of structural weakening or displacement. Paint degradation, cracking putty, and rusted or missing fittings are also frequent issues. Repeated overpainting can obscure detailing or cause operability problems. In some cases, inappropriate repairs or replacements with non-original materials have led to loss of authenticity or function. Air leakage, draughts, and thermal inefficiency are common concerns in unrestored windows.
Illustrations (examples)	 Single-glazed window  T-post window   Cross-post windows without mullions (Krysspostvinduer).   Windows from the Functionalist period (c. 1930–1960).
Thermal transmittance U, W/(m²·K) (indicative average values)	Single-glazed window: **4.0-5.0 W/(m²K)** (DIBK, 2018) (Uvsløkk, 2012). Coupled window (two separate sashes/glazing layers): **1,5 W/(m²K)** (Uvsløkk, 2012). Outer single pane and inner double-glazed insulating unit: **1,0 W/(m²K)** (Uvsløkk, 2012).

5.2 Airtightness

The airtightness values of the Norwegian case studies have not been measured but are expected to be poor. Previous measurements of approximately 40 to 50-year-old Norwegian wooden houses suggest an airtightness of around 5.0 h^{-1} (n_{50}) (Brunsell et al. 1980). It can be anticipated that the studied heritage buildings will have an airtightness range between 5 and 10 h^{-1}.

5.3 Summary of archetype envelope characteristics & baseline definition

5.3.1 Summary of envelope characteristics of case study buildings

Country	Norway	**Building code**	Nedre 1	Nygata
Archetype	Wooden town house	**Heated area (int. dim.), m²**	159	66
Town	Trondheim	**Net area (int. dim.), m²**	159	66
		Envel. area (int. dim.), m²	502	184.8
Exterior wall	**Solid log structure**	U, W/(m²·K)		0.84
		Share of envelope, %		56%
	Vertical plank framing	U, W/(m²·K)	0.8	
		Share of envelope, %	58%	
Exterior walls (facing neighbouring building)	**Vertical plank framing**	U, W/(m²·K)	2.0	
		Share of envelope, %	23%	
Roof	**Type 1**	U, W/(m²·K)	1.0	1.0
		Share of envelope, %	18%	18%
Floor	**Towards the ground**	U, W/(m²·K)	1.0	1.0
		Share of envelope, %	14%	18%
	Towards free air	U, W/(m²·K)		
		Share of envelope, %	4%	
Windows / doors	**Single glazed windows / wooden doors without insulation**	U_{window}, W/(m²·K)	5.0	5.0
		U_{glass}, W/(m²·K)		
		g-value, -		
		Share of envelope, %	6%	8%
		q_{E50}, m³/(h·m²)		
Air tightness	**Envel. average (int. dim.)**	n_{50}, 1/h	5–10 [a]	
Thermal bridges		Lin. th. transm. Ψ, W/(m·K)	0.07 [b]	

[a] Based on literature (Brunsell et al. 1980).

[b] Specific values for thermal bridges in old Norwegian wooden heritage buildings have not been found in the literature. For energy simulations, a normalised thermal bridge of 0,07 W/m²K can be used (according to Table B.3 in NS 3031:2025 Energy performance of buildings. Calculation of energy and power demand).

5.3.2 Baseline definition

Based on the results described in previous subsections, the baseline scenarios describe the building archetypes for two time points to be used in the future as a reference to assess the effectiveness of the innovative retrofit solutions proposed by HeriTACE project. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these types of buildings as if they would be renovated today. In this report, only the baseline scenarios regarding the building envelope are described. The complete baseline scenarios (including heritage value, space conditioning, energy systems and use scenarios) are described in 'D5.4 Baseline scenarios'.

5.3.2.1 Pre renovation baseline

There are two different building envelope scenarios for the pre-renovation baseline. For walls, roofs and floors they are the same, but the situation for the kind of windows is different.

The prevailing construction is a solid timber log structure in the front buildings, and a panelled timber-framing in the back yard buildings. There is clay infill in the wooden ceiling- and basement floors so they remain original. Apart from the original materials, no later insulation layers have been added.

BS1_PB: Old windows*;* In this scenario, the old wooden window frame with old or original single glazing exists. Due to the Norwegian climatic condition an interior single casement is also added in newer times. These windows must be preserved.

BS2_PB: Double-glazed windows*;* In this scenario, all windows have already been replaced with double-glazed windows between 1970 and 1990.

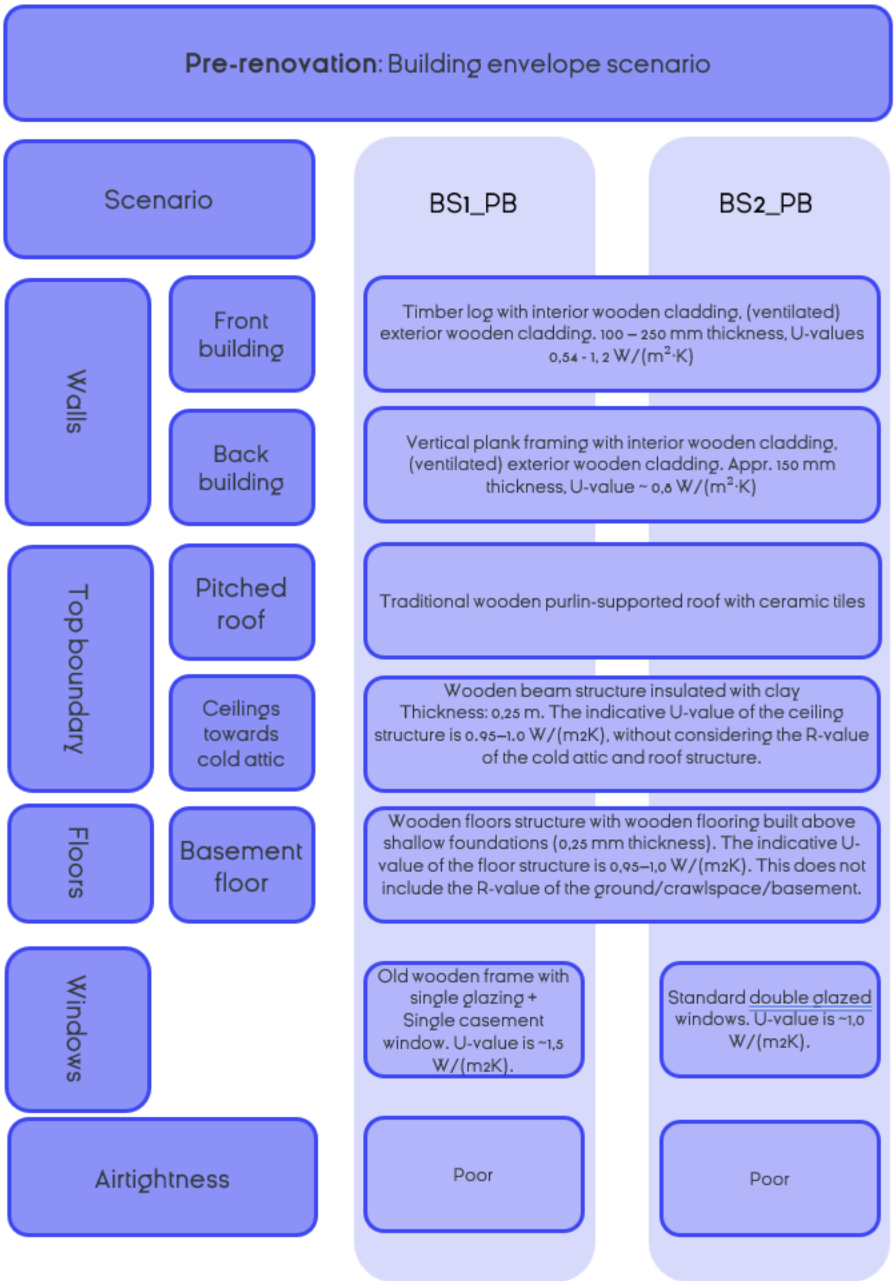


Figure 5-2: Pre-renovation baseline of the Norwegian archetype.

5.3.2.2 Renovation baseline

The renovation baseline corresponds to a renovation according to common practice today.

BS1_RB Restricted

In this scenario, the prevailing construction is a solid timber log structure (100 mm – 250 mm thick) with interior and exterior wooden claddings in the front buildings, and a panelled timber-framing in the back yard buildings, and the walls remain uninsulated. The clay infill in the ceiling- and basement floors is removed, and modern insulation material (typical mineral wool) is added. Removal of the stub loft clay and subfloor materials is permitted, on the condition that the intervention does not compromise any interior elements of heritage value. The existing windows in the front building must be preserved, with the interior single casement added. The restrictions are not evident for the back buildings and new high-performance windows can be applied.

BS2_RB Interior insulation

In this scenario, the cladded solid timber log structure and paneled timber-framing can be insulated from the inside/interior side, while not touching the valuable and original wooden cladding. The interior cladding is most often removed during this process. The stub clay in the ceiling floor and the basement floor is removed, and modern insulation material (typical mineral wool) is added. The old window frames shall remain, but new high-performance glazing is permitted. If the windows are newer, but with poor performance, modern, new wooden windows according to original model, with high-performance glazing can be used.

BS3_RB Exterior insulation

In this scenario, the solid timber log structure in the front buildings and the paneled timber-framing in the back yard buildings can be insulated from the out-/exterior side. The exterior cladding is removed; barrier layers and insulation is added in addition to a new cladding. The clay in the ceiling floor and the basement floor is removed and modern insulation material (typical mineral wool) is added. Contemporary, new wooden windows, according to original model with high-performance glazing, are introduced.

<table>
<tr><th colspan="5">Renovation: Building envelope scenario</th></tr>
<tr><th colspan="2">Scenario</th><th>BS1_RB</th><th>BS2_RB</th><th>BS3_RB</th></tr>
<tr><td rowspan="2">Walls</td><td>Front building</td><td>Timber log with interior wooden cladding, exterior wooden cladding. U-value ~ 0,54 – 2,0W/(m2K)</td><td>Interior insulation (7 cm), interior cladding replaced. U-value ~ 0,30 W/(m2K)</td><td>Exterior insulation, (5–15 cm) exterior cladding replaced. ~ 0,3 W/(m2K)</td></tr>
<tr><td>Back building</td><td>Vertical plank framing with interior and exterior wooden cladding. U-value ~ 0,8 W/(m2K)</td><td>Interior insulation (7 cm) , interior cladding replaced. U-value ~ 0,3 W/(m2K)</td><td>Exterior insulation, (5–15 cm) exterior cladding replaced. U-value ~ 0,3 W/(m2K)</td></tr>
<tr><td rowspan="2">Top boundary</td><td>Pitched roof</td><td colspan="3">Traditional wooden purlin-supported roof with ceramic tiles</td></tr>
<tr><td>Ceilings towards cold attic</td><td colspan="3">Mineral wool or wood fibre insulation (boards or blown-in, 5-15 cm) is added on the attic floor. The indicative U-value of the ceiling structure is 0,49 – 0,22 W/(m²K), without considering the R-value of the cold attic and roof structure.</td></tr>
<tr><td>Floors</td><td>Basement floor</td><td colspan="3">Mineral wool or wood fibre insulation can be added on the basement ceiling. The indicative U-value of the floor structure is 0,49–0,22 W/(m²K). This does not include the R-value of the ground/crawlspace/basement.</td></tr>
<tr><td rowspan="2">Windows</td><td>Front windows</td><td>Old wooden frame with single glazing + Single casement window U-value ~1,0 W/(m2K).</td><td>Old wooden window frames with new high-performance glazing. U-value ~1,0 W/(m2K).</td><td>New wooden windows - original model. High-performance glazing. U-value ~0,85 W/(m2K).</td></tr>
<tr><td>Back windows</td><td colspan="3">New high-performance windows. U-value ~0,85 W/(m2K).</td></tr>
<tr><td colspan="2">Airtightness</td><td>Poor - Worst of the three</td><td>Poor - Middle of the three</td><td>Poor - Best of the three</td></tr>
</table>

Figure 5-3: Renovation baseline of the Norwegian archetype.

6. Estonia

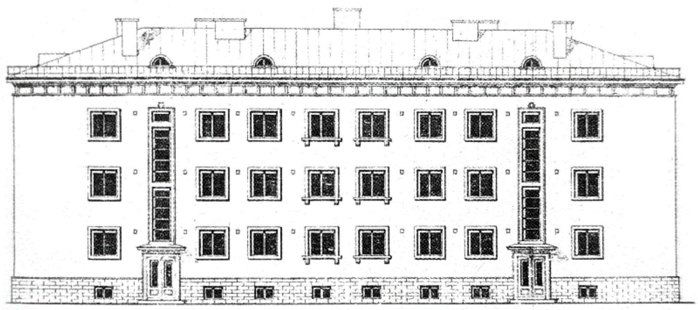
In Estonia the project targets the neighbourhood of "Uus Maailm" in Tallinn. It is characterized by two heritage building archetypes: the **wooden apartment building** (which can be further split into "Lender" and "Tallinn" types) and the **Stalinist-stype brick apartment building**. The neighbourhood, archetype and case study building selection is further detailed in deliverable D5.1.

The **wooden apartment buildings** can mainly be split between 2 subtypes. One is referred to as the 'Lender's' building type originating from the end of the 19th and beginning of the 20th century and was designed for poor peasants of Estonian nationality who came from the countryside to work in various industrial sites and could only afford to rent an inexpensive apartment. The Lender's buildings typically have two floors, are symmetrical and made of limestone (foundation and plinth) and horizontal logs. The facade is covered with horizontal boarding, some are more decorative and others very simple, the front door being the only aesthetically designed element. The roof type is open gable.

Another subtype is the 'Tallinn' building style buildings (1920-1930s) and characterized by one central stairwell made of brick. This building type was designed to be rented mainly to upper working-class and middle-class families but there are also some with very large, bourgeois apartments. Those buildings are constructed of limestone (foundation and plinth), planks or wooden truss and bricks (stairwell). The facade can be covered in wooden boarding or with plaster. The roof type can be hip, jerkinhead, gambrel or mansard. They mostly have two floors but for a short period also adding a third floor was allowed.

Stalinist style apartment buildings constructed in 1940-1955 represent a variety of buildings both small and large, wooden and brick. In this project, Stalinist style buildings made of brick were selected. In Estonia, this type of apartment buildings was built in place of those destroyed in WWII and constructed mainly to accommodate workers who immigrated from Soviet Russia. Behind the highly decorated facades were often apartments with simple living conditions and little decoration.

Wooden apartment building ('Lender' type)



'Stalinist' style brick apartment building

Figure 6-1: Overview of targeted Estonian archetypes by facade.

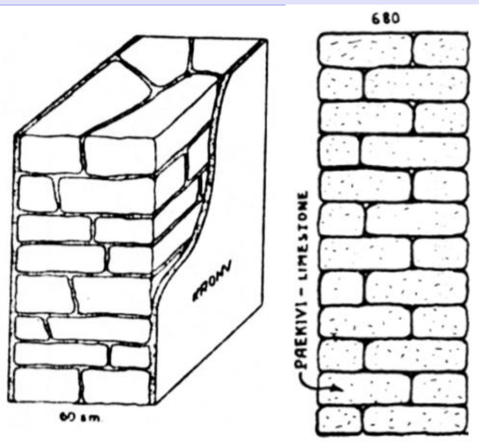
In total, 5 case study buildings are studied in detail (3 wooden and 2 masonry buildings). Airtightness was measured in 3 wooden and 1 brick building. Thermal transmittance was measured mainly on walls in 2 wooden and 2 brick buildings. In all cases the envelope and its components were visually assessed and documented. The investigations spanned from March 2024 until June 2025 and were further complemented by previous studies.

6.1 Envelope characteristics

6.1.1 Walls

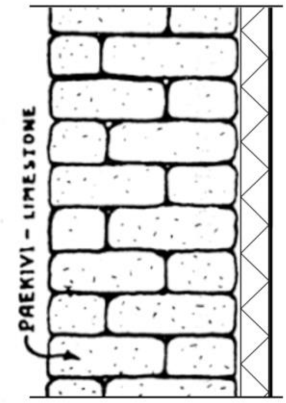
6.1.1.1 Limestone masonry plinth

<table>
<tr><td>Description</td><td>The limestone masonry foundation was used in northern and western Estonia until the 1960s. Stone was readily available in these areas from nearby mines. Weather-resistant limestone plinths were left unplastered and stone surface was built to a high quality without the need for an additional layer of finish. Plinths made of poorer quality limestone were rendered for better durability and appearance.</td></tr>
<tr><td>Typical condition</td><td>If the facades are unmaintained, the facades have progressively developing damage in the exterior plaster or mortar layer due to moisture ingress at joints, damaged flashings, rainwater systems, differential settlement etc.
Unless the basement is heated, ventilated and a water barrier has been installed, the interior surface is moist and suitable for mould growth.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Moisture-related deterioration caused by rainwater penetration (damaged rainwater systems, flashings, wind driven rain), splashing from street, rising damp and leads to frost damage, spalling of stones, and degradation of plaster surfaces. Condensation on interior surfaces along with previous moisture ingress mechanisms leads to mould growth on interior.
The use of ice melting salts on the streets causes chemical degradation too.</td></tr>
<tr><td>Illustration</td><td>

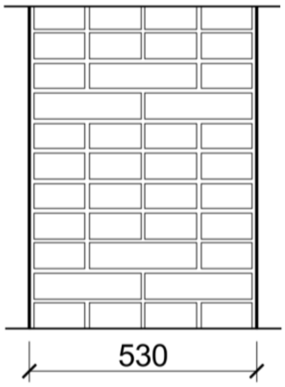


</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>(Plaster)</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>Limestone/mortar</td><td>0.6–0.7</td><td>2.5 / 0.8</td><td>1950 / 1600</td></tr>
<tr><td>(Plaster)</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>TOTAL</td><td>0.6–0.7</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 2.0–2.3 (EN ISO 10211)</td></tr>
</table>

6.1.1.2 Limestone masonry plinth with 100 mm exterior insulation

<table>
<tr><td>Description</td><td>For the last twenty years the renovation practice has been to insulate old solid-stone foundation walls with mainly expanded polystyrene (EPS) boards finished with plaster or cement fibre boards. Also closed-cell PUR foam is used less frequently. If the building has an unplastered good quality stone plinth, the foundation is often insulated only below ground level.</td></tr>
<tr><td>Typical condition</td><td>There was 1 building among the case studies with this solution. The plaster was damaged due to differential settlement and/or frost heaving beneath the sloping concrete slab adjacent to the plinth.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Moisture-related deterioration caused by rainwater penetration (damaged rainwater systems, flashing, wind driven rain), splashing from street, rising damp and leads to frost damage and degradation of exterior plaster. Use of ice melting salts on the streets causes chemical degradation too.
While thermal transmittance is reduced compared to the original structure and condensation is no longer an issue, rising damp and faulty flashings can still result in moist interior surfaces and mould growth.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>(Plaster)</td><td>0.01</td><td>0.8</td><td>1600</td></tr>
<tr><td>Limestone/mortar</td><td>0.6–0.7</td><td>1.9 / 0.8</td><td>1950 / 1800</td></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.8</td><td>1600</td></tr>
<tr><td>Insulation</td><td>0.1</td><td>0.037</td><td>30</td></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.8</td><td>1600</td></tr>
<tr><td>TOTAL</td><td>0.7-0.8</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 0.32 (EN ISO 6946)</td></tr>
</table>

6.1.1.3 Plastered mass masonry wall

<table>
<tr><td>Description</td><td>The construction comprises a 51 cm thick lime-sand or ceramic brick masonry core, finished with 1 cm of plaster on both the interior and exterior faces. Plastered mass masonry walls constructed from locally available materials (limestone, granite, ceramic bricks) were widely used in Estonian dwellings until the mid-20th century. These were then finished with lime-based plaster and paint from both sides for aesthetic reasons and weather protection. From 1910 onwards, silicate bricks began to be used as masonry units. The use of mass masonry walls was driven by their excellent thermal mass, durability, and availability of materials. Plastered walls could be constructed faster and cheaper, because the quality of stones and laying of the wall was not that important compared to unplastered walls.
The standard brick size before WWII was 270x130x70/65 mm, after 1941: 250x120x65 mm.</td></tr>
<tr><td>Typical condition</td><td>Unmaintained facades have progressively developed damage in the exterior plaster layer due to moisture ingress at joints, damaged flashings, rainwater systems, differential settlement etc.
Interior surface may have mould growth on thermal bridges (e.g. corners).</td></tr>
<tr><td>Typical damage mechanisms</td><td>Moisture-related deterioration caused by condensation and rising damp leads to mould growth, spalling of brickwork, and degradation of plaster surfaces. Differential settlement causes cracking of the exterior plaster and leads to moisture ingress and onset of freeze-thaw damage. Condensation on interior surfaces along with previous moisture ingress mechanisms leads to mould growth on interior.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Th. conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>Lime-sand / ceramic brick</td><td>0.51</td><td>1.5 / 0.75</td><td>1950 / 1800</td></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>TOTAL</td><td>0.53</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 1.8 (lime-sand brick); 1.1 (ceramic brick) (EN ISO 6946)
Measured: 1.1 (Kristiina case)</td></tr>
</table>

6.1.1.4 Brick masonry wall with a cavity

Description

Multi-layered air-spaced brick walls started to be promoted in Estonia in the 1930s and became particularly popular after World War II. The inclusion of the cavity mitigated the main issues with mass masonry walls: heat losses and moisture related issues (rainwater penetration and condensation on cold interior surfaces). Both tie stones and steel ties have been used to connect the inner and outer brick layers together. Before WWII the cavity usually appeared on the interior side while post-war cavity is near the exterior surface. A typical solution of the earlier post-war period is to have tie stones every 4^{th} or 6^{th} brick row.

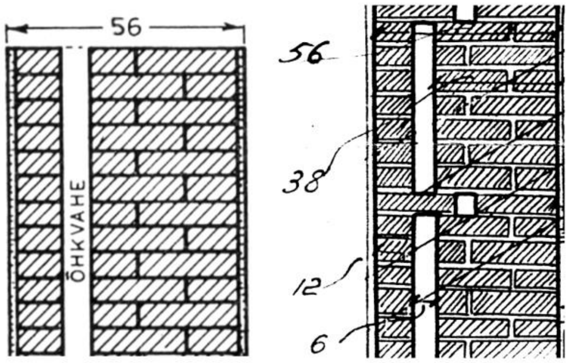
Typical condition

Unmaintained facades have progressively developed damage in the exterior plaster layer due to moisture ingress at joints, damaged flashings, rainwater systems, differential settlement etc.

Typical damage mechanisms

Moisture-related deterioration caused by condensation and rising damp leads to mould growth, spalling of brickwork, and degradation of plaster surfaces. Differential settlement causes cracking of the exterior plaster and leads to moisture ingress and onset of freeze-thaw damage.

Illustration



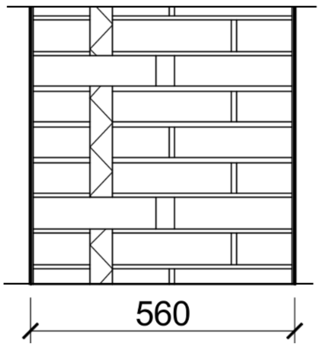
Structure

Material (starting from interior)	**Thickness [m]**	**Thermal conductivity [W/(m·K)]**	**Density [kg/m^3]**
Plaster	0.01	0.8	1800
Lime-sand brick Ceramic brick	0.38	1.5 / 0.75	1950 / 1800
Air gap	0.04	R=0.18 $m^2 \cdot K/W$	1.2
Lime-sand brick Ceramic brick	0.12	1.5 / 0.75	1950 / 1800
Plaster	0.01	0.8	1800
TOTAL	0.56		

Thermal transmittance U, W/(m^2·K)

Calculated (brick ties, every 4^{th} row):
1.5 (lime-sand brick) (EN ISO 10211)
1.0 (ceramic brick) (EN ISO 10211)

6.1.1.5 Brick masonry wall with a cavity + foam insulation

<table>
<tr><td>Description</td><td>If the air gap of a multi-layered brick wall is left empty during its construction, one possible energy renovation measure is to fill it with modern insulation foam to reduce heat loss through the wall and possibly improve thermal comfort for the inhabitants near the walls. However, tie stones will remain a significant thermal bridge and reduce the effectiveness of the insulation layer.</td></tr>
<tr><td>Typical condition</td><td>This solution appeared in 1 case study retrofitted ca. 7 years ago, which may not be long enough for the negative effects to appear. As the structure was not opened, the condition of the materials was not checked.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Moisture penetrates the structure, and when it freezes, it expands, causing the plaster to crack and damaging the load-bearing structure. Prolonged exposure to moisture can also lead to mould formation inside the wall. Insulation of the cavity can lead to higher moisture content of the outer masonry leaf and accelerated degradation/shorter maintenance intervals.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material (starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.8</td><td>1800</td></tr>
<tr><td>Lime-sand brick
Ceramic brick</td><td>0.38</td><td>1.5 / 0.75</td><td>1950 / 1800</td></tr>
<tr><td>Insulation</td><td>0.04</td><td>0.04</td><td>1.2</td></tr>
<tr><td>Lime-sand brick
Ceramic brick</td><td>0.12</td><td>1.5 / 0.75</td><td>1950 / 1800</td></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.8</td><td>1800</td></tr>
<tr><td>TOTAL</td><td>0.56</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated:
1.3 (lime-sand brick) (EN ISO 10211)
0.8 (ceramic brick) (EN ISO 10211)
Measured: 1.5 (Sikupilli case – may have not been completely filled with insulation)</td></tr>
</table>

6.1.1.6 Log/double plank wall with ventilated cladding

Description

This is the main wall type of the wooden apartment building archetype. The use of **log walls** dominated the construction of wooden houses until the beginning of the 20th century, when timber-framed walls became more widespread. Alongside these, horizontal log walls became too material- and time-consuming to construct and provided suboptimal thermal insulation. The introduction of the vertical **double plank wall** accelerated the entire construction process, as construction settlement was reduced. Once the walls and roof were completed, permanent interior finishing could begin immediately. Historically, they have been covered with wooden boarding, but plastered facades also exist (they mimic the façades of more desirable masonry buildings). From an energy efficiency point of view, these walls are generally either inadequately insulated or not insulated at all. Another weakness is the poor airtightness. The typical thickness of logs and double plank section was 15 cm, while the horizontally or vertically installed cladding boards usually 120-150 mm wide.

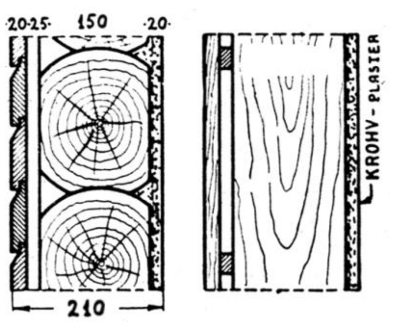
Typical condition

The condition depends largely on the general maintenance of the building – if the roof, rainwater systems and flashings on the facade have been looked after, the wall can be in good condition. Should it not be the case, large parts of the whole structure may be decayed and has to be replaced.

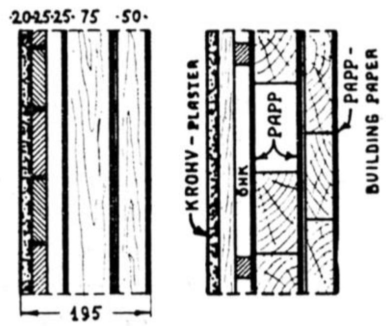
Typical damage mechanisms

Growth of mould and decay fungi caused by e.g. water leakages, high indoor humidity load). Exterior cladding also degrades due to UV radiation and deformations (e.g. differential settlement).

Illustration



Log wall, wooden cladding



Double plank wall, plastered cladding

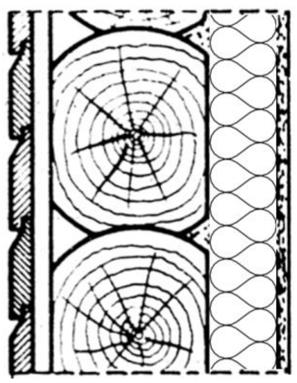
Structure

Material (starting from interior)	**Thickness [m]**	**Thermal conductivity [W/(m·K)]**	**Density [kg/m³]**
Plaster	0.01	0.8	1600
Log / 2 x plank	0.15	0.13	450
Air gap	0.015		
Cladding	0.02		
TOTAL	0.195		

Thermal transmittance U, W/(m²·K)

Calculated: 0.75 (EN ISO 6946)

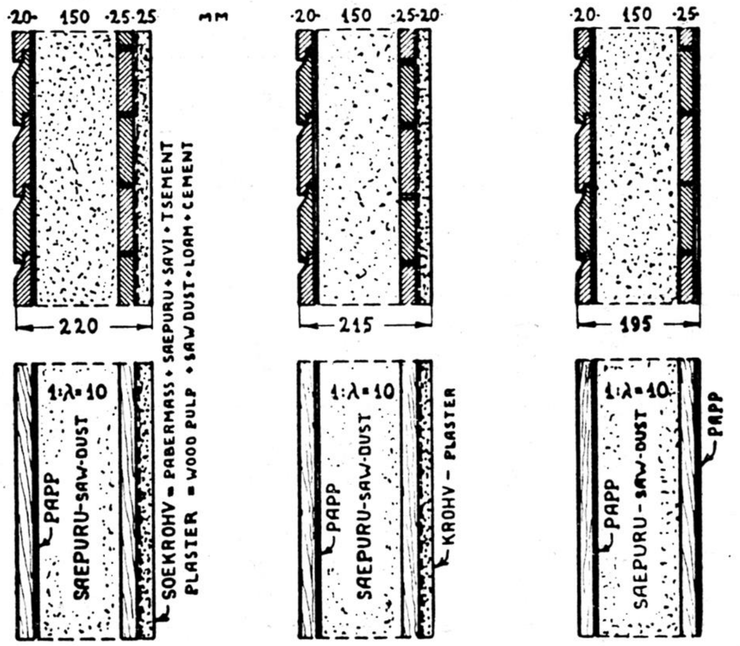
6.1.1.7 Log/double plank wall with ventilated cladding + interior insulation

<table>
<tr><td>Description</td><td>The energy efficiency of log/double plank walls has been improved by adding a suitable interior insulation layer. The traditional insulation solution used for a long time is a plastered reed mat. Modern alternatives include cellulose or mineral wool insulation, which are covered with a water-vapour membrane and a finishing board (for example, gypsum board). An interior insulation layer of up to 5 cm thick is considered a low-risk solution in the Estonian climate if indoor moisture load is low (low occupancy and/or proper ventilation), insulation solution is airtight and rainwater leakages are avoided (Alev & Kalamees, 2016).</td></tr>
<tr><td>Typical condition</td><td>Previous studied have shown both risks and possible safe limits (Alev & Kalamees, 2016; Arumägi et al., 2015) of interior insulation on wooden walls. However, as the critical surface is inside the wall, the condition of as-built solutions has not been verified as no campaigns to open and study them has been done so far.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Growth of mould and decay fungi (caused by e.g. water leakages, high indoor humidity load).
Exterior cladding also degrades due to UV radiation.</td></tr>
<tr><td>Illustration</td><td></td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Gypsum board</td><td>0.013</td><td>0.2</td><td>800</td></tr>
<tr><td>Insulation</td><td>0.05</td><td>0.037</td><td>35</td></tr>
<tr><td>Log /</td><td>0.15</td><td>0.13</td><td>450</td></tr>
<tr><td>Air gap (slightly ventilated)</td><td>0.015</td><td></td><td>35</td></tr>
<tr><td>Cladding</td><td>0.02</td><td></td><td>400</td></tr>
<tr><td>TOTAL</td><td>0.248</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 0.41 (EN ISO 10211)
Measured: 0.33 (Koidu case; possible air leakages?)</td></tr>
</table>

6.1.1.8 Timber frame wall with wooden cladding

Description	Timber frame walls represent a more modern practice compared to traditional solid timber walls. In the past, the voids in these older timber frame walls were filled with sawdust. However, more recent methods involve filling these voids with mineral wool or cellulose wool, which have significantly lower thermal conductivity. There are various finishing options available for both the interior and exterior sides of the walls. The most popular choice for the exterior finish is profiled wooden cladding. These cladding boards typically measure 120-150 mm in width and can be installed either horizontally or vertically.
Typical condition	Condition varies and depends on general building maintenance (roof, rainwater systems and flashings on the facade play a major role). Insulation may not fill the whole cavity anymore (due to settlement, rodents, insects, etc)
Typical damage mechanisms	Mould and decay issues due to moisture leakages (caused by both rainwater leakages, air convection and possibly vapour diffusion). Rodents and insects.

Illustration



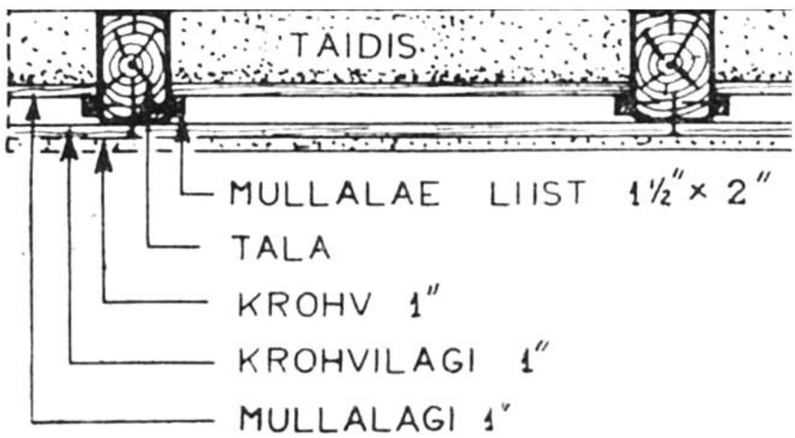
Structure

Material (starting from interior)	**Thickness [m]**	**Th. conductivity [W/(m·K)]**	**Density [kg/m³]**
Lime-cement plaster	0.01	0.80	1600
Wooden board	0.025	0.13	450
Sawdust/lightwght.infill	0.15	0.065	160
Wooden board	0.02	0.13	450
TOTAL	0.195		

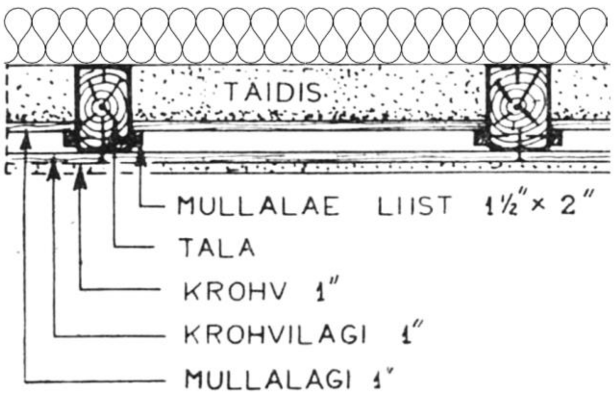
Thermal transmittance U, W/(m²·K)	Calculated: 0.4 (EN ISO 10211, w/o possible gaps in insulation) With additional 50 mm interior insulation: Calculated: 0.28 (EN ISO 10211); Measured: 0.26 (Komeedi case, section betw. studs)

6.1.2 Top boundary

6.1.2.1 Attic floor

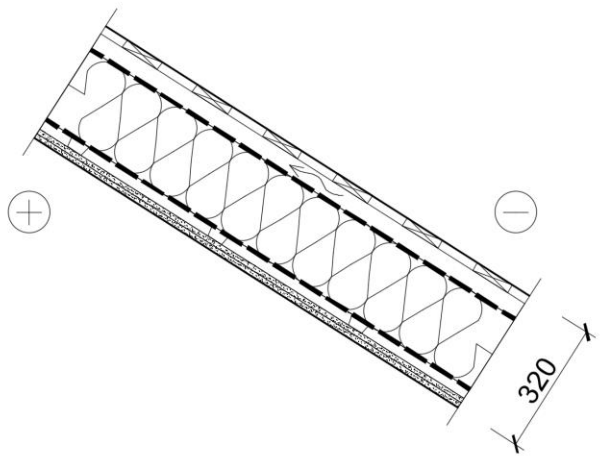
<table>
<tr><td>Description</td><td>The typical attic floor structure is supported by wooden beams with double boarding layer supporting the lightweight infill inbetween. Interior finishing is usually lime plaster on top of a reed, wood chip or steel mesh that is affixed to the wooden boarding. The height of the beams and material of the infill layer vary. Compared to today’s similar structures, the beams are wider (8-12.5 cm) and they are more widely spaced (0.7-1 m c/c).</td></tr>
<tr><td>Typical condition</td><td>The wooden beams are usually in good condition as long as there have been water leakages or the beams supported by wet masonry. No microbiological studies have been performed to our knowledge.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Rot and mould growth due to water and air leakages. Ventilation exhaust from wet rooms may also lead to the attic that can lead to elevated humidity.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness
[m]</th><th>Thermal conductivity
[W/(m·K)]</th><th>Density
[kg/m³]</th></tr>
<tr><td>Lime-cement plaster</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>Wooden boarding</td><td>0.025</td><td>0.13</td><td>450</td></tr>
<tr><td>Air gap</td><td>0.045</td><td>R = 0.16 m²·K/W</td><td></td></tr>
<tr><td>Wooden boarding</td><td>0.025</td><td>0.13</td><td>450</td></tr>
<tr><td>Sawdust/lightweight infill</td><td>0.13</td><td>0.065-0.25</td><td>160</td></tr>
<tr><td>TOTAL</td><td>0.235</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 0.4–0.74 (EN 10211)
Measured: 0.31 (Komeedi case, NB: section between beams, may have 5 cm interior insulation)</td></tr>
</table>

6.1.2.2 Attic floor + loose fibrous insulation

Description	A simple solution for thermal upgrade of the attic floor is to add an additional layer of loose insulation. Depending on the retrofitting era, the additional insulation can either be in the same class as originally (slag, sawdust, etc.) or a more modern material (mineral wool, cellulose insulation).
Typical condition	The wooden beams are usually in good condition as long as there have been water leakages or the beams supported by wet masonry. The addition of insulation to the attic side should improve the hygrothermal conditions of the load bearing beams. No microbiological studies have been performed on these attic floors to our knowledge.
Typical damage mechanisms	As the insulation layer reduces heat flux to the attic, there is a risk increasing relative humidity in the attic and therefore mould growth can occur. Therefore, ventilation of the attic plays an increasingly important role.
Illustration	
Structure	see table below
Thermal transmittance U, W/(m²·K)	Calculated: 0.22–0.28 (dependent on infill, EN 10211)

Material (starting from interior)	**Thickness [m]**	**Thermal conductivity [W/(m·K)]**	**Density [kg/m³]**
Lime-cement plaster	0.01	0.80	1600
Wooden boarding	0.025	0.13	450
Air gap	0.045	R = 0.16 m²·K/W	
Wooden boarding	0.025	0.13	450
Sawdust/lightweight infill	0.13	0.065–0.25	160
Loose fill insulation	0.1	0.045	30
TOTAL	0.335		

6.1.2.3 Insulated roof (insulation between beams)

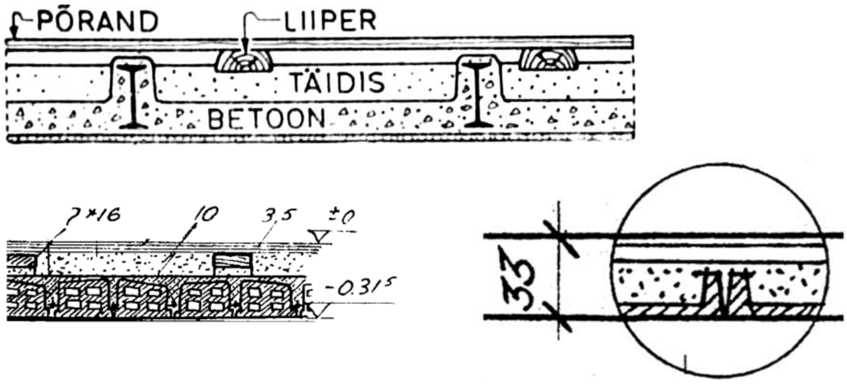
Description	This is an example of a solution (many variations exist) where the attic has been transformed into living space. Conversion of an existing roof to this structure is usually a serious intervention: reliable installation of the roof underlay membrane requires removal (and usually replacement) of the roofing material. Redesign of the load bearing structure might also be necessary – for example Stalinist style buildings typically have roof trusses which leave little room for living space.
Typical condition	No structures were opened, but thermography revealed significant air leakages in the roof structure of a case study building. Typically, if the structure was built before ca 2020s, there is higher probability that airtightness is low and it may also contain other errors (improper or incomplete installation of insulation, lack of underlay membrane, vapour barrier, etc) that affect either thermal and/or hygrothermal performance.
Typical damage mechanisms	Moisture convection due to air leakages, condensation on the underside of roofing due to long-wave radiation, which may drip into the rest of the structure if underlay membrane is missing or damaged and cause moisture damage. Water leakages through joints with chimneys, roof windows, etc may stay undetected due to additional insulation and finishing layers causing mould and decay.
Illustration	
Structure	(see table below)
Th. transm. U, W/(m²·K)	Calculated: 0.25 (EN 10211, without accounting for imperfections)

Material (starting from interior)	**Thickness [m]**	**Th. cond. λ [W/(m·K)]**	**Density [kg/m³]**
2x gypsum board	0.025	0.25	1000
Studs / cavity	0.045	R = 0.18 m²·K/W	450 / 30
Vapour barrier	0.0002	0.4	
Wooden beam / insul.	0.2	0.13 / 0.04	450 / 30
Underlay membrane	0.0005	0.4	
Rafters/vent. cavity	0.045+0.022		
Sheet metal roofing	0.0006		
TOTAL	0.320		

6.1.3 Floors

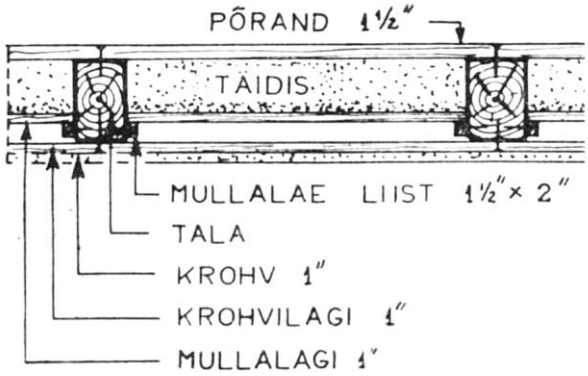
6.1.3.1 Floor between basement and 1st floor

<table>
<tr><td>Description</td><td>The floor between basement and 1st floor is usually a concrete slab that is supported by steel I-beams or sometimes railway rails. The exact configuration varies.</td></tr>
<tr><td>Typical condition</td><td>Typically: good may need maintenance in to rust-proof the bottom flanges of the steel beams.
In severe cases (e.g. unheated and moist cellar) may need significant repairs to retain load bearing capacity as the bottom flange of the beam is severely rusted and is spalling off.</td></tr>
<tr><td>Typical damage mechanisms</td><td>Rusting steel & salt efflorescence caused by moist indoor climate of the cellar and intermittent wetting and drying of the structure.</td></tr>
<tr><td>Illustration</td><td>



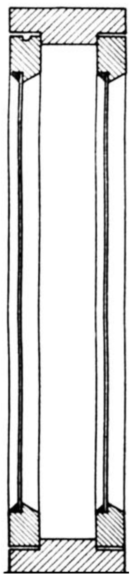
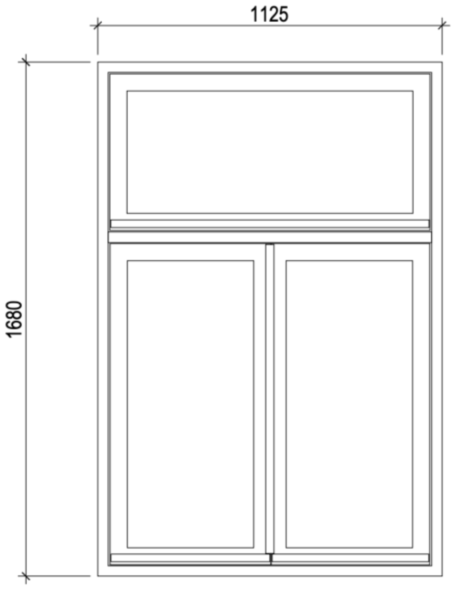
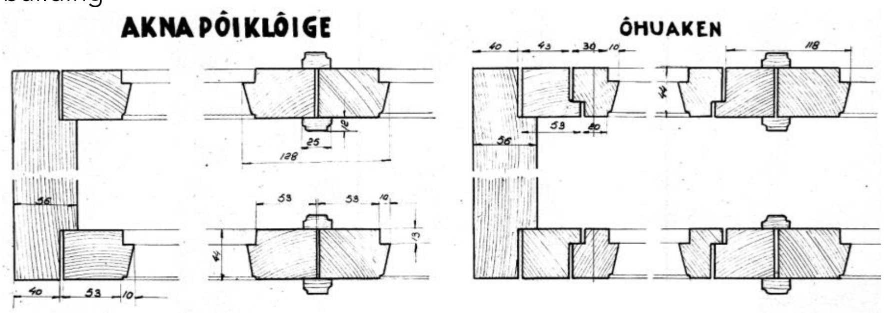
Variations of the structure: from 1930s wooden apt. bldg. (top), from 1940s-1950s Stalinist style apt. bldg. (bottom row)</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Floor boards</td><td>0.035</td><td>0.13</td><td>400</td></tr>
<tr><td>Air cavity</td><td>0.025</td><td>0.2</td><td></td></tr>
<tr><td>Sand/lightweight filling</td><td>0.1</td><td>0.065-0.25</td><td></td></tr>
<tr><td>Concrete</td><td>0.1</td><td>2.1</td><td>2500</td></tr>
<tr><td>Plaster</td><td>0.01</td><td>0.8</td><td>1600</td></tr>
<tr><td>TOTAL</td><td>0.23</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated (EN ISO 10211):
Insulation broken by concrete: 0.90-1.1 (dependent on insulation)
Insulation broken by floor beams: 0.41-0.78 (dependent on insulation)</td></tr>
</table>

6.1.3.2 Intermediate floor (wooden beams)

<table>
<tr><td>Description</td><td>The intermediate floor solution is similar to the attic floor but also incorporates the wooden floorboards. The dimensions and distance (0.7–1 m c/c) between beams vary as does the material used for infill (wood chips, sawdust, sand, slag, …). Currently, the floorboards are often replaced or covered by new materials. Gypsum board suspended ceiling may have also been added.</td></tr>
<tr><td>Typical condition</td><td>As long as water leakages (from pipes, wet rooms, etc.) have been avoided, the condition is good.
RC0</td></tr>
<tr><td>Typical damage mechanisms</td><td>Wooden beam ends may decay if supported by wet masonry. Rot and mould growth due to water leakages.</td></tr>
<tr><td>Illustration</td><td>
</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material
(starting from interior)</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Density [kg/m³]</th></tr>
<tr><td>Lime-cement plaster</td><td>0.01</td><td>0.80</td><td>1600</td></tr>
<tr><td>Wooden boarding</td><td>0.025</td><td>0.13</td><td>450</td></tr>
<tr><td>Air gap</td><td>0.045</td><td>R=0.16/0.21 m²·K/W</td><td></td></tr>
<tr><td>Wooden boarding</td><td>0.025</td><td>0.13</td><td>450</td></tr>
<tr><td>Sawdust/lightweight infill</td><td>0.13</td><td>0.065–0.25</td><td>160</td></tr>
<tr><td>Wooden floor boards</td><td>0.038</td><td>0.13</td><td>450</td></tr>
<tr><td>TOTAL</td><td>0.235</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>Calculated: 0.35–0.6 (dependent on infill, EN 10211)</td></tr>
</table>

6.1.4 Windows

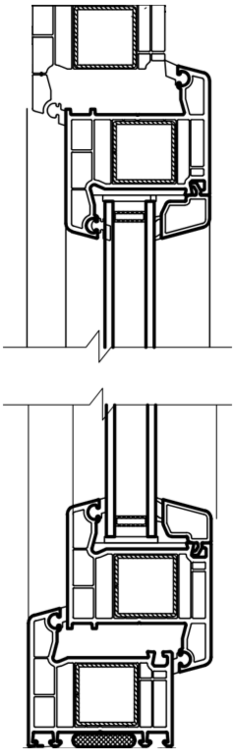
6.1.4.1 Historic double frame double pane window

Description	The original window type of archetypical building was a double wooden frame window with both of them housing a single glass pane. The frames were finished with linseed oil paint, while the panes were sealed using window putty made of chalk and linseed oil. The exterior frame opened to the outside and interior frame to the inside. The latter was usually removed during summer and taped/caulked tight for winter.
Typical condition	The condition is largely dependent on maintenance. A sense of complacency, driven by the low upkeep of modern plastic windows, often leads to the neglect and swift deterioration of older, higher-maintenance wooden frames.
Typical damage mechanisms	UV and moisture cause strain on the paint layer which after cracking and peeling loses its protective capabilities. Rainwater penetration as well as condensation on the interior surface of the outer window causes swelling, cracking and decay of the wooden elements.
Illustration	 A section of a typical window of a wooden apartment building  A view of a typical window of a wooden apartment building.  Horizontal sections of Stalinist apartment building windows. The section on the right shows a characteristic smaller window for ventilation purposes.
Thermal transmittance U, W/(m²·K)	U_w = 2.9 (Calculated)

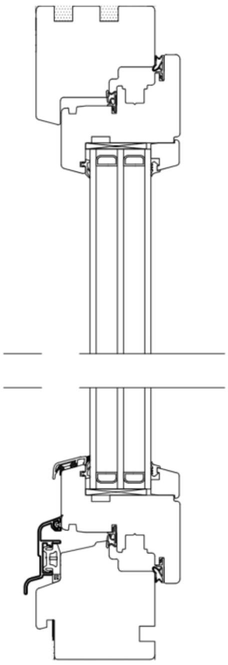
6.1.4.2 Retrofitted historic window (2-pane IGU)

Description	This is either a copy or a retrofitted original type of window where the glass pane in the interior frame has been replaced with a modern 2-pane IGU. As the interior frames are originally rather narrow and it is not possible to fit more efficient IGUs, the whole interior frame may have also been replaced. The exterior frame opens to the outside and interior frame to the inside.
Typical condition	As such retrofitted windows are rather new, their condition is generally good. Main issues concern the paint layer that may have started to age and when left unmaintained, damage will also propagate to wooden parts. Sealants also need regular checking and repairs as necessary.
Typical damage mechanisms	UV and moisture deformations cause strain on the paint layer which after cracking and peeling loses its protective capabilities. Rainwater penetration causes swelling, cracking and decay of the wooden elements of the window.
Illustration	 Image source : Viru Aknad OÜ
Thermal transmittance U, W/(m²·K)	The following values are dependent on filler gas, spacer type, frame distribution, etc. U_g = 1.0–2.0 Calculated U_w = 1.2-1.5

6.1.4.3 Single frame PVC window with 2 or 3 pane IGU

Description	The single PVC-frame windows were mostly used for thermal upgrade during the 1990s and 2000s. While being an affordable and low-maintenance choice, these windows have different frame profiles and have often been configured with ill-fitting frame distribution and installation techniques. The variations with cheaper 2-pane IGU-s also have relatively high thermal transmittance and it could be economically viable to replace them with aesthetically more suitable windows with higher energy efficiency. As the insulating layer is different compared to the original double frame window type, the thermal bridging effect can be increased (causing both thermal and hygric issues) dependent on the installation depth within the wall cross-section.
Typical condition	As the windows are quite durable, the main technical issues concern deformations which cause loss of airtightness and difficulties with opening/closing.
Typical damage mechanisms	Thermal and creep deformations. Degradation of materials due to UV radiation and aging of polymers.
Illustration	
Thermal transmittance U, W/(m²·K)	The following values are dependent on filler gas, spacer type, frame distribution, etc. U_g = 1.1–2.6 (2-pane); 0.8–1.2 (3-pane) Calculated U_w = 1.4–2 (2-pane); 0.9–1.8 (3-pane)

6.1.4.4 Single pane wooden window with 2 or 3 pane IGU

Description	The variations with cheaper 2-pane IGU-s also have relatively high thermal transmittance and it could be economically viable to replace them with aesthetically more suitable windows with higher energy efficiency. As the insulating layer is different compared to the original double frame window type, the thermal bridging effect can be increased (causing both thermal and hygric issues) dependent on the installation depth within the wall cross-section.
Typical condition	As such retrofitted windows are rather new, their condition is generally good. Main issues concern the paint layer that may have started to age and when left unmaintained, damage may also propagate to wooden parts. Sealants also need regular checking and repairs as necessary.
Typical damage mechanisms	UV and moisture cause strain on the paint layer which after cracking and peeling loses its protective capabilities. Rainwater penetration causes swelling, cracking and decay of the wooden elements of the window.
Illustration	
Thermal transmittance U, W/(m²·K)	The following values are dependent on filler gas, spacer type, frame distribution, etc. U_g = 1.1–2.6 (2-pane); 0.8–1.2 (3-pane) Calculated U_w = 1.4–2 (2-pane); 0.9–1.6 (3-pane)

6.2 Airtightness

The airtightness was measured using a standardized fan pressurization method in accordance with EN ISO 9972, employing an automated performance testing system. Measurements were carried out in one apartment within each of the studied buildings, as the measurement of the whole building would require coordination and disturbance of all the apartments. In Komeedi case (which is a smaller building), an additional measurement was conducted for the entire building.

Comparing the air leakage between different apartments, the airflow rate at a pressure difference of 50 Pa was divided by the apartment's envelope area, which includes internal walls and floors. This resulted in the air leakage rate at 50 Pa, denoted as q_{E50}, expressed in ($m^3/h{\cdot}m^2$). Results of the measurements are presented in Table 6-1.

Table 6-1: Results of airtightness measurements.

Name	Structure type	Built	Air leakage rate q_{E50}, $m^3/(h{\cdot}m^2)$		
			Depress.	**Press.**	**Avg.**
Koidu, single apt	Wood	1931	5.6	-	5.6
Komeedi, single apt X	Wood	1932	7.1	6.8	6.9
Komeedi, single apt Y	Wood	1932	10.5	11.0	10.8
Komeedi, whole building	Wood	1932	9.5	11.6	10.6
Pilve, single apt	Wood	1940	8.1	8.7	8.4
Sikupilli, single apt	Brick / Timber frame	1958	9.2	9.5	9.4

The measured results in the current study are of the same order of magnitude as those reported in a previous study of wooden apartment buildings (Kalamees et al. 2011). In that study, the average air leakage rate of all measured apartments was q_{50} = 10 $m^3/(h{\cdot}m^2)$, ranging from 3.8 to 22 $m^3/(h{\cdot}m^2)$, and the air change rate at 50 Pa was n_{50} = 13 h^{-1} (range: 4.8–24 h^{-1}). In the mentioned study of wooden apartment buildings, airtightness was measured both at the apartment level and, in one case, for the building as a whole. In that specific case, the results showed that the average air leakage rate measured apartment by apartment was 7.6 $m^3/(h{\cdot}m^2)$, while the corresponding value obtained from measuring the entire building was 9.2 $m^3/(h{\cdot}m^2)$ (Klõšeiko et al. 2021). In the current study, whole-building airtightness was measured for the Komeedi building, and the result was 10.6 $m^3/(h{\cdot}m^2)$, indicating a similar trend in the relationship between apartment-level and whole-building measurements.

In a study assessing the technical condition of Estonia's brick apartment building stock (Kalamees et al. 2010), the airtightness of building envelopes was measured in 30 apartments using fan pressurization tests. The results were expressed as air leakage rate (q_{E50}) and air change rate at 50 Pa (n_{50}). The average air leakage rate across all measured apartments was q_{50} = 4.0 $m^3/(h{\cdot}m^2)$, and the corresponding average air change rate was n_{50} = 5.7 h^{-1}. The measurement conducted in the Sikupilli case study building showed a higher air leakage value compared to the average of the brick apartment buildings. This can be explained by the specific characteristics of the measured apartment, which was a two-storey unit expanded into the attic space. As a result, the main floor had external walls typical of brick apartment buildings, while the attic extension was built using timber construction. Furthermore, during the construction process, limited attention was given to ensuring airtightness, which is also reflected in the higher measurement results.

An overview of airtightness measurements in Estonian buildings has been presented in a separate study (Hallik et al 2023), where characteristic values of airtightness are reported based on building construction type and age. The results of that analysis are summarized in Table 6-2.

Table 6-2: An overview of previous airtightness measurements of comparable apartment building types in Estonia (Hallik et al 2023).

			Air leakage rate q_{E50}, m³/(h·m²)			
Structure type	**Built**	**n**	**mean**	**σ**	**median**	**IQR**
Log	1921-1945	16	8.8	1.9	8.8	7.1—10.3
Brick	1946-1970	11	4.7	1.2	4.2	3.6-5.5

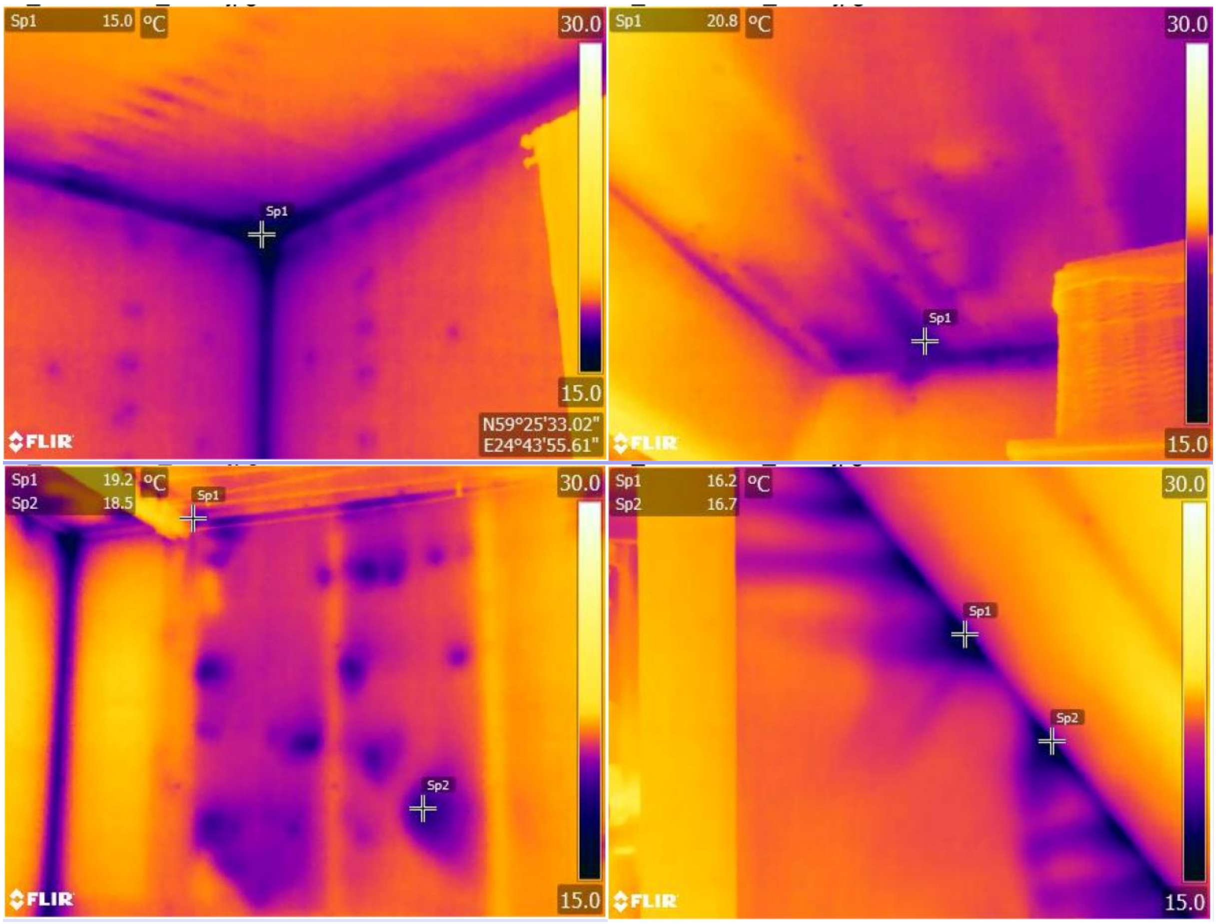


Figure 6-2: Illustrative examples of typical air leakage locations detected with thermography under blower door depressurization.

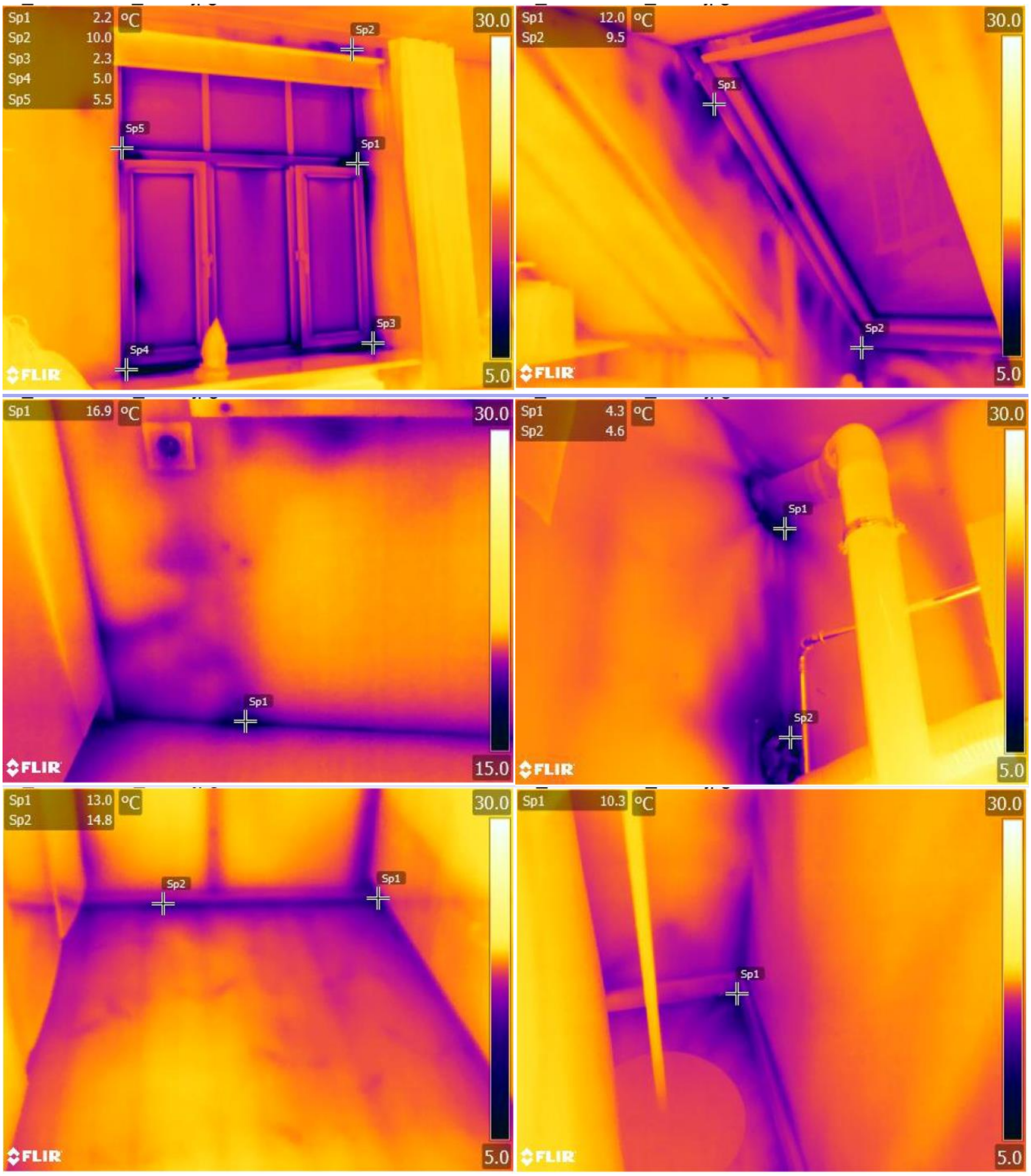


Figure 6-3: Illustrative examples of typical air leakage locations detected with thermography under blower door depressurization.

In older wooden and brick apartment buildings, typical air leakage often occurs at various construction junctions and penetrations (see Figure 6-2 and Figure 6-3). In wooden buildings, common leakage areas include wall-to-floor and wall-to-wall connections, where gaps or insufficient sealing allow uncontrolled air movement. Window-to-wall joints are also frequently leaky, especially where original sealing materials have deteriorated over time. In brick apartment buildings, air leakage is often observed at the interfaces between different structural elements, such as where interior or exterior walls meet floors or other walls, as well as at window perimeters. In both construction types, penetrations for building services–such as pipes, ducts, and electrical conduits–are frequently not properly sealed, resulting in visible thermal bridges and direct air infiltration. These issues are typically confirmed and visualised through thermographic imaging, which highlights critical leakage areas that significantly impact the building's airtightness and thermal performance.

Another important aspect affecting airtightness in older apartment buildings is the condition of existing chimneys. In both wooden and brick buildings, unused or partially used chimneys can be significant sources of uncontrolled air leakage, especially if flue dampers are missing or sealing at chimney penetrations is inadequate. Cracks in the masonry or degraded mortar joints allow air to pass through, reducing the overall airtightness of the building envelope. In addition to energy loss and reduced indoor comfort, poorly sealed chimneys can also pose fire safety risks, particularly in wooden structures, where leakage paths may pass through combustible materials. Ensuring proper sealing and, where necessary, professional closure of unused chimneys is essential for both energy efficiency and occupant safety.

In many renovation projects involving wall insulation, insufficient attention has been paid to ensuring airtightness. Thermographic images often reveal potential leakage areas behind internal insulation layers, especially in cases where the existing wall structures were insulated from the inside without adequate sealing. These unsealed junctions and penetrations allow cold air to infiltrate behind the insulation, cooling down inner wall surfaces. If water vapour from the indoor environment is able to penetrate through the internal finishing layers and reach these cold zones, there is a significant risk of condensation and mould growth within the wall structure. This highlights the critical importance of integrating proper airtightness measures into any wall renovation strategy, particularly when using internal insulation systems.

6.3 Moisture safety on interior surface (temperature factors)

Preliminary assessment of the hygrothermal performance of the details can be done based on temperature factors. 2D thermal modelling using LBNL Therm based on ISO 10211 of wooden log apartment building details was performed in a previous study (Kalamees et al. 2011). The study on brick apartment buildings (Kalamees et al. 2010) did the same for brick walls with a cavity filled with mineral wool insulation. The summary of these linear thermal transmittances and temperature factors are given in Table 6-3.

Estonian National Annex to EN ISO 13788:2012 gives the critical temperature factor in NA.8–9 and Tables NA.4–5. For buildings built before the year 2000 and if the indoor air humidity class is 2 (low occupancy living spaces) or less, the f_{Rsi} should be ≥ 0.65. When the humidity class is 3 (high occupancy living spaces) should be ≥ 0.8. Indoor air quality measurements presented in D3.2 of HeriTACE project show that in Estonian cases the humidity class III is quite prevalent and in one apartment even class IV was measured. These findings are corroborated by a summary of previous measurements (Ilomets et al. 2018). The modelled temperature factors are below 0.8 for several details (wall-wall corner, wall-window, wall-attic floor) of masonry walls with 50mm insulation in cavity and even worse on mass masonry walls. This highlights the need for a thermal upgrade of such structures and improved ventilation strategies.

Table 6-3 An overview of previous studies presenting the linear thermal transmittances and temperature factors of envelope details. (Kalamees et al. 2010, Kalamees et al. 2011)

	Type	Corner	Wall-basement ceiling	Wall-int. floor	Wall-attic floor	Wall-window
Lin. thermal transmittance Ψ, W/(m·K)	Wood	0.05	0.18	0.01	0.15	0.01
	Brick (50 mm ins. in cavity)	0.23–0.29	0	0.01	0.41–0.58	0.35–0.49
Temperature factor f_{Rsi}, -	Wood	0.8	0.76	0.86	0.87	0.84
	Brick (50 mm ins. in cavity)	0.72	0.83	0.83	0.72	0.57
	Brick (mass masonry)	0.48–0.59				

In at least 1 apartment in brick building the risks had materialized – a recurring mould growth (cleaned regularly) was present on a corner (see Figure 6-4). The already risky detail was made worse by placing a cupboard in front of it, further reducing surface temperature and (instantaneous f_{Rsi} was measured at 0.34) increasing relative humidity.

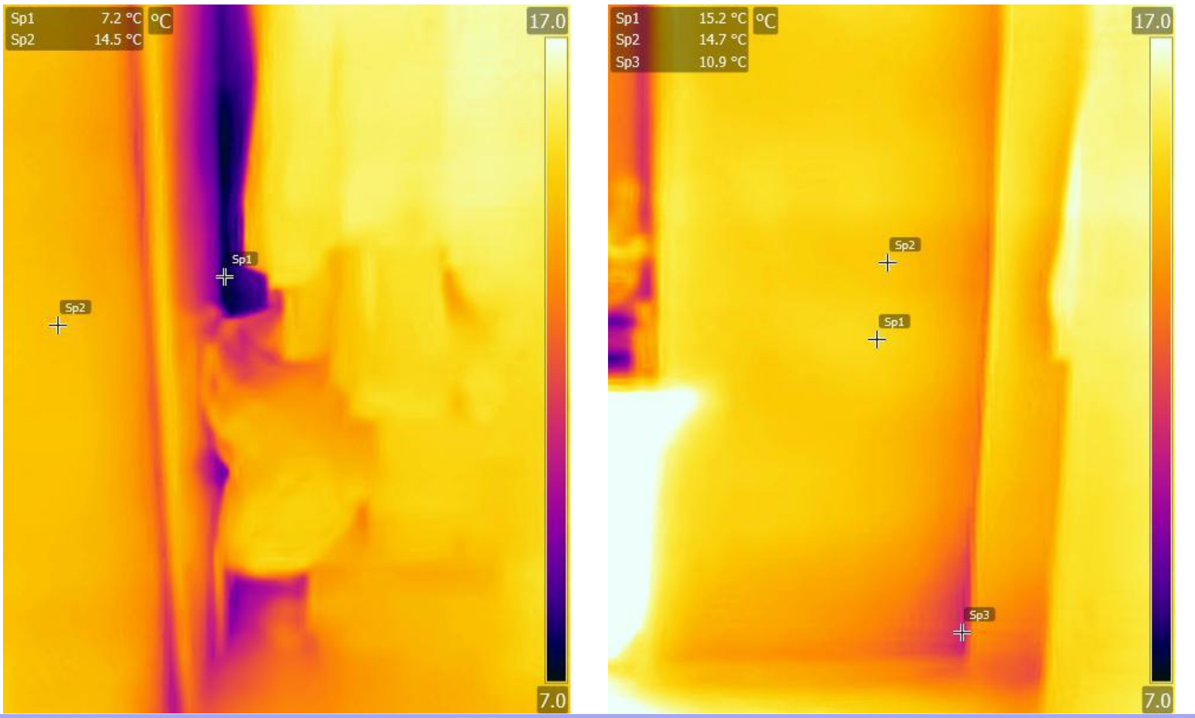


Figure 6-4: Problematic corner detail of a mass masonry wall studied in HeriTACE project. Sp1 of left thermogram shows surface temperature of the corner that also happens to behind a cupboard resulting in a very low temperature factor of f_{Rsi} = 0.34 and recurring mould growth.

6.4 Technical condition of archetype envelope

6.4.1 Overall Condition Assessment of Buildings in the Uus-Maailm Area

The studied milieu-valuable area of Uus-Maailm has previously been thoroughly monitored, and the condition of the buildings was evaluated by (Liiva et al., 2024). A total of 43 apartment buildings were assessed, 53% of which had log structures and 47% were masonry buildings. The study found that approximately 50% of the facades and plinths in the area needed renovation. Only 30% of the investigated buildings had retained their original materials after renovation; however, this did not negatively impact on the overall aesthetic evaluation of the buildings.

The study by Liiva et al. (2024) concluded that successful renovation outcomes depend on careful planning that respects the historical context of the buildings. Their assessment indicated that the use of modern materials can be acceptable, as evidenced by the relatively good condition of previously renovated buildings in the Uus-Maailm area. However, the study also noted that partial renovations—such as the replacement of windows without a consistent visual strategy—often resulted in fragmented appearances that detract from the architectural coherence of the facades. Based on these findings, full and cohesive renovation strategies are recommended to better preserve the aesthetic and cultural value of the area.

Previous study involving 133 wooden buildings in Tallinn, Tartu, Pärnu and Viljandi have demonstrated that regular maintenance plays a critical role in preserving the good condition of these structures (Klõšeiko et al., 2011). One of the primary causes of rapid deterioration was inadequately designed or poorly maintained rainwater drainage systems.

As previous studies had already examined statistical trends regarding the condition of buildings in the area, this study focused on a smaller number of case study buildings, allowing for a more detailed technical assessment of each.

6.4.2 Aspects of wooden buildings

Condition of Wooden Cladding

Timber façades across the inventoried wooden buildings exhibit typical age-related deterioration. Common issues include paint damage, biological growth (e.g. mould, algae), and, in some cases, wood rot in the cladding material.

Figure 6-5: shows an example of prematurely deteriorated paint on wooden cladding. During renovation, the ventilation cavity behind the cladding was insufficient. The paint layer cracked due to a combination of UV exposure and the dimensional changes caused by fluctuating moisture levels in the façade. This initial cracking allowed moisture ingress. As the paint layer probably had relatively high-water vapour diffusion resistance, moisture remained trapped behind it, increasing the moisture content of the cladding and creating favourable conditions for biological growth and further deterioration. This damage mechanism is significantly exacerbated by the lack of proper ventilation behind the cladding.

In addition to ensuring proper ventilation behind the facade cladding and selecting appropriate paint coatings, careful attention must also be paid to detailing. Effective rainwater management is essential for the long-term durability of timber facades. Key elements include adequately extended eaves, well-maintained gutters and downpipes, and, where possible, a subsurface rainwater management system. Window flashings must have a sufficient slope, and proper detailing. Rainwater management systems and flashing must be installed immediately after the application of cladding and regularly inspected for potential damage. Poorly designed or neglected details can concentrate water in specific areas of the facade, significantly accelerating localised deterioration of both the cladding and the underlying structural components (Figure 6-5:).

Figure 6-5: Condition of painted wooden cladding (left); damage to the load bearing structure due to faulty window flashing becomes visible after removal of the cladding (right). Photos: Paul Klõšeiko.

Condition of the limestone masonry plinth

Plinth areas, particularly those exposed to limestone, were generally in relatively good condition but showed localised signs of degradation in several places in the lower area. A common issue, caused by rising street levels over the decades, has resulted in door and window thresholds sitting below the asphalt surface (Figure 6-6). This problem is particularly acute in Estonia and has been observed in many smaller towns, with numerous examples of buildings where the plinth height has disappeared because of the elevated street levels (Alev, 2023). The situation is further exacerbated by inadequate rainwater management systems.

Figure 6-6: Limestone plinth area that has been submerged below the asphalt surface. An additional barrier made from kerbstones to prevent street surface runoff from entering the windows has proven to be insufficient. Photo: Paul Klõšeiko.

Frost damage in the plinth area was observed in several of the monitored buildings. Plaster detachment may have been further exacerbated by incompatibility between the limestone masonry substrate and the applied plaster. Deterioration typically begins at the lower sections of the plinth and spreads upwards. It is clearly visible that, even after renovation, no waterproofing layer was applied over the plaster plinth to prevent capillary suction. In the absence of a capillarity-blocking layer on the lower 5 cm area in contact with the ground, the plinth area could exhibit early signs of deterioration, indicating the need for further maintenance interventions.

Figure 6-7: Signs of frost damage in the plinth area of a building that has log walls with ventilation cladding and plastered finish. On the right-hand side, the old plaster has delaminated from the limestone masonry. On the left-hand side, the plinth has been renovated, but early signs of deterioration are already visible in the lower section. Photo: Paul Klõšeiko.

Despite the delaminated plaster in the plinth area, the façade plaster on the same building remained in relatively good condition, especially considering that the cement-lime plaster was estimated to be between 50 and 85 years old. This suggests that ventilated plaster systems incorporating a waterproof construction board beneath the plaster system can serve as a durable and reliable solution over several decades.

6.4.3 Aspects of masonry buildings

Facades

The façades of the masonry buildings were generally in good condition. None of the investigated buildings featured externally insulated walls beneath the plaster layer. The plaster on the renovated facades retained its original finish structure and smooth appearance with original detailing and was generally well-preserved. However, some cracking was observed, typically resulting from structural movements.

If such cracks reappear after renovation, they should be routinely repaired using plaster and paint. Otherwise, the cracks are likely to widen, allowing water to infiltrate and freeze, leading to further frost damage. It may also be advisable to address the root causes of the issue. However, this may involve more complex construction work in the basement to reinforce the building's foundations, and these structural problems should be tackled in the first phases of the renovation work.

For masonry buildings, selecting a suitable paint system for the rendered surface is crucial. Several cases have been identified where paint began to peel from the plaster surface after a relatively short period. This issue is typically caused by using paint with too high-water vapour resistance. Paint applied to facades must be vapor-permeable to allow excess moisture within the wall to dry out. When choosing paint, it is also important to consider the subsurface. If the facade has already been painted, it is essential to ensure that the bond between the old paint and plaster is adequate; if necessary, the old paint layer must be removed first. Figure 6-8 shows an example of a renovated building in Tallinn that was covered with a paint layer that was too vapour tight. Unfortunately, this was not the only instance of such damage in the area.

Figure 6-8: Cracks in the plastered mass masonry wall that have reappeared after replastering (left). Too vapour tight paint has started to peel off (right). Photos: Paul Klõšeiko.

Plinth area

Masonry buildings featured plinths constructed from the same materials as those in the plinths of wooden buildings, resulting in comparable damage mechanisms. In one renovated case, the plinth area had been externally insulated, and the appearance of the original concrete masonry was recreated using a modern ETICS system, with plaster system applied over the insulation layer.

As illustrated in Figure 6-9, the finishing plaster has detached from the underlying reinforcement layer in the lower portion of the plinth. The masonry-like surface texture had been formed within the finishing layer itself, while the base coat with reinforcement mesh remains largely intact. This approach, while a cost-effective way to imitate the original structure, raises concerns about long-term durability and frost resistance, as there is an increased risk of water penetration inside the ETICS system, leading to potential frost damage. The deterioration at the base of the plinth appears to have been exacerbated by a concrete strip poured directly against the plinth surface, thereby causing mechanical stresses on the plaster system. Best practice would require physical separation between such elements. Additionally, the absence of an upturned waterproofing detail at the base of the plinth has likely contributed to increased moisture ingress and accelerated deterioration.

Moreover, there is visible paint peeling on the upper section of the plinth Figure 6-9, left. This may have been caused by insufficient sealing around service penetrations, leading to moisture accumulation in the base coat and subsequently resulting in peeling paint.

Figure 6-9: Left: lower section of the ETICS plinth, where plaster is in direct contact with the concrete strip cast against the plinth surface. Right: damage is commonly tied to faulty rainwater systems highlighting the importance of timely maintenance. Photos: Paul Klõšeiko.

It is also noteworthy that, in many masonry buildings, only the plinth area has been insulated, while the rest of the facade has been left uninsulated due to the presence of (in many cases relatively simple) decorative elements on the facade. This approach results in a pronounced offset between the plinth and the facade surface.

In addition to the fact that this solution often produces a visually unappealing outcome, it requires precise detailing to ensure long-term durability. The upper edge of the insulation must be sloped outwards, the plinth render must be turned to meet the facade plaster, and cement-based waterproofing must be applied on top. Only then can the metal flashing be attached to the top, with an adequate slope. If these details are not properly executed, water may penetrate behind the plinth insulation, leading to moisture accumulation and subsequent deterioration of the underlying structure.

6.5 Archetype envelope characteristics

6.5.1 Summary of envelope characteristics of case study buildings

Table 6-4: Stalinist brick apartment buildings: envelope characteristics of case study buildings. Blue shading denotes measured values.

Country	Estonia	**Building code**	Kristiina	Sikupilli
Archetype	Brick apt. bldg.	**Heated area (int. dim.), m²**	2312	554
Town	Tallinn	**Net area (int. dim.), m²**	2898	554
		Envel. area (ext. dim.), m²	3439	1141
Exterior wall	**Plastered masonry wall with cavity injected with urea foam, t = 56 cm**	U, W/(m²·K)		1.5
		Share of envelope, %		39.0
		Technical state		RC0
	Plastered masonry wall, t=53 cm	U, W/(m²·K)	1.1	
		Share of envelope, %	47.2	
		Technical state	RC1	
Plinth	**Limestone masonry, t = 70 cm**	U, W/(m²·K)	2.2	
		Share of envelope, %	(224 m²)	
		Technical state	RC0	
	Limestone masonry, t = 70 cm + 10 cm exterior insulation	U, W/(m²·K)		0.32
		Share of envelope, %		14.1
		Technical state		RC2
Top boundary	**Ceiling betw apt. and attic**	U, W/(m²·K)		0.3
		Share of envelope, %		14.5
		Technical state		Not assessed
	Ceiling betw apt. and attic + 100 mm loose mineral wool	U, W/(m²·K)	0.28	
		Share of envelope, %	22.1	
		Technical state	Not assessed	
	Insulated sloping roof (between beams)	U, W/(m²·K)		0.25 (presuming no imperfections)
		Share of envelope, %		5.6
		Technical state		Not assessed
Bottom boundary	**Basement ceiling (unheated basement)**	U, W/(m²·K)	0.8	
		Share of envelope, %	20.1	
		Technical state	Not assessed	
	Slab on ground (heated basement)	U, W/(m²·K)		0.5
		Share of envelope, %		21.0
		Technical state		RC0
Windows	**Original/authentic window (1+1 pane, double frame)**	U_{window}, W/(m²·K)	2.9	
		Share of envelope, %	0.4	
		Technical state	RC1	
	Modern window (2 pane IGU, single PVC frame)	U_{window}, W/(m²·K)	2.2	2.2
		U_{glass}, W/(m²·K)	2.0	2.0
		Share of envelope, %	8.0	7.3
		Technical state	RC0	RC0
	Roof window	U_{window}, W/(m²·K)		2.2
		U_{glass}, W/(m²·K)		2.0
		Share of envelope, %		0.8
		Technical state		RC1
Air tightness	**Envelope average (int. dim.)**	q_{E50}, m³/(h·m²)		9.2 (apt, incl. masonry 2. floor + timber fr. attic)

Table 6-5: Wooden apartment buildings: envelope characteristics of case study buildings. Blue shading denotes measured values.

Country	Estonia	**Building code**	Koidu	Komeedi	Pilve
Archetype	Wooden apt. bldg.	**Heated area (int. dim.), m²**	303	158	454
Town	Tallinn	**Net area (int. dim.), m²**	381	239	556
		Envel. area (ext. dim.), m²	667	469	778
Exterior wall	**Log/double plank wall with ventilated cladding**	U, W/(m²·K)	0.75		0.75
		Share of envelope, %	19		22.9
		Technical state	R1		RC2
	Log/double plank wall with ventilated cladding + 5 cm interior fibrous insulation	U, W/(m²·K)	0.33	0.4	0.4
		Share of envelope, %	19	26.3	22.9
		Technical state	RC1	RC1	
	Timber frame wall with wooden cladding + 5 cm interior fibrous insulation	U, W/(m²·K)		0.28	
		Share of envelope, %		12.2	
		Technical state		RC1	
	Staicase wall: log/double plank wall with ventilated cladding	U, W/(m²·K)		0.8	
		Share of envelope, %		4.1	
		Technical state		RC1	
	Staircase wall: lime-sand brick masonry	U, W/(m²·K)	2.3		2.3
		Share of envelope, %	4.5		6.9
		Technical state	RC0		RC1
Plinth	**Limestone masonry t = 60 cm**	U, W/(m²·K)	2.3	2.3	2.3
		Share of envelope, %	(68 m²)	(52 m²)	(81 m²)
		Technical state			
Top boundary	**Ceiling betw apt. and attic**	U, W/(m²·K)		0.31	0.4
		Share of envelope, %		21.7	19.6
		Technical state		Not assessed	Not assessed
	Insulation between rafters	U, W/(m²·K)	0.25	0.31	
		Share of envelope, %	31.7	7.9	
		Technical state	Not assessed	Not assessed	
Bottom boundary	**Betw basement & 1st floor (r/c concrete, sand, wooden boards)**	U, W/(m²·K)	0.4	0.4	0.6
		Share of envelope, %	19	21.9	20.3
		Technical state			
Windows	**Original type window (1+1 pane, double frame)**	U_{window}, W/(m²·K)	2.9	2.9	
		Share of envelope, %	0.6	0.3	
		Technical state	RC2	RC0	
	Modernized/modern window (1+2 pane, double wooden frame)	U_{window}, W/(m²·K)	1.5	1.5	1.5
		Share of envelope, %	4.9	3.5	1.1
		Technical state	RC1	RC1	RC0
	Modern window (2 pane IGU, single frame)	U_{window}, W/(m²·K)	1.7	1.7	1.7
		Share of envelope, %	1.2	1.4	6.8
		Technical state	RC0	RC0	RC0
Air tightness	**Envelope average (int. dim.)**	q_{E50}, m³/(h·m²)	Single apt 5.6	Bldg: 10.6; Apts: 7.1; 10.5	Single apt 8.1

6.5.2 Baseline definition

Based on the results described in previous subsections, the baseline scenarios describe the building archetypes for two time points to be used in the future as a reference to assess the effectiveness of the innovative retrofit solutions proposed by HeriTACE project. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these types of buildings as if they would be renovated today. In this report, only the baseline scenarios regarding the building envelope are described. The complete baseline scenarios (including heritage value, space conditioning, energy systems and use scenarios) are described in 'D5.4 Baseline scenarios'.

6.5.2.1 Pre-renovation baseline

During the Soviet occupation of Estonia, the archetypical buildings didn't receive much attention besides minimal maintenance, there was also constant shortage of goods, and the buildings were owned by the state. This means that by the beginning of 1990s when Estonia regained independence, the buildings were essentially either having the original building components or they had been replaced by the same type as the original.

BS1_PB: Wooden apartment building

This scenario applies to the pre-renovation state of the wooden apartment building archetype – the load bearing walls are either of wooden log or double plank type with ventilated cladding. The windows are either original (double wooden frame, both housing single glass pane) or Soviet era replacements of the same type. The top boundary of the heated volume is usually the attic floor made of wooden lightweight beams with lightweight fillings or sand in between. The basement is unheated, and its ceiling is made of concrete slab, which may be supported by steel I-beams or railway rails within its volume. The foundation wall/plinth is made of limestone masonry which may or may not be plastered on the outside.

BS2_PB: Stalinist style brick apartment building

This scenario describes the envelope components of the brick apartment building archetype. The main differences compared to the BS1_PB are the wall type (brick masonry with or without an air cavity) and due to that, also the inherently higher airtightness. Windows are still either original or the same type as the original windows. The type is the same as those of the wooden buildings in scenario BS1_PB (double wooden frame, both have single glass pane), but here they typically have slightly different size and frame distribution.

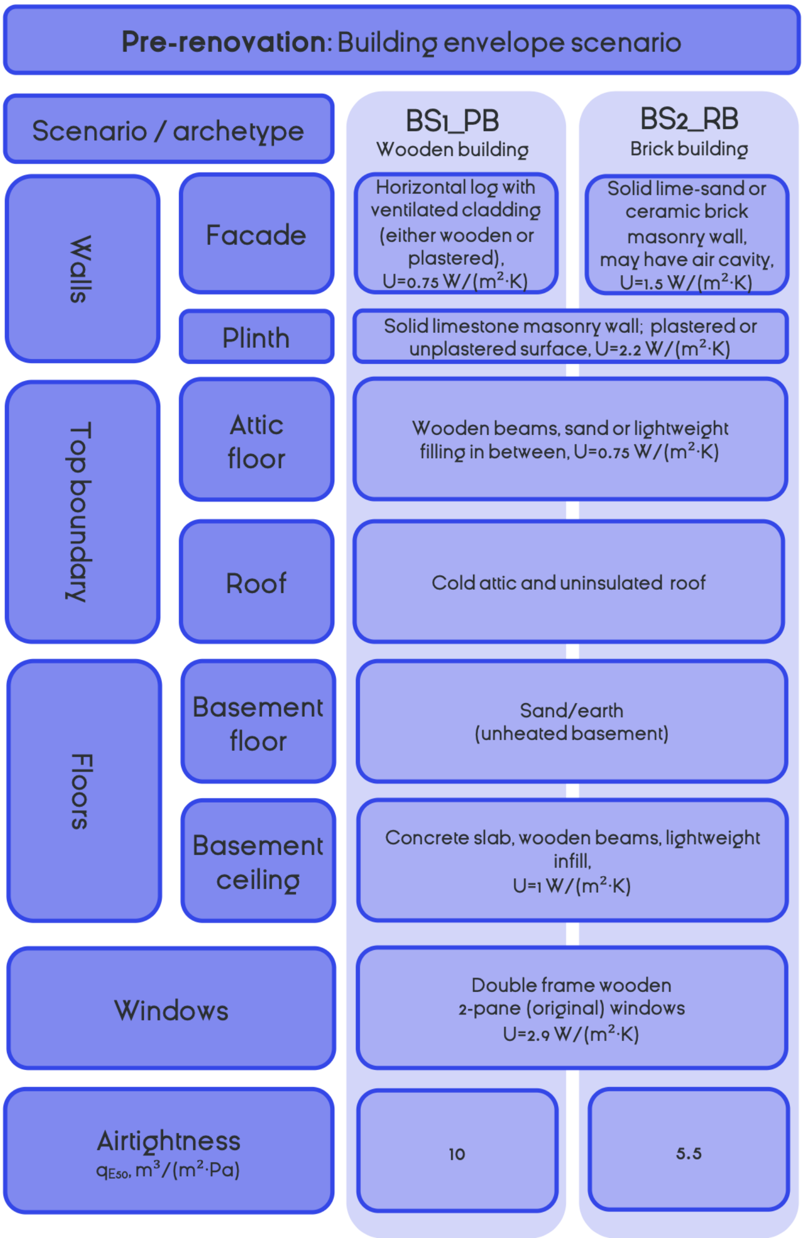


Figure 6-10: Pre-renovation building envelope scenarios.

6.5.2.2 Renovation baseline

BS1_RB: Wooden apartment building, low intervention

This scenario describes a renovation scenario where stepwise retrofitting has led to partial interior insulation, a mix of original type and modern (single frame, 2-pane IGU) windows and insulated top and bottom boundaries (basement ceiling and attic floor, respectively). Replacement of windows and partial insulation of exterior walls increases airtightness compared to pre-renovation state.

BS2_RB: Wooden apartment building, moderate intervention

This scenario builds on the previous one, however, here the 30 mm mineral wool wind barrier board is used as exterior insulation in addition to the existing interior insulation. Due to attic and basement conversion to living space, roof and basement floor are insulated. As the insulation covers the whole wall envelope, airtightness is higher compared to the previous scenario.

BS3_RB: Brick apartment building, low intervention

Here the exterior surface has had no interventions besides stepwise replacement of windows, which results in a mix of various types with different thermal properties. The attic floor is insulated with ca 100 mm loose fill insulation and the basement ceiling with 50 mm mineral wool insulation. The airtightness of plastered masonry is significantly higher than that of wooden buildings and slightly increased over the pre-renovation scenario due to replacement of windows.

BS4_RB: Brick apartment building, moderate intervention

A 50 mm insulation and plaster finishing is added to the exterior surface. Similarly to the previous scenario, the windows are a mix of various types with different thermal properties. Due to attic and basement conversion to living space, roof and basement floor are insulated. The airtightness is on the same level as in the previous brick building scenario.

Renovation: Building envelope scenario

Scenario / archetype		BS1_RB Wooden building	BS2_RB Wooden building	BS3_RB Brick building	BS4_RB Brick building
Walls	Facade	Horizontal log with wooden cladding ($U = 0.75\ W/(m^2{\cdot}K)$) + 50 mm interior insulation (ca 50% of wall area insulated, $U = 0.4\ W/(m^2{\cdot}K)$)	Horizontal log with wooden cladding, 30 mm ext. ins. ($U = 0.44\ W/(m^2{\cdot}K)$) + 50 mm interior insulation (ca 50% wall area, $U = 0.30\ W/(m^2{\cdot}K)$)	Solid lime-sand or ceramic brick masonry wall, may have air cavity, $U=1.5\ W/(m^2{\cdot}K)$	Solid lime-sand or ceramic brick masonry wall, may have air cavity, ext. insulation 50 mm $U= 0.45\ W/(m^2{\cdot}K)$
Walls	Plinth	Solid limestone masonry wall, plastered or unplastered exposed stone surface, $U = 2.3\ W/(m^2{\cdot}K)$ Additional insulation if existing plinth plastered and basement transfrmed to living space, $U = 0.32\ W/(m^2{\cdot}K)$			
Top boundary	Attic floor	Sand or lightweight filling between wooden beams, 100 mm loose fiber insulation $U = 0.25\ W/(m^2{\cdot}K)$	Wooden beams, sand or lightweight filling inbetween $U=0.75\ W/(m^2{\cdot}K)$	Sand or lightweight filling between wooden beams, 100 mm loose fiber insulation $U = 0.25\ W/(m^2{\cdot}K)$	Wooden beams, sand or lightweight filling inbetween $U=0.75\ W/(m^2{\cdot}K)$
Top boundary	Roof	Cold attic and uninsulated roof	Insulated roof (attic converted to apartments) $U = 0.2\ W/(m^2{\cdot}K)$	Cold attic and uninsulated roof	Insulated roof (attic converted to apartments) $U = 0.2\ W/(m^2{\cdot}K)$
Bottom boundary	Basement floor	Sand/earth (unheated basement)	Concrete slab + 100 mm EPS insulation $U = 0.18\ W/(m^2{\cdot}K)$	Sand/earth (unheated basement)	Concrete slab + 100 mm EPS insulation $U = 0.18\ W/(m^2{\cdot}K)$
Bottom boundary	Basement ceiling	Concrete slab, insulated with 50 mm mineral wool $U = 0.4\ W/(m^2{\cdot}K)$	Concrete slab	Concrete slab, insulated with 50 mm mineral wool $U = 0.4\ W/(m^2{\cdot}K)$	Concrete slab
Windows		Double frame 2-pane windows (original type, ca 10%, $U_w = 2.9\ W/(m^2{\cdot}K)$) Double frame 1+2-pane IGU windows (modern, ca 90% $U_w = 1.2\ W/(m^2{\cdot}K)$)	Mix on different windows: 1+1-pane double wooden frame original type, $U_w = 2.9\ W/(m^2{\cdot}K)$ 1+2-pane double frame, $U_w = 1.5\ W/(m^2{\cdot}K)$ 3-pane IGU, single frame, $U_w = 0.9\ W/(m^2{\cdot}K)$		
Airtightness q_{E50}, $m^3/(m^2{\cdot}Pa)$		9	7	4	4

Figure 6-11: Overview of Estonian envelope renovation scenarios.

7. Italy

In Italy, the historical city center of Mantova is studied. The most common building archetype at neighbourhood scale in Mantova is the **Gothic lot,** a typical medieval townhouse with a narrow street-facing facade and greater depth, often featuring three floors and a rear courtyard used for hygiene and domestic activities. Its layout is functional, with stairs positioned either centrally or along the length, and includes light wells to improve natural lighting. The **Palazzetto** archetype defines, instead, 17th – 19th century buildings that resembles a Gothic lot but with a greater width, often with three or four floors including a mezzanine and basement. It includes a noble floor with higher ceilings, a rear courtyard, and sometimes L-shaped extensions. It reflects later historical evolutions and renovations. Another Mantovan building archetype is the **Extended building**, or houses in line. It results from merging multiple Gothic lots. These buildings have wider, often irregular facades with multiple entrances, including carriage access, and feature more symmetrical internal layouts. Finally, **Courtyard buildings** represent a larger and more complex Mantovan archetype, characterized by more refined structures built around an internal courtyard. They typically have two or three levels and multiple staircases separating noble and service areas, showing a complex internal organization due to historical layering. The neighbourhood, archetype and case study selection is further detailed in deliverable D5.1.

The investigation of the case study buildings was conducted as part of the current task T2.1, alongside related tasks focusing on the case studies in other WP, namelyT3.1, T4.1 and T5.1. The aim was to collect on-site information for the four selected building archetypes - since the latter have considerable similarities in terms of building envelope characteristics, the selected case studies can be considered a good sample of the various building archetypes. Two of the examined buildings are currently in use, which limited The archetype of the Gothic Lot archetype (represented by the case study *Romano*), the Extended Building (represented by the case studies *Leonardo* and *Vincenzo*) and the Palazzetto (represented by the case study *Montanara*) differ in age, size and internal distribution but not so much in the type of walls, windows and roof. Also, the Courtyard building archetype (represented by the case study *Vescovile*) has a similar wall build-up – however being thicker – and windows of larger dimensions.

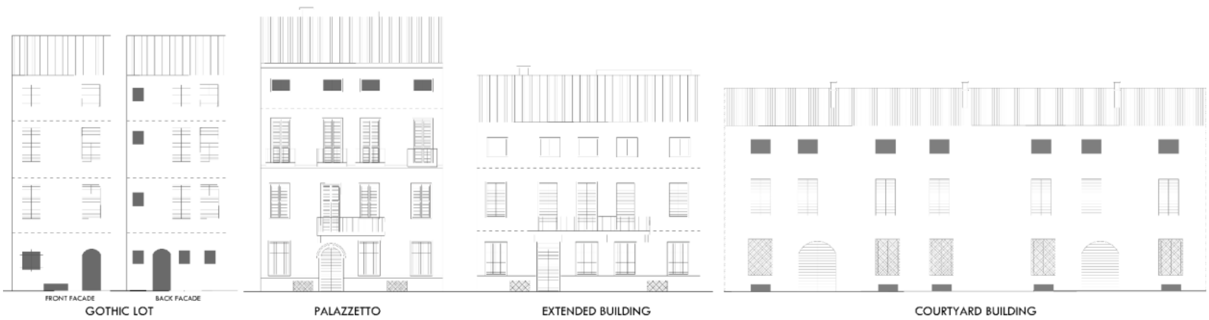


Figure 7-1: Overview of townhouse archetypes by facade (IT).

A range of investigations was carried out across the different case studies. In nearly all cases, a technical inventory was compiled, documenting the typical building envelope elements, their surface areas, and construction build-ups. In addition, a heritage expert assessed the technical condition of the elements. In situ measurements of thermal resistance were conducted in the two cases which were heated. Finally, air tightness measurements were performed on two case study buildings on building level using the blower door method and in one building on window level.

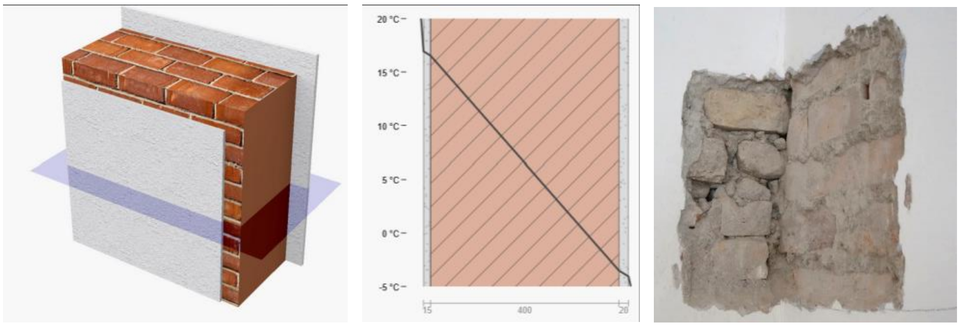
7.1 Envelope characteristics

7.1.1 Walls

7.1.1.1 Masonry walls with original plaster

Description	The historic buildings in the city centre of Mantova – as well as in numerous other Italian cities with medieval roots – have in common that the load bearing structure is typically solid masonry wall made of raw bricks with lime plaster both on the interior and on the exterior side. The thickness of the walls varies with the archetype: Gothic Lot and Palazzetto archetype would typically have a wall with triple leave on the front side, resulting in a thickness of 44 to 46 cm. The wall of the back façade is typically a double leave with a total thickness between 32 and 34 cm. The Extended Building archetype does not differentiate between front and back façade. The wall of the ground floor would typically have a thickness of more than 40 cm. The thickness of the wall would however decrease in the upper floor – in the case of the Leonardo e.g. to 32 cm. The Courtyard building archetype is much larger and has respectively walls with a thickness of up 60 to 80 cm in the lower floors, tendency to become thinner with higher floors and towards the courtyard. The front facades can be decorated – especially for the more prestigious archetype of the courtyard building, but in a more limited way also for a Gothic lot, as e.g. the stone columns on the main façade of *Romano* show. The interior surfaces are often decorated with frescoes (e.g. *Leonardo* both ground floor and upper floor, and *Montanara* still conserved under the recent plaster).
Typical condition	RC1: The walls are usually structurally intact. The plaster can show some points of humidity, especially those towards the backyard which receive less attention.
Typical damage mechanisms	Solid brick masonry walls can experience various degradation mechanisms, such as salt efflorescence from the bricks, flaking of plaster and paint layers on facades due to cyclical expansion and contraction, and solar exposure. Plastered finishes may also accumulate dirt from urban pollution. Mould growth on the interior surface is relatively rare, especially if the windows are still the original ones and respectively not air tight. In rooms with high humidity loads as e.g. bathrooms, mould growth might however be observed.

Illustration



(left) sketch and calculation created with ubakus.de, (right) fragments of masonry visible under the plaster in *Romano*.

Structure

Masonry wall with original plaster					
Material	Thickness [m]	Thermal conductivity Lambda [W/mK]	Density Rho [kg/m³]	Thermal capacity cp [J/kgK]	Vapour resistance μ [-]
Interior					
Lime plaster	0.015	0.87	1400	1000	10
Masonry + Lime mortar	0.28… 0.42… 0.76	0.47… 0.70	1200… 1800	1000 1000	10 10
Lime plaster	0.02	0.87	1400	1000	10
Exterior					
TOTAL	0.32…0.80				

Thermal transmittance U, W/(m²·K)

- Front facade: 0.8…0.9 W/m²K (based on measurements carried out according to ISO 9869 and calculations)
- Back facade: 1.0 … 1.2 (based on measurements carried out according to ISO 9869 and calculations)

7.1.1.2 Masonry walls with new plaster

<table>
<tr><td>Description</td><td>The main part of the description of 7.1.1.1 Masonry walls with original plaster applies also here. Looking at the HeriTACE case studies in Mantova makes however also clear that the original plaster has not in all cases be preserved: Montanara e.g. has at the interior a new lime plaster, and so does Romano. In Montanara the main façade has recently be replastered, in Romano both main and internal façade have a recent plaster with a base in cement mortar.

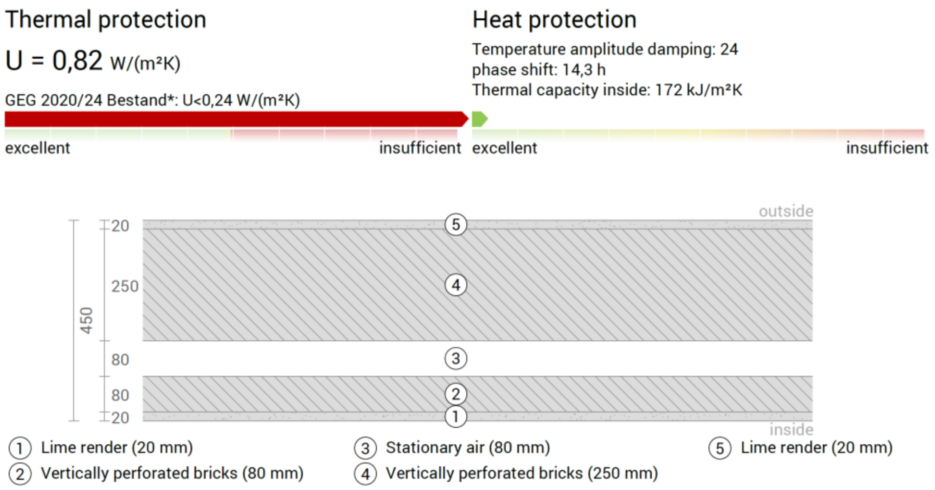
Actually, a cement-based plaster would be the typical choice for new plasters on the outside, and the difference in behavior is the reason to define it a separate wall type.</td></tr>
<tr><td>Typical condition</td><td>RC1. Condition is usually good, also because usually recent. Material incompatibilities might however have induced salt damage.</td></tr>
<tr><td>Typical damage mechanisms</td><td>In addition to the damage mechanisms described above, a new cement-based plaster might induce additional problems in terms of salt efflorescence and humidity problems being shifted to other areas.</td></tr>
<tr><td>Illustration</td><td>See 7.1.1.1 and 7.5.1</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th colspan="6">Masonry wall with new lime cement plaster</th></tr>
<tr><td>Material</td><td>Thickness [m]</td><td>Thermal conductivity Lambda [W/mK]</td><td>Density Rho [kg/m³]</td><td>Thermal capacity cp [J/kgK]</td><td>Vapour resistance μ [-]</td></tr>
<tr><td>Interior</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lime plaster</td><td>0.015</td><td>0.87</td><td>1400</td><td>1000</td><td>10</td></tr>
<tr><td>Masonry + Lime mortar</td><td>0.28…
0.42…
0.76</td><td>0.47…
0.70</td><td>1200…
1800</td><td>1000
1000</td><td>10
10</td></tr>
<tr><td>Lime Cement plaster</td><td>0.02</td><td>1</td><td>1800</td><td>1000</td><td>15-35</td></tr>
<tr><td>Exterior</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>TOTAL</td><td>0.32…0.80</td><td></td><td></td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>The thermal transmittance U remains practically unchanged.

What changes is the resistance to water vapour sd, which increases in the new outermost layer.</td></tr>
</table>

7.1.1.3 Masonry walls with burnt brick

Description	Annexes as e.g. the one in *Romano* dating from the mid of the 20th century would typically still be built in masonry, but with burnt bricks, often also with an air layer between the inner hollow bricks and the outer solid bricks.
Typical condition	RC1. Condition is usually good, just maintenance of plaster needed.
Typical damage mechanisms	Same as the other masonry walls.

Illustration & Structure



[according UNI/TR 11552:2014]

Masonry wall with new lime cement plaster					
Material	Thickness [m]	Thermal conductivty Lambda [W/mK]	Density Rho [kg/m³]	Thermal capacity cp [J/kgK]	Vapour resistance μ [-]
Interior					
Lime plaster	0.02	0.7	1400	1000	10
Hollow brick	0.08	0.4			5-10
Air	0.02-0.12	R~0.18 m²K/W			1
Hollow brick	0.25	0.4	1200...	1000	5-10
Lime plaster	0.02	0.9	1800	1000	10
Exterior					
TOTAL	0.32...0.80				

Thermal transmittance U, W/(m²·K)	~0.8 W/m²K (typical range, calculated acc. to EN 6946 .

7.1.2 Top boundary

7.1.2.1 Pitched roof

<table>
<tr><td>Description</td><td>All archetypes would typically have a double-pitched roof with wooden planking, joists and wooden beams with a circular section. Where the dimension of the attic rooms is very large, there might be support points for the roof structure with brick pillars. The ridge of the two pitches rests on the central spine wall of the building. External cladding in antique tiles. The wooden trusses are the ancient ones</td></tr>
<tr><td>Typical condition</td><td>The wooden structure of the roof is in a fair condition; it would be necessary to deepen its mechanical resistance.</td></tr>
<tr><td>Typical damage mechanisms</td><td>There is an inherent risk of wood rot, however this has not been observed in the case study buildings. Rainwater entering in heavy storm events leaves traces on the wooden structure, but since the attics are not used and well-ventilated a fast drying usually prevents major damage.</td></tr>
<tr><td>Illustration</td><td>

Roof construction seen from the attic – *Montanara* on the left, *Romano* on the right


Exterior view on the roof tiles.</td></tr>
<tr><td>Structure</td><td>
<table>
<tr><th>Material</th><th>Thickness [m]</th><th>Thermal conductivity [W/(m·K)]</th><th>Resistance [m²K/W]</th><th>U-value [W/m²K]</th></tr>
<tr><td>exterior</td><td></td><td></td><td>0.1</td><td></td></tr>
<tr><td>wooden planking</td><td>0.03</td><td>0.13</td><td>0.231</td><td></td></tr>
<tr><td>joists</td><td>0.16 (thick) 0.10 (wide)</td><td>0.13</td><td>minimal see 8.5.1</td><td></td></tr>
<tr><td>interior</td><td></td><td></td><td>0.1</td><td></td></tr>
<tr><td>TOTAL</td><td></td><td></td><td>0.431</td><td>2.23</td></tr>
</table>
</td></tr>
<tr><td>Thermal transmittance U, W/(m²·K)</td><td>~2 W/m²K (typical range, calculated acc. to EN 10211)</td></tr>
</table>

7.1.2.2 Pitched roof with insulation

Description

Even if not encountered in the case studies, pitched roofs have often already been insulated, as it is a quite straightforward and easy measure with limited impact on the heritage value. Also, if the roof has been renewed (be it for statical reasons or in the context of a change of use) this was typically combined with the insulation of the roof.

The thickness of the insulation layer would typically have been between 30 and 50mm before EPBD requirements entered into force.

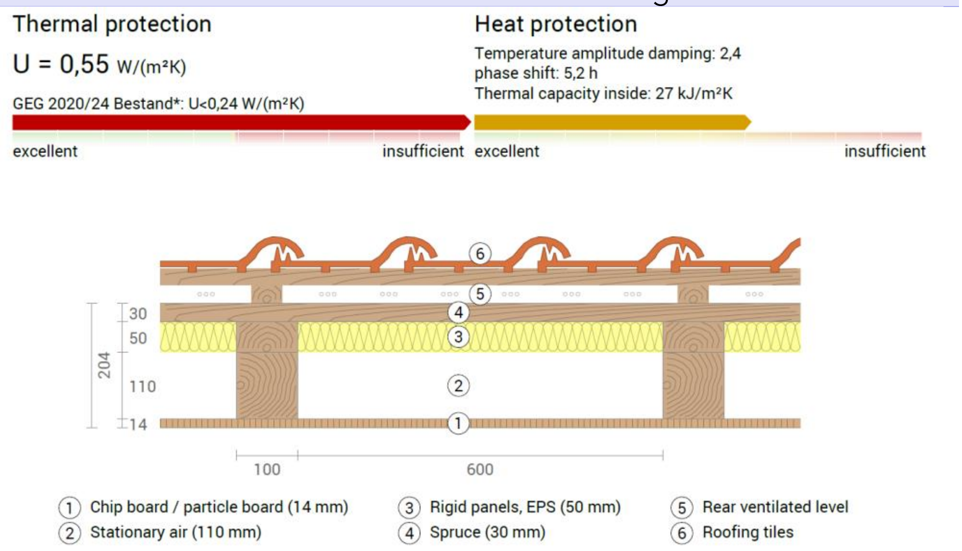
Typical condition

Typically good condition

Typical damage mechanisms

When insulated, the resistance to vapour pressure should get smaller for layers the more outside they are. If this is not observed moisture can accumulate in the construction and lead to damage.

Illustration



Structure

Material	**Thickness [m]**	**Thermal conductivity [W/(m·K)]**	**Resistance [m²K/W]**
exterior			0.1
1 wooden planking	0.03	0.13	0.231
2a EPS	0.05	0.04	1.125
3a air layer	0.11		0.18
2b+3b joists	*0.16*	*0.13*	*1.23*
4 wooden panel	0.014	0.13	0.108
interior			0.1
TOTAL			1.97/*1.77*
U-value			0.55 W/m²K

Thermal transmittance U, W/(m²·K)

~0.55 W/m²K (typical range, calculated acc. to EN 6946 and EN 10211 leading to the same result)

7.1.2.3 Attic Floor

Description

Since in most cases the attic is not used as living space, the attic floor is usually the thermal envelope. It is composed of wooden floorboards resting on a framework of joists and main beams.
The false ceiling (i.e. the side towards the last storey) is made of reed and plaster mortar (gypsum or lime) and is often characterized by decoration, as e.g. in *Montanara* oval decorative stuccoes placed in the centre of the room, with a pattern that encased the wooden beams. In some rooms this false ceiling has been removed
The upper finish in the attic would typically a cast plaster floor

Typical condition

All floors appear in a good state of conservation.
It could however be necessary to verify the stability at the point of interlocking in the walls

Typical damage mechanisms

Ceiling in reed, under a layer of gypsum mortar.

Structure

Material	Thickness [m]	Thermal conductivity [W/(m·K)]	Resistance [m²K/W]
exterior			
1 cast plaster /screed	0.03	1.4	0.021
2 wooden floorboards	0.03	0.13	0.231
3a air layer			0.18
3b joists	*0.04..0.12*	*0.13*	*0.31 .. 0.92*
4 reeds	0.01	0.12	0.083
5 gypsum pasters	0.01	0.7	0.014
main beams			do not contribute
interior			0.1
TOTAL			0.73/*0.85..1.47*
U-value			1.38..1.32 W/m^2K

Thermal transmittance U, W/(m²·K)

1.3 to 1.4 W/m^2K (typical range, calculated acc. to EN 6946)

Thermal capacity of inner layers – seen from below (room side) 40 kJ/m^2K

7.1.3 Floors

7.1.3.1 Wooden Floors with false ceiling

Description	Floors also between the different storeys are typically composed of wooden floorboards resting on a framework of joists and main beams. The false ceiling is made of reed and plaster mortar and may be characterized by decorative stuccoes placed in the centre of the room, with a pattern that encased the wooden beams (see *Montanara*). The cladding can be a parquet (typically from 1st storey upwards) or gres, tiles and terracotta (typically on the ground floor, where the use might also have been different, e.g. warehouse or similar)
Typical condition	All floors appear in a good state of conservation. In some cases where the floor is exposed, the addition of more recent joists has been found. It could be necessary to verify the stability at the point of interlocking in the walls
Typical damage mechanisms	
Illustration	See more images under 7.1.2.3  *Montanara* Decorations found in the corridor leading to the courtyard, from the late 19th century
Structure	See 7.1.2.3, differing only in layer 1, which is on the storeys used as living space (i) parquet (slightly higher thermal resistance – however between used floor not of importance) or (ii) gres or (terracotta) tiles (similar thermal behavior as screed)
Thermal transmittance U, W/(m²·K)	1.3 to 1.4 W/m²K (typical range, calculated acc. to EN 6946), of limited importance for floors between heated spaces Thermal capacity of inner layers seen from below 40 kJ/m²K with parquet, 33 kJ/m²K with tiles, from above 47 kJ/m²K with parquet, 68kJ/m²K with tiles (www.ubakus.de)

7.1.3.2 Wooden Floors with exposed construction

Description

In some cases, these false ceilings have been removed (differing also from room to room in a building), or have from the beginning not been added, as decorated areas as found in *Leonardo* do suggest.

Typical condition

All floors appear in a good state of conservation.
In some cases where the floor is exposed, the addition of more recent joists (on the second floor) has been found. It could be necessary to verify the stability at the point of interlocking in the walls

Typical damage mechanisms

Illustration

See images under 7.1.2.3


Exposed wooden floor at *Leonardo* – plain in the kitchen (left) and with 16th century decorations on the right.

Structure

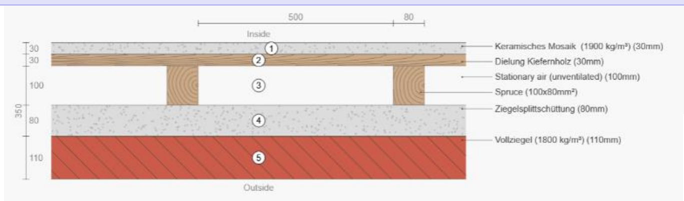
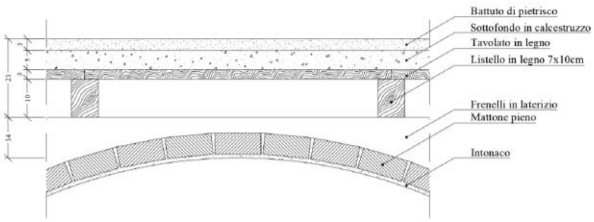
Material	**Thickness [m]**	**Thermal conductivity [W/(m·K)]**	**Density [kg/m³]**
above			
1 parquet or tile	0.03	0.13/1.4	0.231/0.021
2 wooden floorboard	0.03	0.13	0.231
joists	do not add to thermal resistance		
beams	do not add to thermal resistance		
below			0.586/0.442
TOTAL			1.7/2.3 W/m²K

Thermal transmittance U, W/(m²·K)

~2.3 W/m²K (typical range, calculated acc. to EN 6946), of limited importance for floors between heated spaces

Thermal capacity of inner layers – seen from above 14.7 kJ/m²K
Seen from below 25 kJ/m²K

7.1.3.3 Ground floor slab over cellar (sometimes on vaults)

Description	Wooden floorboard resting on a framework of joists and main beams (also with ceiling vaults). Cladding in terracotta tiles/stone
Typical condition	
Typical damage mechanisms	
Illustration	 created with www.ubakus.de  Dall'Orto 2021  Brick vaults in the cellar of *Leonardo*

Structure

Material	Thickness [m]	Thermal conductivity [W/(m·K)]	Density [kg/m³]
interior			
1 terracotta or gres	0.03	1.0	0.030
2 wooden floorboards	0.03	0.13	0.23
3a air layer	0.10		0.23
3b joists	*0.10*	*0.13*	*0.78*
4 brick fragments	0.08 (0.14-0.4)	0.12	0.195
5 bricks	0.11	0.81	0.136
exterior			
TOTAL	0.31-0.41		0.82/*1.47*
U-value			0.84 W/m²K

Thermal transmittance U, W/(m²·K)	~0.8-0.9 W/m²K (typical range, calculated acc. to EN 6946)

7.1.4 Windows

7.1.4.1 Original single glazed wooden windows

Description	Original windows are characterized by a slender wooden frame construction and single glazing. They are typically double sash windows, divided horizontally with sash bars. Usually, they are positioned at half depth of the wall (or a bit mor to the inside)
Typical condition	RC 0 – RC 3: vulnerable component. It can be in good condition, if maintained with care (paint layer), more often is shows deformation, flaking of paint layers
Typical damage mechanisms	Shrinking and swelling of wooden parts lead to deformation and loosening of connections, but also to cracks in the paint via which humidity can enter. Outside moisture from driving rain, inside moisture from condensation on single glazing.
Illustration	 *Vescovile* Foto between 1925 and 1950, https://catalogo.beniculturali.it/detail/PhotographicHeritage/0303253313
Thermal transmittance U, W/(m²·K)	Single glazing: U_g = 5.8 W/m²K Window: U = 4.8 W/m²K for a frame ratio of 30% (5.0 W/m²K for 25% frame, 4.5 W/m²K for 40% frame)

7.1.4.2 Replica wooden window with double glazing

Description	
Illustration	 *Vescovile* Roberto Rubiliani, April 2024 https://maps.app.goo.gl/qSZMKadD2AHJ1FK47
Thermal transmittance U, W/(m²·K)	Double glazing: U_g = 1.5 … 1.2 W/m²K Window: U = 1.8 W/m²K…1.6 W/m²K (based on calculations, depending on window geometry)

7.1.4.3 Wooden window with double glazing

Description	In many cases the original windows have been replaced. Usually with wooden windows with double glazing, sometimes also with PVC frames. The new windows are in many cases again two-sash windows, but the horizontal division with sash bars is often lost. It is however also not seldom that the windows are replaced with single sash windows. The thickness of the frame will typically be less slender.
Typical condition	Usually in fairly good conditions. Sealants are often to be replaced. They are, however, more difficult to repair.
Typical damage mechanisms	Similar to the above, but no more issue with condensation on the inner side of the glazing, and due to thicker frames usually less deformation.
Illustration	   *Montanara* *Romano* *Leonardo*
Thermal transmittance U, W/(m²·K)	Early double glazing: U_g=2.8 W/m²K, after 1990 U_g=1.5 to 1.2 W/m²K Window: U_w=2.6 W/m²K, after 1990 U_w=1.8 to 1.5 W/m²K (based on calculations, depending on window geometry)

7.1.4.4 Exterior wooden shutters with slats

Description	Wooden shutters with tilted slats serve as a traditional way to control light, airflow and provide security and privacy. They are also used in winter (during night, to obscure and decrease heat loss) but are particularly important in summer, when they serve (i) during the day to shade the ambients from directly entering sun radiation, which would lead to overheating or excessive cooling demand, while still allowing some daylight to enter and (ii) during night when windows can be kept open for ventilation while still providing security. The tilting angle of the slats can in many cases be changed from a closed position to nearly 90° so that the amount of daylight and ventilation can be adjusted to the needs. Furthermore, the closing mechanism allows also to fix the two shutters in a slightly open position, allowing for more ventilation, while still providing obsczrance and privacy. In some cases the shutters are constructed in a way that the lower part can be open towards upside (see foto below), which allows for shading while still allowing to only considerable ventilation but also to look outside and interrelate with the life on the street.

Typical condition	Wooden shutters need regular care of the paint layer. If this is not done, the cracking paint allows water to enter the wooden parts, which leads to deformation and loosening of slats
Typical damage mechanisms	UV, Fainting and flaking of paint layer, deformation
Illustration	  (left) *Vescovile* David Tomaszewski, Aug 2019, https://maps.app.goo.gl/M25ZiKRryhjHg52x9 (right) damaged shutters in Via Trento, Mantova  Shutters with tiltable slats and lower part openable
Thermal transmittance U, W/(m²·K)	For single glazed windows: U_w=4.8 W/m²K is reduced to U_{ws}=2.25..3.5 W/m²K with closed shutter For double glazed windows: U_w=1.6 W/m²K is reduced to U_{ws}=1.2…1.4 W/m²K with closed shutter. Reduction of solar load: Fc-value 0.15 (closed fins to 0.25 (open fins, i.e. 45°) [values according to DIN 4108-2, (depending also on glazing)]

7.1.4.5 Exterior wooden shutters

Description	Wooden shutters can also be of simpler construction, featuring just plain wooden panels. The light and ventilation control is rather limited with these.
Illustration	  *Montanara* backyard, and one more building in via same street
Thermal transmittance U, $W/(m^2 \cdot K)$	For single glazed windows: $U_w=4.8\ W/m^2K$ is reduced to $U_{ws}=2.25..3.5\ W/m^2K$ with closed shutter For double glazed windows: $U_w=1.6\ W/m^2K$ is reduced to $U_{ws}=1.2…1.4\ W/m^2K$ with closed shutter. Reduction of solar load: Fc-value 0.15 (depending also on glazing)

7.1.4.6 Interior Shutters

Description	Interior wooden shutters have been found in three of the four case study buildings: In *Vescovile* they are part of the wooden casing of the whole window reveal. In *Leonardo* and *Romano* there is no wooden case of the reveal. In all three cases the shutters are foldable in order to fit in the space of the window reveal. The interior shutters are typically mounted on the window frame. In terms of reducing solar loads, they are unfortunately much less efficient than exterior shutter
Typical cond.	RC0. Typically good conditions
Illustration	   *Vescovile* *Leonardo* *Romano*
Thermal transmittance U, $W/(m^2 \cdot K)$	For single glazed windows: $U_w=4.8\ W/m^2K$ is reduced to $U_{ws}=2.25..3.5\ W/m^2K$ with closed shutter For double glazed windows: $U_w=1.6\ W/m^2K$ is reduced to $U_{ws}=1.2…1.4\ W/m^2K$ with closed shutter. Reduction of solar load: Fc-value 0.65-0.85 (depending also on glazing)

7.2 Airtightness

There exist several studies on the airtightness of the existing building stock in Italy and South Europe. D'Ambrosio Alfano et. al. (2012) for example have done a blower door study on 20 buildings and found the average n_{50} value to be 7.3 1/h. The analysed buildings date from 1810 to 2010 – five of the buildings being from before the oil crisis in the 70ies. Excluding one extremely leaky building with n_{50}=23,3 1/h, the average of the "old" buildings is with 6.53 1/h very similar to the overall average of 6.83 1/h (own calculation based on the data reported in the paper). Sealing the windows in their first analysed case reduced n_{50} from 7.3 1/h to 4.57 1/h.

Fernández-Agüera et al (2019) studied nearly 40 buildings (with 159 dwellings) in Spain, and report for buildings with thick monolithic masonry walls a median n_{50} value around 6 1/h which is clearly below the median of the whole sample. A study by Sfakianaki et al.(2008) in Greece related the n_{50} value to the frame lengths and found R^2 of this correlation highest in low-airtightness building.

To complete the information from literature with on-site data, at two of the HeriTACE case study buildings in Mantova a Blower Door test on building level was performed.

Figure 7-2: Blower Door test at *Leonardo*. First on ground level with door closed (n_{50}=3,9 1/h) then on the overall building (n_{50}=4.7 1/h).

At *Leonardo* the Blower Door Test has first been performed on the ground floor only (volume 435 m³, floor area 150 m²), closing and sealing the door to the staircase at the end of the corridor leading to the upper floor. The test in depressurisation resulted with n_{50}=3.83 1/h slightly lower than the test in pressurisation with n_{50}=3.97 1/h. The thermography done on the window in the dining room before and after the depressurisation test (thus after having aspired cold air) show actually some un-tightness, especially for the right window (see Figure 7-3). The n_{50} value of the second test with the door ato the staircase t the end of the corridor open (volume now 1075 m³, floor area 359 m²) results in a lower overall airtightness with n_{50}=4.9 1/h in depressurisation and n_{50}=4.5 /1/h in pressurisation. The windows at the ground floor are fairly new windows with double glazing and sealing.

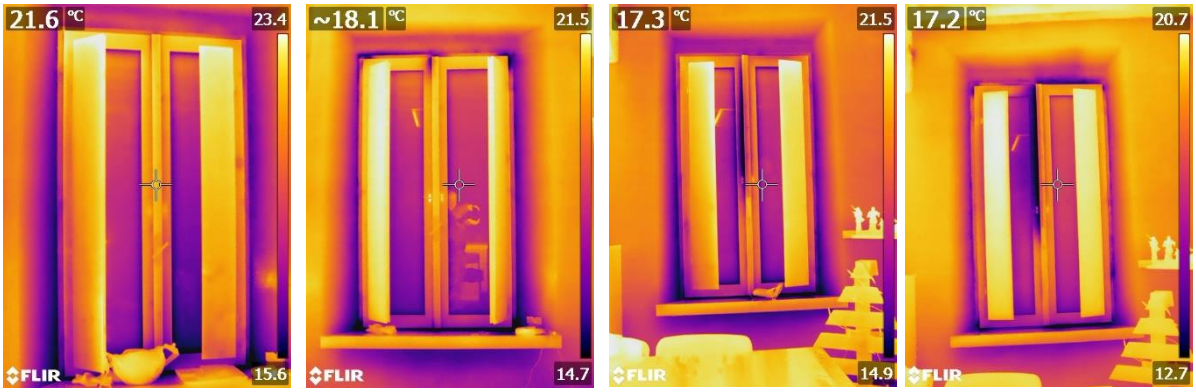


Figure 7-3: Thermogarphy of the two windows in the dining room before and after the blower door test in depressurisation show air leakage.

At *Montanara* the Blower Door test was done during a running construction site. This means, that the results might not depict directly the use phase, but it allowed on the other hand site to do the test in several steps – closing one "leakage source type" after the other. The Blower Door test was done on the whole building excluding the cellar, i.e. the base variant was already done, sealing the opening towards the cellar (see Figure 7-4). That this sealing was difficult to archive under construction site conditions adds uncertainty to the measurements – it had to re-seal several times, but the operators observed the situation closely.

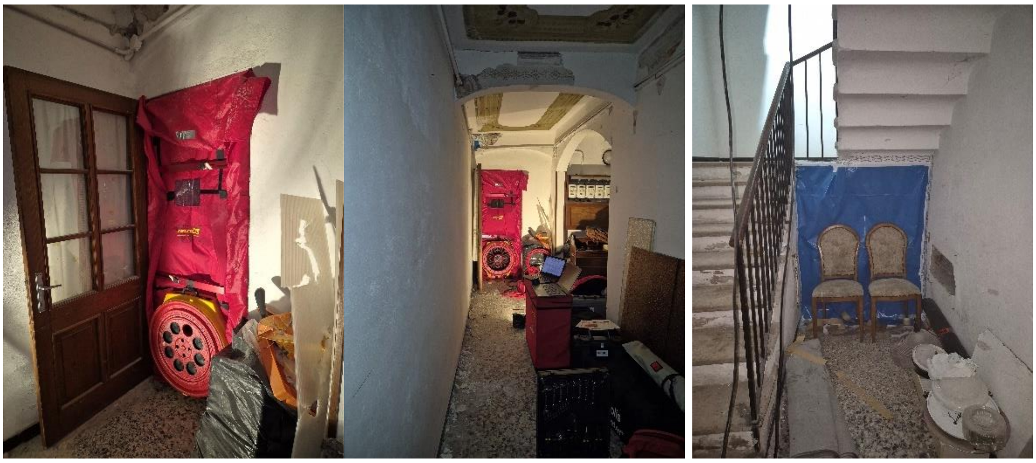


Figure 7-4: Installation of the Blower Door at *Montanara* (left and middle) and sealing towards the cellar (right)

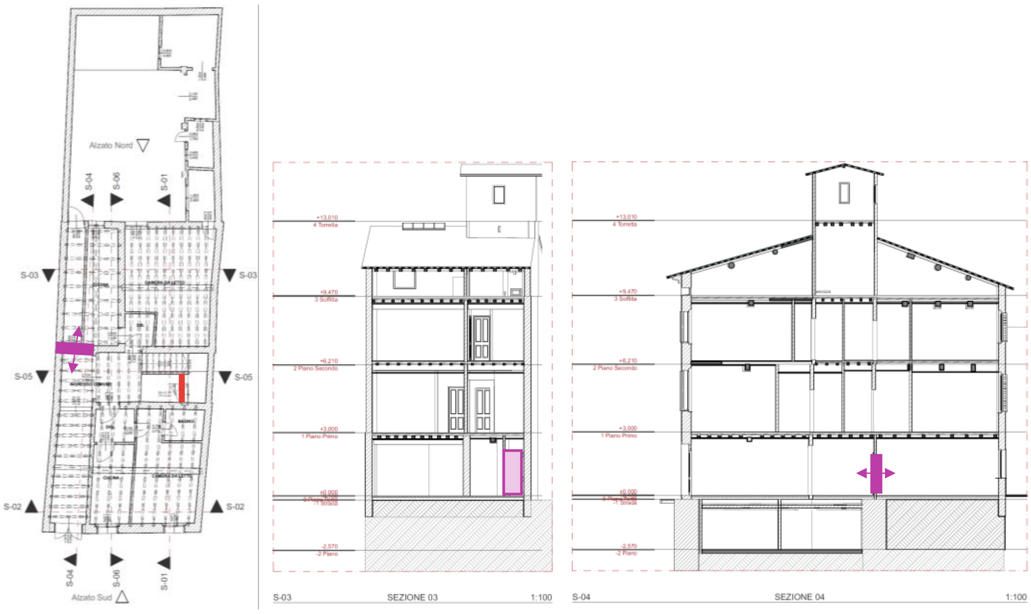


Figure 7-5: position of blower door and sealing of opening towards the cellar at *Montanara*.

The first test was done both under depressurisation and pressurisation. Since the test under pressurisation brought a large amount of dirt from the courtyard and corridor into the buildings, it was not repeated in the following steps. The second step was **closing all obvious holes** due to the construction site (open holes for dismounted flue chimneys). This resulted in an **n_{50}=6.16 1/h**.

The next steps consider improvements of the envelope:
In step 3 the **ventilation openings** which any Italian appartement needs to have if a **gas heater** is present. This results in a an **n_{50}=5.83 1/h** reducing the n_{50} value by 0,3 1/h or rather the effective leakage area ELA_{50} by **ΔELA_{50}=100 cm²** to 1780 cm².
In step 4 the visibly leaky door from the ground floor appartement to the backyard was sealed all around, resulting in an **n_{50}=5.41 1/h** reducing the n_{50} value by 0,42 1/h or rather the effective leakage area ELA_{50} by **ΔELA_{50}=130 cm²** to 1650 cm².

In step 5 the ancient main front door was sealed all around, resulting in an **n_{50}=5.14 1/h** reducing the n_{50} value by 0,27 1/h or rather the effective leakage area ELA_{50} by **ΔELA_{50}=80 cm²** to 1580 cm².

Also, in the case of *Montanara* the windows were fairly new ones. The still quite high n_{50} value of the last step is most probably due to considerable leaks towards the attic and through the glazed upper closer of the staircase.

Table 7-1 Blower Door tests at *Montanara* in different sealing steps

	n_{50} (depression)	n_{50} (pressure)	Δ	notes
1	6.57	5.43		Base case, only opening to the cellar sealed. Measurement with pressurisation brought too much dirt into the building and was thus not repeated in the following cases.
2	6.16		0.41	Closing holes which are due to the construction site
3	5.83		0.30	Closing the six ventilation openings for gas heaters
4	5.41		0.42	Sealing the small untight door towards the backyard
5	5.14		0.27	Sealing the ancient main entrance door

Figure 7-6: two kinds of leakage source sources at Montanara closed in step two (holes dur to building site – red), and step three (holes needed when gas boilers are present in the flat- blue).

From the above literature together with the measurements done in the two case studies in the deliverable *D5.4 on the baseline scenarios* an n_{50} value of 7.5 1/h is proposed for modelling the scenario with all windows still original, n_{50}=6 1/h for those where part of the windows has already been changed and n_{50}=4.5 1/h for existing buildings with all windows changed. For a business-as-usual renovation scenario (going beyond a mere change of windows) the reduction of n_{50} to 3 1/h is proposed.

7.3 Moisture safety on interior surface (temperature factors)

Moisture safety evaluations will be done (i) on the renovation scenarios for temperature and humidity distribution in the wall and (ii) on the basis of the dynamic simulations of both the baseline and renovation scenarios with regard to interior surface temperatures, relative humidities near the surface and resulting mould risk for spatially and temporally non constant use of the rooms.

A preliminary analysis of a mould risk in a not insulated corner situation shows that the climate in Mantova might lead to potentially critical situations actually in the warm seasons- and that however both approaches in **EN ISO 13788** have **limitations in their models**:

For both measured U-values a corner situation has been modelled with mould simulator, resulting for *Leonardo* (U=0,82, thickness 44cm) in an **f_{Rsi}=0.816 for the undisturbed wall** and **f_{Rsi}=0.681 for the corner**. For Vescovile (U=0,852, thickness 70cm) in an f_{Rsi}=0.808 for the undisturbed wall and f_{Rsi}=0.668 for the corner. These values have then compared with the minimum $f_{Rsi,min}$ which depends on the respective climate:

Applying the moisture excess approach of the **maritime climate model** leads to presumably too high expected interior relative humidities due to the fact that interior temperatures in are assumed to be 20°C in heated months and the average of the outdoor temperature respectively 18°C in not heated months. Actually, for the data in Table 7-2 and Table 7-3May and September were assumed "heated", otherwise RH would have been even higher and $f_{Rsi,min}$=1. The **low assumed interior temperature outside winter** does of course not influence $T_{i,min}$, which is just a function of the interior moisture and depends on the exterior moisture plus the assumed excess moisture of the applied moisture class. $f_{Rsi,min}$, however, depends on the assumed interior temperature, and seen from the hand side, the calculated $T_{i,surf}$ for the respective months depends on the interior air temperature assumed.

Table 7-2 Applying the model for maritime climate and humidity class 3 (building with unknown occupancy) results in May being the most critical month – since the 18°C and 82% RH outside result in 20°C and 79.8% inside. The assumption of 20°C inside seems, however, not realistic.

	period	Ti	Te	Ppv_i	Pv_a	RHi	RHe	Ti,min	fRsi,min
1	January	20	1,5	*1432*	676	61,3	99,2	15,8	0,771
2	February	20	2,3	*1396*	668	59,7	92,6	15,4	0,738
3	March	20	8,4	*1305*	794	55,8	72,0	14,3	0,510
4	April	20	12,9	*1449*	1097	62,0	73,7	15,9	0,427
5	May	20	18,0	*1864*	1694	**79,8**	**82,0**	20,0	**0,977**
6	June	22,1	22,1	*1799*	1699	67,6	63,8	19,4	0
7	July	23,5	23,5	*2223*	2123	76,7	73,3	22,8	0
8	August	24,6	24,6	*2409*	2309	77,9	74,6	24,2	0
9	September	20	19,3	*1796*	1672	76,9	74,6	19,4	0,053
10	October	20	12,7	*1711*	1352	73,2	92,0	18,6	0,805
11	November	20	7,5	*1558*	1015	66,7	97,9	17,1	0,767
12	December	20	3,4	*1413*	724	60,4	92,8	15,6	0,732

Table 7-3 Applying the model for maritime climate and humidity class 2 (offices, dwellings with normal occupancy and ventilation) results in May being the most critical month – since the 18°C and 82% RH outside result in 20°C and 79.8% inside. The assumption of 20°C seems not realistic.

	period	Ti	Te	Ppv_i	Pv_a	RHi	RHe	Ti,min	fRsi,min
1	January	20	1,5	*1182*	676	50,6	99,2	12,8	0,611
2	February	20	2,3	*1157*	668	49,5	92,6	12,5	0,574
3	March	20	8,4	*1149*	794	49,2	72,0	12,4	0,341
4	April	20	12,9	*1353*	1097	57,9	73,7	14,9	0,277
5	May	20	18,0	*1837*	1694	**78,6**	**82,0**	19,7	**0,859**
6	June	22,1	22,1	*1799*	1699	67,6	63,8	19,4	0
7	July	23,5	23,5	*2223*	2123	76,7	73,3	22,8	0
8	August	24,6	24,6	*2409*	2309	77,9	74,6	24,2	0
9	September	20	19,3	*1787*	1672	76,5	74,6	19,3	-0,068
10	October	20	12,7	*1613*	1352	69,0	92,0	17,6	0,675
11	November	20	7,5	*1390*	1015	59,5	97,9	15,3	0,623
12	December	20	3,4	*1189*	724	50,9	92,8	12,9	0,571

Applying the **continental climate approach** which estimates interior temperatures and humidities based on the daily mean of the exterior temperature according to the chart in Figure A.1 in EN ISO 13788, leads to presumably too low interior moisture loads. The assumed interior vapour pressure resulting from the estimated interior temperature T_i and relative humidity RH_i is considerably lower than the one resulting from the moisture excess model considering Mantova's exterior moisture (compare Table 7-4 to Table 7-2 and Table 7-5 to Table 7-3).

Table 7-4 Applying the model for continental climate and high occupancy B results in January being the most critical month. This model seems to underestimate the interior moisture.

	period	Ti	Te	Ppv_i	Pv_a	RHi	RHe	Ti,min	fRsi,min
1	January	20	1,5	*1204*	676	51,5	99,2	13,1	**0,626**
2	February	20	2,3	*1223*	668	52,3	92,6	13,3	0,622
3	March	20	8,4	*1365*	794	58,4	72	15,0	0,57
4	April	21,5	12,9	*1608*	1097	62,9	73,7	17,6	0,547
5	May	24,0	18,0	*2029*	1694	68	82	21,3	0,553
6	June	25	22,1	*2216*	1699	70	63,8	22,8	0,229
7	July	25	23,5	*2216*	2123	70	73,3	22,8	-0,499
8	August	25	24,6	*2216*	2309	70	74,6	22,8	-4,802
9	September	24,7	19,3	*2150*	1672	69,3	74,6	22,3	0,555
10	October	21,4	12,7	*1594*	1352	62,7	92	17,4	0,547
11	November	20	7,5	*1344*	1015	57,5	97,9	14,8	0,582
12	December	20	3,4	*1248*	724	53,4	92,8	13,6	0,616

Table 7-5 Applying the model for continental climate and normal occupancy A results in January being the most critical month. This model seems to underestimate the interior moisture.

	period	Ti	Te	Ppv_i	Pv_a	RHi	RHe	Ti,min	fRsi,min
1	January	20	1,5	*1087*	676	46,5	99,2	11,5	**0,542**
2	February	20	2,3	*1106*	668	47,3	92,6	11,8	0,536
3	March	20	8,4	*1248*	794	53,4	72	13,6	0,451
4	April	21,5	12,9	*1481*	1097	57,9	73,7	16,3	0,394
5	May	24,0	18,0	*1880*	1694	63	82	20,1	0,346
6	June	25	22,1	*2058*	1699	65	63,8	21,6	-0,193
7	July	25	23,5	*2058*	2123	65	73,3	21,6	-1,32
8	August	25	24,6	*2058*	2309	65	74,6	21,6	-7,979
9	September	24,7	19,3	*1995*	1672	64,3	74,6	21,1	0,325
10	October	21,4	12,7	*1466*	1352	57,7	92	16,1	0,396
11	November	20	7,5	*1227*	1015	52,5	97,9	13,4	0,469
12	December	20	3,4	*1131*	724	48,4	92,8	12,1	0,526

The f_{Rsi}=0. 668..0.681 of the corner situation would be too low assuming the maritime approach (recommended for Italy) for a number of months with humidity class 3 assumption, and in October even for humidity class 2.

The described limitations call, however, for an assessment based on dynamic data, actual use patterns and moisture loads which are decisive not only for the accurate prediction at the interior surface but also within the construction as Panico et al. have shown.

7.4 Technical condition of archetype envelope

The building envelopes of the examined case studies are generally in (fairly) good conditions – this is especially true, if buildings are used and therefore well maintained.

Where buildings have not been used for several years, their technical conditions tend to get worse quickly.

Roofs structures are usually still the original ones, also ancient tiles have often been preserved. Rainwater entering in storm events leaves traces on the wooden structure, but since the attics are not used and well-ventilated fast drying usually prevents major damage (see images under 7.1.2)

The solid brick masonry of the walls is in a good overall state.
The plaster finish on the exterior might show soiling and also points of humidity, particularly on the back and secondary facades. This can be due to leaky rain gutters in drains, but also to local differences of water uptake with driving rain (due to cracks but not only) and protection from driving rain. Detachment of the upper paint or even plaster layers can also be observed, it is however not too frequent. In the lower parts salt efflorescence and powdering of plaster and/or stone. Where the exterior plaster has already been replaced, it usually shows less damage, would however, from heritage point of view be easier to be replaced with a more energy efficient solution as e.g. insulating plaster.

Figure 7-7 Façade photos from HeriTACE case studies and other buildings in Mantova.

The interior finish is often characterised by multiple layers of paint and shows the temporal stratification. In most of the investigated case studies in Mantova frescos and decoration where found, in most cases covered by later layers of plaster and paint.

If the original windows are still there, they will typically show damages – unless they have been cared for well, which unfortunately is not the common case: Shrinking and swelling of wooden parts leads to deformation and loosening of connections and – together with degradation due to UV light - also to cracks in the paint via which humidity can enter. On the outside moisture derives mainly from driving rain, on the inside from condensation on single glazing. Also, windows which have already been changed in the last decades might be in need of intervention, at least the sealing is in most cases to be repaired. If the double glassed windows are "first generation" considerable potential for an improvement in energy performance is there. If they do in their character are not consistent with the building, the occasion might be taken to replace them with energy-efficient windows which do better fot the character of the building. Otherwise replacing only, the glazing can avoid unnecessary waste and keep trace of the renovation history.

The wooden shutters will usually have suffered from shrinking and swelling with changing temperatures and humidity: connections might have loosened, slats fallen out (see photo 7.1.4.4), and the paint will be flaking off. This can however be well repaired and also kept to a minimum with regular care. If the shutters have already been changed to PVC shutters, damages as discolouring due to UV and material degradation like getting brittle are more difficult to counteract and prevent.

Floors are usually in a good state of conservation, as the investigation at the HeriTACE case studies showed. It could be necessary to verify the stability at the point of interlocking in the walls. In some buildings/rooms the false ceiling made of reed and plaster has been removed, at the building site of *Montanara* the architect has opened it in several places, which allowed to sow the good condition of the construction.

Both the ceilings and the interiors walls show frequently decorations and frescoes. They are in most cases appreciated by the owners and users as beautiful witnesses to the story of the building. Not in all cases does it make sense to exhibit them, they might also stay protected by the following layers. In both cases interventions will have to be chosen in a way not to interfere with them, which does not only mean, that these decorations are "materially" kept, but also that e.g. interior insulation in a room with stucco decoration all around the ceiling might not be an option.

Figure 7-8: Examples of interior decoration at HeriTACE demo cases.

7.5 Archetype envelope characteristics

Based on the observations and measurements made in the case-study buildings and taking into account literature, expertise and experience of Eurac Research, Politecnico die Milano and ZH on the characteristics and renovation of heritage buildings, for each Italian archetype as described in 'D5.1 Case-study selection at building and neighbourhood levels', a pre-renovation and renovation baseline for the building envelope is derived. The pre-renovation baseline is the condition in which these types of buildings were before the introduction of EPBD regulations (situation in '90-'00). The renovation baseline is the condition of these type of buildings as if they would be renovated today with a "business as usual" approach. In this report, only the baseline scenarios regarding the building envelope are described. The complete, but also more synthetic description of baseline scenarios (including heritage value, space conditioning, energy systems and use scenarios) are described in 'D5.4 Baseline scenarios'.

7.5.1 Pre-renovations baseline

There are three main different building envelope scenarios for the pre-renovation baseline:

- BS1_PB refers to the situation with very little intervention.
- BS2_PB refers to the situation with windows (all or part of them) having been replaced
- BS3_PB refers to a situation with interventions also in the roof and potentially the basement floor

While in D5.4 the focus is on the energy performance related characteristics, and one common scheme can cover all archetypes (similar to the situation in Belgium), the schemes in this report differentiate between (i) Gothic Lot and Palazzetto, (ii) Extended Building and (iii) Courtyard Building: They include also information on originality and conservation status of materials which do not influence the energy performance (e.g. roof tiles, plaster, etc.), but are important for the selection of interventions. And they point out the peculiarities of the archetypes in terms of interior decorations, intermediate floor, courtyard elements.

While the description in D5.4. is "by scenario", here some more details "by envelope component" are described, where relevant also pointing at differences among the typologies.

7.5.1.1 Walls

All Pre-Renovation baseline scenarios do have in common is that the walls of the front and back facades are solid masonry walls made of raw bricks with interior lime plaster and exterior lime plaster (7.1.1.1) perhaps with the exterior plaster having been replaced (0) and burnt bricks only used for repair, changes or annexes (7.1.1.3).

In two case study buildings the actual thermal performance of the wall has been measured (according to the method described in 2.3.1). In *Vescovile* a wall on the ground floor towards the courtyard building has been chosen. The measured U-value results in U=0.85 W/m²K. Considering a thickness of 70 cm of the wall, this corresponds to an average thermal conductivity λ=0.7 W/mK, which is in correspondence with the value of 0.72 W/mK given in UNI/TR 11552:2014 for MLP01 Muratura in mattoni pieni. The measurement at *Leonardo* lead to a value of U=0.81 W/m²K, which for a thickness of 44 cm corresponds to a much lower average thermal conductivity λ=0.42 W/mK. Research in different material databases, as e.g. the one in www.ubakus.de would give a λ=0.47 W/mK for a density ρ=1200 kg/m³. It seems just reasonable that there is a considerable variety for thermal conductivity. In 7.1.1, both these values have been reported, the proposed U-values of 0.8 to 0.9 W/m²K for the front wall correspond finally to both measured value and take into account that thicker walls of larger buildings might have been built with higher density bricks. The U-value of 1.0 to 1.2 for the backyard wall has been determined based on the lower λ=0.47 W/mK applied to the usually thinner backyard walls (32-36cm instead of 40-44cm).

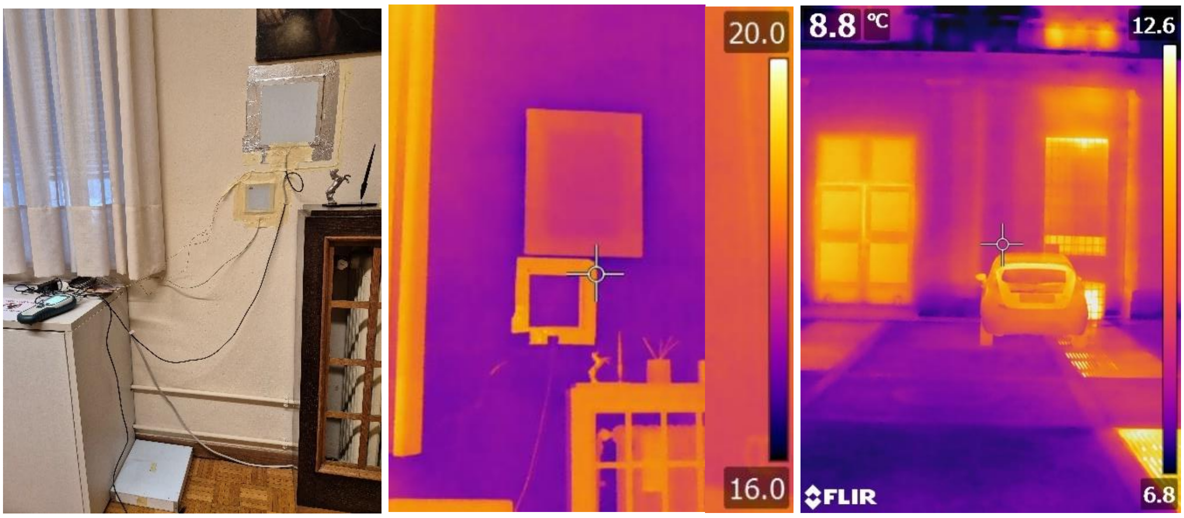


Figure 7-9: U-value measurement at Vescovile. Installation and IR image inside and outside.

Figure 7-10: More IR image of the Courtyard façade at *Vescovile*.

Option two for the masonry wall differs just in the assumption that the exterior plaster has been changed to a cement-based plaster. This would not influence the thermal performance but rather the hygrothermal situation, since the cement plaster has higher vapour resistance. This does result in a situation where condensation can occur at the interface from masonry wall to lime cement plaster, as Figure 7-11 shows. The calculation confirms however that there is sufficient drying reserve (DIN 68800-2), or rather the drying time according to DIN 4108-3 is with 14 days clearly below the limit of 90 days.

The higher vapour resistance might still lead to the shift of the drying horizon for rising damp and thus the shift of potential damage to other, higher areas.

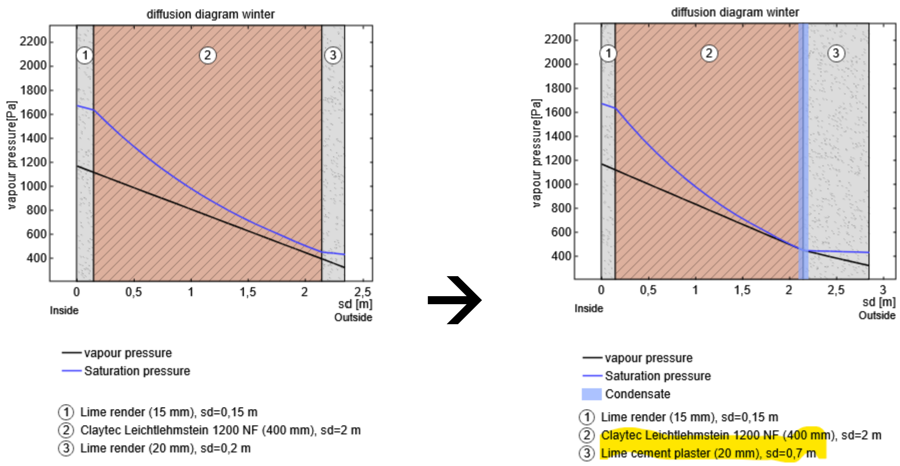


Figure 7-11: Diagram showing the vapour pressure gradient in a masonry wall with lime plaster (left) and lime cement plaster (right) over the cumulative sd-value on the x-axis.

For all typologies the pre-renovation baseline 1 (BS1_PB) refers to a solid masonry wall with original lime plaster. In the Gothic Lot and Palazzetto the plaster at the back faced would typically be in a condition to be restored, while for the Courtyard building decorations are pointed out.

Pre-renovation baseline 2 (BS2_PB) differentiates for the Gothic Lot and Palazzetto typologies between the situation where the plaster is in condition to be restored (BS2.1_PB) and where is has already been replaced with a new plaster (BS2.1_PB) – both for front and back facade. For the Courtyard Building the front façade would be in need to be restored, while the back façade has already been renovated.

Pre-renovation baseline 3 (BS3_BP) considers all facades having a new plaster (or cladding).

7.5.1.2 Top boundary

The attic is in most cases unused, which makes the uppermost floor the thermal envelope – it is composed of wooden floorboard resting on a framework of joists and main beams and the ceiling side is made of reed and plaster (7.1.2.3).

For the Gothic Lot, the Palazzetto and the Extended Building typologies, decorations of the floorboard are mentioned in both pre-renovation baseline 1 and 2 (BS1_PB and BS1_PB), while pre-renovation baseline 3 (BS3_PB) assumes the attic floor – as the floors on other storeys – to have been reinforced. In Courtyard Buildings the floors (attic and other) have already been reinforced in pre-renovation baseline 2.

The roof itself typically has a double-pitched roof with wooden planking, joists and wooden beams with a circular section (7.1.2.1). The tiles are in most cases the ancient ones. Where the attic space has however been transformed into living space, or where a more high-quality storage space was sought, the roof has been insulated (7.1.2.2).

For Gothic Lot and Palazzetto the roof is typically still in its original state in pre-renovation baseline scenarios 1 and 2 (BS1_PB and BS1_PB), while pre-renovation baseline 3 (BS3_PB) considers a small addition of insulation and the external cladding or tile to have been renovated. For the Extended and the Courtyard Buildings typologies three scenarios are considered: pre-baseline scenario 1 (BS1_PB) with the still original roof structure and ancient tiles, pre-baseline scenario 2 (BS2_PB) with a restored roof structure and new tiles and pre-baseline scenario 3 (BS3_PB) with a new roof structure including also insulation on the inside.

7.5.1.3 Floors

At the bottom, the thermal envelope is formed by the basement ceiling. This typically consists of cement tiles or gres laid on wooden floorboards, which rest on joists supported by a masonry slab or by vaults (7.1.3.3).

In all typologies pre-renovation baseline scenario 1 and 2 (BS1_PB and BS1_PB) consider no changes have been made to the original structure, while pre-renovation baseline 3 (BS3_PB) would consider wooden parts to be reinforced or a new slab with insulation being installed (if not on cellar). The "no cellar" scenario is actually only considered for typologies Gothic Lot, Palazzetto and Extended Building with tiles on sandbed in scenarios 1 and 2. For the Courtyard Building the potential presence of vaults for the masonry slab is underlined.

7.5.1.4 Windows

Original windows are single windows with wooden frame and single glazing (7.1.4.1). In BS1_PB, all the windows are assumed to be the original single-glazed ones. However, they have often already been replaced (7.1.4.3), which is considered in BS2.1_PB (part changed) and BS2.2_PB as well as BS3_PB (all changed).

As a special case for the Courtyard Building a scenario BS1.2_PB has been introduced here for situations where the original windows have been replaced by replica with double glazing (7.1.4.2). For the Extended and Courtyard building no differentiation between a scenario 2.1 and 2.2 is made – BS2_PB in these typologies considers part of the windows having been replaced.

7.5.1.5 Airtightness

As explained in section 7.2, based on both the literature and measurements from the two case studies, the following n_{50} values are assumed for the pre-renovation baselines: 7.5 1/h for buildings where all windows are still original (BS1_PB), 6 1/h for buildings where some windows have been replaced (BS2.1_PB) and 4.5 1/h for buildings where all windows have been replaced (BS2.2_BP and BS3_PB).

7.5.1.6 Shutters

All typologies do have wooden shutters. The improvement of the U-value with closed shutters Uws can be estimated as $U_{ws}=1/(1/U_w+\Delta R)$. The final value and the relative improvement depend thus on the U_w value of the window: for a single glazed window the improvement is high, for a modern window with insulation glazing the difference is not that big anymore. **ΔR** of a typical Italian shutter would range between **0.08 m²K/W** with slats in "open" position" and **0.24 m²K/W** with closed slats. For a single glazed window with **U_w=4.8 W/m²K** this results in a final **U_{ws}=2.25 ... 3.5 W/m²K**, and thus a reduction of losses from **30 ... 50%.** For an (old) double glazed window with **U_w=1.6 W/m²K** the shutter reduces the U-value to **U_{ws}=1.2 ...1.4 W/m²K**, and thus by **10 ... 25%**

A major benefit of shutters is however their contribution to **shading and reducing thermal loads** – while still allowing for a minimum light to enter. The **Fc-value** of typical Italian shutters ranges from **0.15** (closed fins to **0.25** (open fins, i.e. 45°).

Whether shutters are original or new goes with the window scenarios were windows have been replaced (also with replica) the shutter can be considered to be new, too.

7.5.1.7 Interiors

The Courtyard building typology will show important stuccos, tapestries and frescoes on the interiors, which still are original and in place in pre-renovation baseline 1 (BS1_PB), stuccos and frescoes can be found in this scenario also in the other typologies.

Pre-renovation baseline 2 considers part of the decorations being still in place, and part of the interiors having been renovated. Pre-renovation baseline 3 (and for the typologies Gothic Lot and Palazzetto) actually already pre-renovation baseline 2.2) consider all interiors renovated.Furthermore, the pre-renovation baseline for the Gothic Lot and Palazzetto describes the wind towers: the staircase is typically extended to form a wind tower, and element which connects envelope considerations with ventilation – and is thus considered in work package 3.

For the Courtyard building the portico is included as characterising element in the pre-renovation baseline – in scenarios 2 and 3 considered to have been renovated.

<table>
<tr><th colspan="6">**Pre-renovation:** Building envelope scenario</th></tr>
<tr><th colspan="2">Scenario/ Gothic Lot and Palazzetto</th><th>BS1_PB</th><th>BS2.1_PB</th><th>BS2.2_PB</th><th>BS3_PB</th></tr>
<tr><td rowspan="2">Walls</td><td>Front facade</td><td>A relatively narrow and well preserved wall masonry in raw brick with interior lime plaster and exterior lime plaster (more than 40 cm)</td><td>Solid masonry wall in raw brick (more than 40 cm) to be restored</td><td colspan="2">Solid masonry wall (more than 40 cm) with new plaster</td></tr>
<tr><td>Back facade</td><td>Solid masonry walls made of raw bricks with interior lime plaster and exterior lime plaster (more than 40 cm) to be restored</td><td>Solid masonry wall in raw brick (more than 40 cm) to be restored</td><td colspan="2">Solid masonry wall (more than 40 cm) with new plaster</td></tr>
<tr><td>Top boundary</td><td>Pitched roof</td><td colspan="3">Original wooden double-pitched roof with wooden planking, joists and wooden beams with a circular section. The ridge of the two pitches rests on the central spine wall of the building. External cladding in antique tiles.</td><td>Small addition of insulation. External cladding in recovered/renovated tiles.</td></tr>
<tr><td rowspan="2">Floors</td><td>Basement floor</td><td colspan="3">tiles on sand bed (if not on a cellar)</td><td>Tiles on a insulated new slab (if not on a cellar)</td></tr>
<tr><td>Wooden floor</td><td colspan="3">25 cm decorated wooden floorboard resting on a framework of joists and main beams. cladding in terracotta tiles</td><td>35 cm reinforced mix wooden floorboard. cladding in new terracotta tiles</td></tr>
<tr><td rowspan="2">Windows</td><td>Front windows</td><td colspan="2">Original wooden frame Single glazing</td><td colspan="2">Standard double-glazed windows</td></tr>
<tr><td>Back windows</td><td>Original wooden frame Single glazing</td><td colspan="3">Standard double-glazed windows</td></tr>
<tr><td colspan="2">Interiors</td><td>interiors are decorated with stuccos and frescoes</td><td>interiors are partially decorated and partially have been renovated</td><td colspan="2">interiors have been renovated.</td></tr>
<tr><td colspan="2">Wind tower</td><td colspan="4">The staircase is extended to a from a wind tower</td></tr>
<tr><td colspan="2">Shading</td><td>Original interior / exterior wooden shutter</td><td colspan="2">Original interior / exterior wooden shutter on main façade + new shutters in the back facade</td><td>New shutters</td></tr>
<tr><td colspan="2">Airtightness</td><td>n50=7,5</td><td>n50=6</td><td colspan="2">n50=4,5</td></tr>
</table>

Figure 7-12: Pre-Renovation Baseline for the Italian Archetypes “Gothic Lot” and “Palazzetto”.

Pre-renovation: Building envelope scenario

Scenario/ Courtyard building		BS1.1_PB	BS1.2_PB	BS2_PB	BS3_PB
Walls	Exterior facades	Well preserved brick masonry (more than 40 cm) with exterior cladding and internal plaster and decorations		brick masonry (more than 40 cm) with exterior cladding to be renovated/ preserved	brick masonry (more than 40 cm) with new plaster/cladding
	Courtyard facades	Well preserved brick masonry (more than 40 cm) with exterior and internal plaster and decorations		brick masonry (more than 40 cm) with renovated exterior plaster	brick masonry (more than 40 cm) with new plaster
Top boundary	Pitched roof	Original wooden roof with wooden planking, joists and wooden beams with a circular section. External cladding in antique tiles.		Restored wooden double-pitched roof. External cladding in new tiles.	New roof structure with interior insulation. External cladding in new tiles.
Floors	Basement floor	masonry ground floor slab (sometimes on vaults)			masonry new ground floor slab (sometimes on vaults)
	Floor ceiling	decorated wooden floorboard resting on a framework of joists and main beams (also with ceiling vaults). cladding in terracotta tiles/stone		decorated reinforced wooden floorboard resting on a framework of joists and main beams (also with ceiling vaults). cladding in terracotta tiles/stone	
Windows	Exterior windows	Original wooden frame Single glazing		Original wooden frame Single glazing + some standard double-glazed windows	Standard double-glazed windows
	Courtyard windows	Original wooden frame Single glazing	Replica of original wooden frame double glazed windows	Standard double-glazed windows	
Interiors		interiors are decorated with important stuccos, tapestries and frescoes		interiors are (all/partially) decorated and/or have been (all/partially) renovated	interiors have been partially renovated
Courtyard elements		Original portico in the courtyard		Renovated portico in the courtyard	
Shading		Original interior / exterior wooden shutter	Original exterior façade wooden shutter + new shutters on the courtyard		New shutters
Airtightness		n_{50}=7.5	n_{50}=6		n_{50}=4.5

Figure 7-13: Pre-Renovation Baseline for the Italian Archetype "Courtyard Building".

Pre-renovation: Building envelope scenario

Scenario/ Extended building		BS1_PB	BS2_PB	BS3_PB
Walls	Exterior facades	Solid masonry walls made of bricks with interior lime plaster and exterior lime plaster		Solid masonry walls made of bricks with a new plaster
Top boundary	Pitched roof	Original wooden double-pitched roof with wooden planking, joists and wooden beams with a circular section. External cladding in antique tiles.	Restored wooden double-pitched roof with wooden planking, joists and wooden beams with a circular section. External cladding in new tiles.	New roof structure with interior insulation. External cladding in new tiles.
Floors	Basement floor	tiles on sand bed (if not on a cellar)		tiles on an insulated new slab (if not on a cellar)
	Wooden Floors	25 cm decorated wooden floorboard resting on a framework of joists and main beams. cladding in terracotta tiles		35 cm reinforced mix wooden floorboard. cladding in new terracotta tiles
Windows	Front windows	Original wooden frame Single glazing	Original wooden frame Single glazing + some standard double-glazed windows	Standard double-glazed windows
Interiors		interiors are decorated with stuccos and frescoes	interiors are partially decorated and partially have been renovated	interiors have been renovated
Shading		Original interior / exterior wooden shutter	Original interior / exterior wooden shutter on main façade + some new shutters	New shutters
Airtightness		n50=7.5	n50=6	n50=4.5

Figure 7-14: Pre-Renovation Baseline for the Italian Archetype "Extended Building".

7.5.2 Renovation baseline

The renovation scenarios for the envelope retrofit which take up the "Business as Usual" scenario from D2.2 differ mainly in how the walls are insulated (scenarios 1, 2 and 3). Here an additional Scenario 0 is introduced with no changes on the windows and a scenario where the attic is transformed from an unused to a used space (scenario option b, applicable to 0 to 3).

One scheme with the twice four scenarios (0 to 3, with variant b) has been developed for all archetypes, as at this stage the differentiation would not bring an added value – not like the pre-renovation baseline where the peculiarities of the archetypes will inform the later HeriTACE solution development. The combination of these baseline envelope renovation scenarios with scenarios for intervention on the HVAC system and energy sources are described in D5.4.

Common elements are

- Insulation of the **ground floor** - insulation materials are placed against the ceiling of the basement or on the floor side, if there is now cellar or vaults do not allow insulation from below from the ceiling of the below cellar.
- Insulation of the **unused attic** with an insulation layer laid **on the attic floor** which keeps the roof itself untouched. The chimney/ventilation tower has to be considered separately
  [Scenario b considers a **change in use of the attic to living space** – and respective insulation of the roof between and/or below the rafters]
- Replacement of the **windows**, be they original or already changed some decades ago, with wooden double-glazed windows.
  [BS0_RB considers the front windows not being changed, only windows of the back facade (for Gothic lot and Palazzetto), courtyard facade (for Courtyard)
- This change together with the at least partial work on the plastering and the insolation basement and uppermost ceiling will lead to **increased airtightness**.
- The **shutters** and existing **shading system** are sometimes repaired, more often replaced – but from an energy performance point of view this is less important than the fact that they are not disused.

Where the scenarios differ is mainly whether and how the walls are treated:

On annexes in the back and sometimes also on the back façade itself **exterior insulation** might be allowed from conservation point of view, which is considered in BS2_RB. In such cases the **minimum insulation level** (U=0.34W/m²K) can be reached with approximately 7 to 8 cm of an insulation material with thermal conductivity λ of 0.04 W/(m·K). For most of the financial incentive programmes a U-value of U=0.23W/m²K has to be reached, which results in 12 to 15 cm of insulation. **Listed buildings can be exempted from reaching the minimum values.**

On the front façade an intervention from outside will in most of the cases be avoided, and also on back facades this is often the case. In this case, for the renovation baseline, **interior insulation** is chosen, which is the case for BS3_RB. **Minimum insulation levels** (U=0.42W/m²K, for interior insulation it is 30% higher) can be reached with 5 cm of an insulation material with λ=0.04 W/(m·K) or ~7cm of an insulation material with λ=0.06 W/(m·K) as e.g. insulating plaster.
With interior insulation the thermal inertia of the respective wall is not available any more for mitigating overheating in summer. However, historic buildings do also have considerable mass in partition walls and ceilings. Whether these are enough will be investigated in the simulation studies.

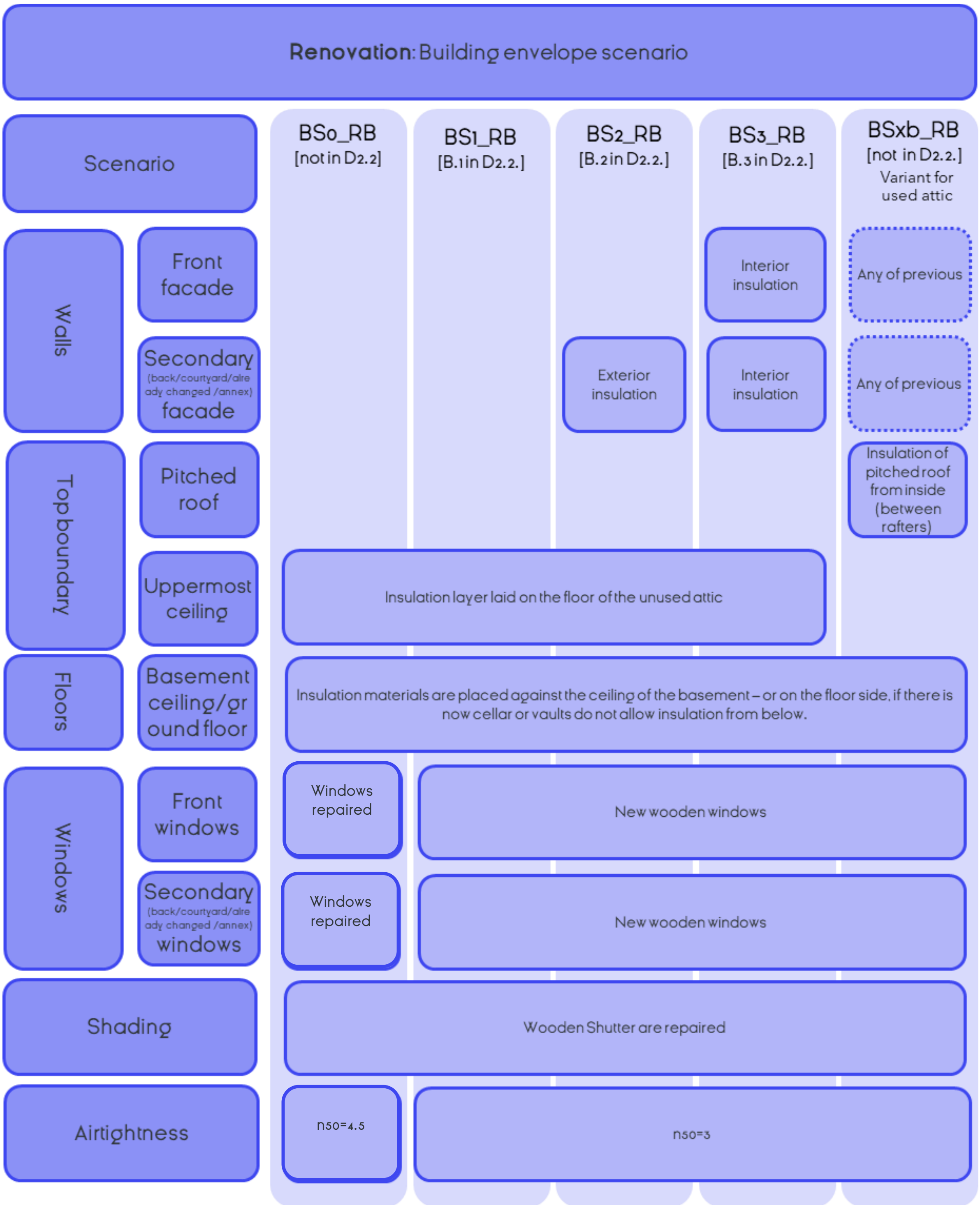


Figure 7-15: Renovation Baseline (Business as Usual) for the Italian Archetypes.

8. Conclusion

The contents of this deliverable form the basis for development of retrofit scenarios and modelling of the targeted building archetypes (D5.1) in Belgium, Norway, Estonia and Italy. The measurement of thermal transmittance, airtightness, thermography, and assessment of envelope condition augmented by numerical and literature analysis contribute to good background to build on.

8.1 Country specific conclusions

8.1.1 Belgium

- A total of 15 cases was selected for the case study analysis (across different WP)
  - In 13 cases, valid air tightness measurements were carried out
  - In 7 cases, thermal transmittance measurements were carried out, mainly on facades (or party walls)
  - In 11 cases, a detailed analysis of the building envelope was made
- The different archetypes were all constructed in the same way, with the same materials. No notable difference regarding airtightness, thermal transmittance, condition, damage, … was noted.
- All cases were generally found to be in good condition.
  - The walls were typically well preserved, and structurally they were in excellent condition. Where damage was observed, it was most often limited to the finishing layer, which tended to show signs of cracking, particularly on the rear façade.
  - Roofs were usually in good condition, provided they remained watertight. However, the roof supporting structures occasionally appeared to be under-dimensioned.
  - The majority of deterioration was observed in the wooden windows, where instances of wood rot were not uncommon.
- Typical for the Belgian archetypes are the the solid masonry façade walls, party walls and internal (bearing and non-bearing) walls.
  - Front facades are characterized by their very high heritage value. Consequently, they were never energetic retrofitted, but often restored and well maintained. The measured and calculated thermal transmittance range between 0.86 and 1.38 W/m²K, which are quite low due to the large thickness of these walls. The thermal transmittance is also a lot lower than that of a party wall in these archetypes (U = 2.07… 2.47 W/m²K) or than the thermal transmittance of an insulated cavity wall, that is standard practice in houses of the late 20th century.
  - Back facades have limited heritage value and are sometimes retrofitted with external insulation. Party walls and the walls of the annex are typically thinner than the façade walls.
  - A range of pitched roofs have been encountered in the cases. From uninsulated roof structures to fully insulated and finished roofs. A lot of attic spaces are converted into bedrooms, apartments or office spaces. When the attic has become a livable space, the roof is often renovated, insulated and properly finished, so that it can be a decent space.

- The window types observed across the cases exhibit significant variation. As original single glazing contributes to substantial heat loss and increases the risk of condensation, and the timber frames are frequently affected by wood rot, many original windows have been replaced. Windows in the rear façade are typically substituted with modern units that comply with the applicable standards at the time of replacement. In contrast, greater care is generally taken with those in the front façade due to its heritage value. In these instances, replacement windows are often modelled according to the original design, or the existing frames are retained and fitted with improved (thin) glazing (although this does not achieve the same thermal performance as entirely new windows). In some cases, the original windows are preserved and well maintained.
- The front façade typically represents between 10 and 16% of the heat loss area, while other elements make up a larger part of the envelope, with the pitched roof (up to 25%), the floor boundary (up to 25%) and the windows (up to 21%) as the largest parts. Investing a lot of energy in retrofitting the front façade, which is often highly valuable and difficult to insulate, seems like a less interesting option.
- A lot of construction details and connections seem to induce a risk for mould growth or surface condensation, although it is rarely encountered. The low moisture load in these buildings (as described in D3.2) in combination with a leaky envelope and window opening behaviour can be the reason why it is prevented so far. Making the envelope more airtight during retrofit or introducing a higher moisture load (by intensifying the use of the building), can hold risk to mould growth, certainly when interior insulation is added.

- Airtightness measurements show a broad variety in the airtightness of the Belgian heritage townhouses. The q_{E50} value ranges from 4.81 m³/h·m² to 13.3 m³/h·m².
  - Heritage townhouses do not perform per se worse than non-heritage buildings. They do perform worse than the Flemish average for new buildings.
  - In instances where the roof had been recently insulated and fitted with a vapour barrier, airtightness was significantly improved compared to unrenovated buildings. However, this is not a guarantee for a good airtightness.

8.1.2 Norway

- In Norway, the primary focus of measurement efforts was on indoor air quality (as detailed in D3.2) and laboratory investigations into interior insulation solutions for plank walls (task T2.4 of the HeriTACE project). The envelope characteristics presented here summarize findings from previous studies.
- A defining feature of the building envelope of the Norwegian archetype, constructed with load-bearing timber logs or vertical planks, is that the exterior holds significant heritage value for townhouses intended for habitation. In many cases, replacement of old exterior elements is not feasible, especially if the wood remains in good condition. However, if there is considerable deterioration (e.g rot), modifications to exterior elements may be allowed. Wood townhouse building envelope parts are generally in decent conditions since they have been inhabited in modern times and maintenance have been done.

- The typical thermaconditions of the Norwegian archetype indicate a U-value for the floor andhasling structures ranging from 0.95 to 1.0 W/(m²·K) while wall structures exhibit a U-value of 0.8 W/(m²·K). The thermal performance of windows varies from 1.5 W/(m²·K) for coupled windows (featuring two separate sashes/glazing layers) to 1.0 W/(m²·K) for an outer single pane paired with an inner double-glazed insulating unit. The airtightness is expected to be low, previous measurements suggest n_{50} around 5-10 1/h.
- Interventions, particularly involving interior insulation, can elevate the risk of moisture problems (such as mould and rot), especially as climate change leads to increased temperatures and humidity in the coming years.

8.1.3 Estonia

- The wooden apartment buildings are characterized by low airtightness. The measured q_{E50} levels are similar to previous studies ca 15 years ago, which suggests that interior insulation (that has now been more widely installed) has not improved it.
- While the main wall structure was inherently different between Estonian archetypes (wood vs brick), the rest of the components shared a lot more technical commonality with similar structures for top and bottom boundaries, intermediate floors and original and currently installed window types.
- Masonry walls have low thermal performance. Need thermal upgrade due to moisture risks (especially if indoor air moisture load is high, as measured in case study buildings), heat losses and thermal discomfort – especially as they form ca 40-50% of the envelope area.
- Facades and plinths of ca 40-50% of the buildings in the neighbourhood are in a need of repairs within 5 years or sooner – this could be combined with energy renovation measures for a win-win situation.
- The damage to the facades is often due to infrequent or -adequate maintenance. Unmaintained rainwater systems have the highest impact on the rest of the building.
- The plinths of both wooden and Stalinist brick apartment buildings are made of limestone masonry with very high thermal transmittance (U ≈ 2.0–2.3 W/(m²·K)) and moisture issues (capillary rise, splashes from the street). Possible basement conversions to living spaces require further interventions to ameliorate said issues.

8.1.4 Italy

- The buildings are in a fairly good state. Driver for renovation will often be a change in owner or in use. Since in these cases interventions on the façade(s) and windows are very common, HeriTACE might provide solutions which are more compatible with the heritage values than business as usual interventions in the renovation baseline as described here.
- Masonry walls do have a U-value of ~0.8-0.9 W/m²K (1.0-1.2 W/m²K the backyard facades or higher floors), the uppermost ceiling depending on whether they have a false ceiling with reed ad plaster or exposed wooden structure 1.3-1.4 W/m²K respectively 2.3 W/m²K, ground floor slabs 0.8-0.9 W/m²K. Where the attic space has already been changed to living space also the pitched roof has been insulated to a U-value of around 0.5 to 0.6 W/m²K or better in recent renovations. Where single windows are still in place, they have a U-value of ~4.8 W/m²K. Where they have

already been replaced with double glazed windows, it depends on when this happened: before 1990 U_w=2.6 W/m²K can be estimated, afterwards 1.5 to 1.8 W/m²K. The airtightness depends to a considerable extent on whether windows have been replaced: between n_{50}=4.5 and 7.5 1/h for pre-renovation, and n_{50}=3 to 4.5 1/h for the renovation baseline.

- There is potential for improving the energy performance of the single components and of the overall building envelope. The quantitative energy analysis of the pre-renovation and renovation baselines should look also at losses through the single components (windows, roof, floor, front façade, back façade, …) in order to inform the development of HeriTACE renovation scenarios.
- Moisture aspects should be investigated with dynamic simulations as both approaches to assess f_{Rsi} versus $f_{Rsi,min}$ via EN 13788 showed limitations.

8.2 Overall conclusions

There is distinction between front and back facades of the buildings in Belgium, Italy and Norway – front façades typically have high heritage value and past and future retrofit efforts target the back façade, where more effective measures could be applied. Other less visible areas such as attic floors and basement ceilings have often already undergone such modifications.

The results highlight that isolated interventions are often not enough to overcome inherent shortcomings the historic building envelopes have (e.g. low airtightness of wooden walls, moisture and thermal issues with masonry walls).

Thermography and thermal modelling indicated hygric risks based on low temperature factors (f_{Rsi}) on existing Belgian, Estonian and Italian envelope details – this could be followed up using more detailed hygrothermal modelling which also takes hygrothermal buffering and actual climate conditions into account.

The need for retrofit solutions for masonry and timber walls in the Nordic regions is evident (both according to measurements, modelling and interviews with the inhabitants) and is something that tasks T2.3 and T2.4 have set out to develop. These measures could be essential for achieving the 60% energy reduction target that is set as an objective of the project.

The studied archetypes are rather leaky – especially the ones with wooden walls. So much so that the low airtightness has been the basis ventilation. However, good airtightness is required for heat recovery of modern air handling systems to be effective. At the same time, ventilation is required for mitigating hygric risks in envelope components if airtightness is improved. This is an example of how intertwined different building components are and how the retrofit scenarios need to be holistically designed and materialized.

Due to high occupancy, the indoor air humidity loads in Estonia are high enough to be risky for both wooden walls with interior insulation and masonry walls without insulation. While loads elsewhere were currently not as high, it might serve as a cautionary tale if townhouses are converted for multi-family use.

The baseline scenarios were compiled to describe the building components of Belgian, Norwegian, Estonian and Italian archetypes for building energy modelling. While done separately for each country, this resulted in surprisingly similar envelope component characteristics between the countries – dispite being in different climatic zones. Pre EPBD scenarios (1990s–2000s) generally described the envelopes in their thermally unaltered state (beside occasional window upgrade). Masonry walls had thermal transmittance U ≈ 1–2 W/(m²·K), wooden walls 0.5–1.2 W/(m²·K) and top and bottom boundaries 0.5–1 W/(m²·K). Windows were either single (U_w ≈ 6 W/(m²·K)) or double glazed (U_w ≈ 3 W/(m²·K)). In renovation scenarios (i.e. if retrofit was done today) the thermal transmittances of insulated walls, top and bottom boundaries were in the range of 0.2–0.4 W/(m²·K) and those of windows in the range of 0.85–1.5 W/(m²·K). Of course, the share of envelope where these measures can be applied is bound by specific local conditions.

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D2.2 Energy conservation measures inventory. https://zenodo.org/records/15364987

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D4.1 R²ES-based energy supply concepts for heritage buildings in historical neighbourhoods. https://zenodo.org/records/15656204

D5.1 Case-study selection at building and neighbourhood levels. https://zenodo.org/records/15365504

D5.2 Cultural heritage analysis and value assessment. https://zenodo.org/records/15656263

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