

Opaque Building Envelope

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Abstract The refurbishment of building opaque envelope represents an important approach for the reduction in global European energy consumption as prescribed by the Directive 2010/31/EU. Therefore, the knowledge of existing housing stock and their hygrothermal behaviour is necessary to define effective energy conservation measures. In this chapter, starting from the definition of the main thermal and hygrometrical parameters, a systematic analysis of the most common wall typologies in European construction is carried out for the definition of a structure catalogue. Moreover, for a set of envelope insulation interventions, the hygrothermal behaviour is evaluated and some diagrams for the assessment of the optimal intervention are defined. Finally, the incidence in terms of energy performance is tested considering a case study.

Nomenclature

A_f	Internal floor area of the conditioned space (m^2)
EP_{gl}	Global energy performance index ($EP_H + EP_w$) [$kWh/(m^2 \text{ year})$]
$EP_{H,env}$	Energy performance index in the heating season for building envelope [$kWh/(m^2 \text{ year})$]
EP_H	Energy performance index in the heating season [$kWh/(m^2 \text{ year})$]
f_a	Decrement factor (-)
L	Thickness (cm)
M_s	Specific mass (kg/m^2)
$Q_{H,gn}$	Total heat gains for the heating mode (MJ)
$Q_{H,ht}$	Total heat transfer for the heating mode (MJ)
$Q_{H,nd}$	Building energy need for continuous heating (MJ)
Q_{int}	Sum of internal heat gains (MJ)
$Q_{l,e}$	Emission subsystem thermal losses (MJ)
Q_{sol}	Sum of solar heat gains over the given period (MJ)

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Q_{tr}	Total heat transfer by transmission (MJ)
Q_{ve}	Total heat transfer by ventilation (MJ)
R	Thermal resistance (m^2K/W)
S	Time shift (h)
U	Thermal transmittance [$W/(m^2 K)$]
Y_{ie}	Dynamic thermal transmittance [$W/(m^2K)$]
ϕ_{int}	Heat gains from internal heat sources (W)
η_e	Emission subsystem efficiency (-)
$\eta_{H,gn}$	Gain utilization factor (-)
$\eta_{y\lambda}$	Heating system global efficiency (-)
ρ	Density (kg/m^3)
c	Heat capacity [$J/(kg K)$]
λ	Thermal conductivity [$W/(m K)$]
κ_i	Areal heat capacity [$kJ/(m^2 K)$]

1 Introduction

The energy-saving target, in the refurbishment of existing buildings, requires considerable efforts on the choice of appropriate solutions that must be energy-efficient and feasible from a technical and economical point of view. Actions on the building envelope are not always possible, and in any case, they must be evaluated with care: higher thermal insulation can be achieved, for example, causing worse hygrometrical behaviour of the walls. Moreover, under certain conditions, it may be convenient to consider jointly the choices for a good thermal insulation and for a good sound insulation.

The improvement of the energy performance of existing buildings is one of the primary goals of the most recent European Directives, starting from 2002/91/EC.

In the case of renovation or maintenance of building walls, the minimum requirements imposed at national level usually indicate precise limits for the values of walls thermal transmittance. In addition, the problem of indoor overheating in summer is considered in some countries by imposing limits related to the thermal inertia parameters (periodic thermal transmittance, decrement factor, etc.).

Moreover, in addition to the correct evaluation of the thermal and hygrometric parameters of existing structures, the definition of organic strategies to improve the energy performance of the building envelope may be useful.

The need to follow the regulatory minimum requirements must be blended with the technical feasibility and the most appropriate choice of insulating materials.

The classification and analysis of existing walls is a starting point for the study and the choice of appropriate energy-saving actions, taking into account also the issues related to heat storage and hygrometrical aspects.

In the following, a brief overview on typical building walls around Europe is considered. The calculation method of the energy performance of buildings is resumed, and the significant parameters of the opaque envelope are highlighted. Some definitions and fundamental concepts, on which the calculations to be carried out are based, are briefly summarized. The application of the calculation methods is supported by examples. Some considerations on the choice of insulating materials are proposed, considering both the thermal and hygrometrical behaviours of walls.

2 Residential Building Structures of the Twentieth Century: Database of Walls and Buildings

The analysis of the existing building stock represents the first step to define general actions for improving the quality of constructions. In particular, it is useful to catalogue the main building typologies and their structural features according to the construction period and the geographical area, as reported in Table 1 (COST C16, 2007).

As it is shown in Table 1, it is apparent that in the central-northern part of Europe, the concrete and the precast panels are the main technologies, while in the Mediterranean area the envelope is often made of hollow and massive bricks.

Furthermore, in the past recent years, the aim of some research programmes is the definition of a database of existing construction typologies, which represents a strategic operation aimed to begin a structured energy refurbishment programme for low-performance buildings.

Wider information on the existing structures are useful for calculations of standard interventions, which allow to reach established efficiency levels in a systematic way; therefore, their collection may represent a first step for planning.

Some European projects were devoted to a better knowledge of existing building energy performance and refurbishment. An organized analysis of the existing building stocks (INVESTIMMO 2001–2004) provides for useful information related to the most common deterioration problems of the envelope structures and the general state of conservation of European constructions. The analysis was developed on 300 buildings in six Europe countries (Italy, Denmark, Switzerland, Germany, Greece and France) and it highlights that quite half of the buildings considered had façade thermal insulation damaged. If the results can be projected on a larger scale, the energy saving from the façade's restoration could be significant globally.

Moreover, a more recent database of construction typologies, energy-related properties of structure and energy performance assessment (TABULA, 2009–2012) allows defining effective energy conservation measures.

In particular, it aimed to assess how a set of parameters (i.e. construction year, building size) influences the energy performance of existing buildings and the possibilities of energy saving; this acknowledgement allows to define, at national level, general plans for renovation and energy refurbishment.

Table 1 Main features of the European housing stock

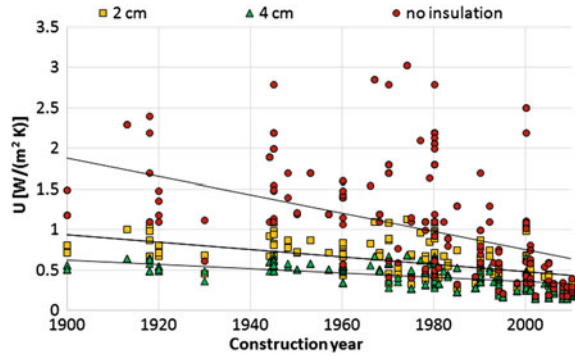
Country	Period	Typology	Walls	Outside finishing
Portugal	1950–1960 1960–1980	Multi-family	Single/double-leaf hollow brick walls	Stone, concrete. Plaster, paints, ceramic tiles
Italy	1949–1956 1957–1980	Building block Building block, tower	Single/double-layer hollow brickwork, precast concrete panels	Plaster, paints
Greece	1949–1980	Building block	Massive/perforate brickwork	Plaster, light-colour paints or ceramic stone tiles
Cyprus	1949–1980	Building block	Single-layer brickwork	Plaster, reflective paints
Netherlands	1946–1960 1960–1980	Building block Building block	Concrete block walls, concrete panels	Brick, plaster, concrete panels
Belgium	1949–1980	Building block, row houses	Concrete panels	Concrete, plaster
France	1949–1974 1975–1989	Building block Building block	Concrete walls, concrete panels	Stone, plaster, concrete panels
Sweden	1950–1960 1960–1980	Building block, tower Building block	Brickwork, precast concrete panels	Concrete, plaster, metal sheet
Denmark	1946–1980	Building block	Massive brick masonry, precast concrete panels, lightweight panels	Facing bricks, fibre- reinforced plaster
Germany	1949–1980 1958–1978	Building block Small multi- family, big multi-family	Massive/perforated brick work, concrete panels	Brick, stone metal or wood coverings, concrete, plaster, paints
Poland	1947–1974	Building block	Precast concrete panels	Plaster, paints, concrete
Hungary	1960–1969 1970–1980	Building block Building block	Precast concrete panels	Concrete

The high thermal transmittance of the building envelope evaluated for a 230 multi-storey buildings sample taken all over Europe confirms the problem of the lack of insulation and the need of refurbishment (Fig. 1, no insulation dots). The U -values show a global reduction quite only in the last 10 years.

Furthermore in Fig. 1, the possible reduction in wall thermal transmittance is shown applying an insulation layer, respectively, 2 and 4 cm of mineral wall [$\lambda = 0.036 \text{ W}/(\text{m K})$]. It is apparent that the thermal transmittance decreases according to the insulation thickness with the best results for the worst cases. Therefore, the most effective actions can be addressed to the thermal insulation of buildings with the lowest energy performances: the results may contribute better to optimize the efforts required by the European Directives.

The scenario analysis of the possible energy savings through the improving of building energy performance represents a target of a more general European

Fig. 1 Thermal transmittance U related to building construction year



refurbishment planning. In particular, the project EPISCOPE (2013–2016), based on the national residential building typologies developed during the TABULA project, is planned to track the energy refurbishment progress of housing stock at different scales. Various refurbishment measures will be determined and compared with those activities needed to attain the relevant climate protection targets.

The preliminary analysis of TABULA proposed two refurbishment levels, to enhance the energy saving of the actual existing building (Level 1):

- Level 2: standard refurbishment measures, commonly used in the countries.
- Level 3: advanced refurbishment measures that use the best available technologies.

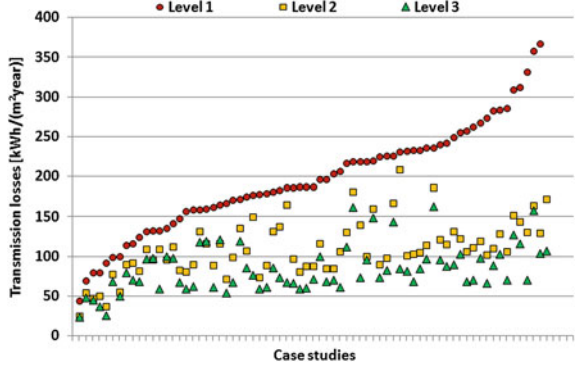
In Fig. 2, transmission losses of a series of multi-familiar houses, built in the twentieth century (most of all after the Second World War, until 1995), are shown, referring to the existing conditions (Level 1) and the two levels of interventions (2 and 3).

It is apparent, also from these calculations, that the energy refurbishment of high-loss buildings, both because of the climate conditions and because of the level insulation of the actual envelope, is associated to high energy savings. On the other hand, increasing the energy performance of low-losses buildings is harder, even adopting advanced refurbishment techniques. Anyway, only in a few cases, the annual transmission losses account for less than 50 kWh/(m² year) although the thermal transmittance of the envelope is reduced to 0.07–0.3 W/(m² K).

3 Building Energy Performance: The Envelope Influence Calculation by Means of a Quasi-Steady-State Approach

The EN ISO 13790 Standard (Energy performance of buildings—Calculation of energy use for spaces—heating and cooling) provides, at European level, some indications on the calculation methods for the design and evaluation of thermal and energy performance of buildings.

Fig. 2 Annual transmission losses according to the existing situation (*Level 1*) and intervention (*Levels 2 and 3*)



Two approaches are possible:

- quasi-steady-state methods, calculating the heat balance over 1 month or the whole season, taking into account dynamic effects by the simplified determination of a gain utilization factor;
- dynamic methods, calculating the heat balance over 1 h and taking into account the heat stored and released from the mass of the building in a detailed way.

The building energy need for space heating, $Q_{H,nd}$, in conditions of continuous heating, is calculated by:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} Q_{H,gn} \quad (1)$$

where

- $Q_{H,nd}$ is the building energy need for continuous heating, assumed to be greater than or equal to 0 (MJ);
- $Q_{H,ht}$ is the total heat transfer for the heating mode (MJ);
- $Q_{H,gn}$ gives the total heat gains for the heating mode (MJ);
- $\eta_{H,gn}$ is the dimensionless gain utilization factor and the total heat transfer, $Q_{H,ht}$, is given by

$$Q_{H,ht} = Q_{tr} + Q_{ve} \quad (2)$$

where Q_{ve} is the total heat transfer by ventilation and Q_{tr} is the total heat transfer by transmission, which depends on temperature difference between indoor and outdoor environment ($\theta_i - \theta_e$), on the heating or cooling time period t and on H_{tr} , the overall heat transfer coefficient by transmission, determined by

$$H_{tr} = H_D + H_g + H_U + H_A \quad (3)$$

where

- H_D direct heat transfer coefficient by transmission to the external environment (W/K);
- H_g steady-state heat transfer coefficient by transmission to the ground (W/K);

- H_U transmission heat transfer coefficient by transmission through unconditioned spaces (W/K);
- H_A heat transfer coefficient by transmission to adjacent buildings (W/K).

In general, H_x , representing H_D , H_g , H_U , or H_A , consists of three terms (see EN ISO 13789):

$$H_x = b_{tr,x} \left[\sum_i A_i \cdot U_i + \sum_k l_k \cdot \psi_k + \sum_j \chi_j \right] \quad (4)$$

where

- A_i area of the i -element of the building envelope (m^2);
- U_i thermal transmittance of the i -element of the building envelope [W/(m^2 K)];
- l_k length of the k -linear thermal bridge (m);
- ψ_k linear thermal transmittance of the k -thermal bridge [W/(m K)];
- χ_j point thermal transmittance of the j -point thermal bridge [W/(K)];
- $b_{tr,x}$ adjustment factor for the external temperature.

The adjustment factor $b_{tr,x}$ has to be applied when the envelope element borders on a space which has a different temperature than external environment. As established by the EN ISO 13790, for the monthly and seasonal applications, the total heat transfer by transmission, Q_{tr} , is calculated for each month or season and for each zone and depends on the overall heat transfer coefficient by transmission and on the monthly mean external and internal temperatures.

4 Main Parameters for the Thermal Characterization of Walls

As seen in the previous section, the evaluation of the envelope thermal losses requires the assessment of the heat transfer coefficient H_{tr} , which depends on the thermal transmittance of the building walls and thermal bridges.

4.1 Building Walls: Thermal Transmittance

In order to define the thermal transmittance of walls, different methodologies could be applied as shown in Fig. 3.

The thermal transmittance evaluation for new construction buildings represents an easy operation, since the thermo-physical properties are reported in the technical documents of the project. On the other hand, for existing constructions, the data related to the thermal behaviour of materials are usually not easily available.

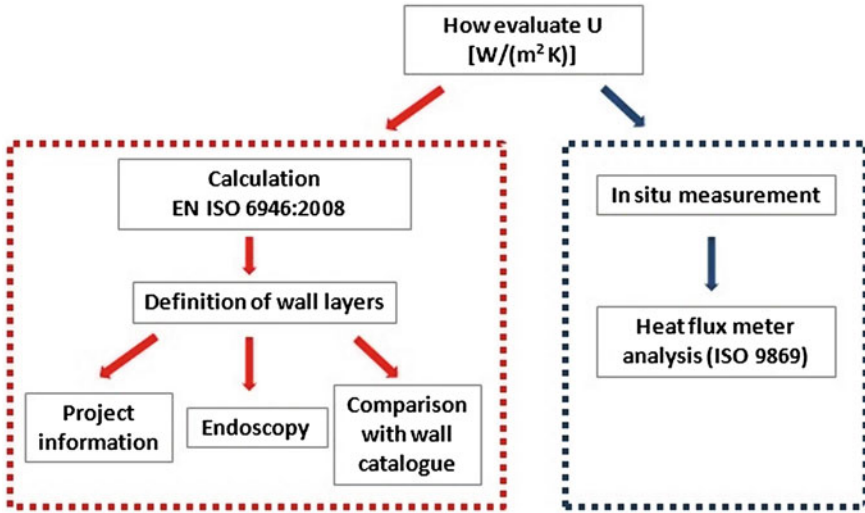


Fig. 3 Wall U -value definition

Surface heat transfer coefficients and air layer thermal resistances can be calculated according to the values defined by the EN ISO 6946 Standard, which reports all the indications for the evaluation of thermal transmittance.

4.1.1 Example of Thermal Transmittance Evaluation

Given a wall structure with its layers' characteristics and thermal properties, it is possible to calculate the thermal transmittance. In Table 2, the calculation details are reported, considering that:

- the thermal resistance of homogeneous layers can be calculated as: $R = L/\lambda$
- the thermal transmittance U is obtained as: $U = 1/R_t$.

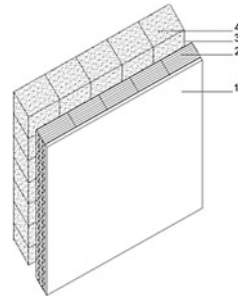
4.2 Thermal Bridges Evaluation

In the envelope energy performance assessment, thermal bridges play an important role because they influence the heat flow rate and the internal surface temperature, as indicated in the Eq. 4 for the heat transfer coefficient.

Thermal bridge is defined as follows: *part of the building envelope, where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between*

Table 2 Example of thermal transmittance evaluation

Layer	L (cm)	ρ (kg/ m ³)	λ [W/ (m K)]	R (m ² K/ W)
Internal surface resistance				0.13
1 Internal plaster	2	1,400	0.700	0.029
2 Hollow bricks ^a	8	800	–	0.200
3 Air layer ^b	2.5/ 30	1.2	–	0.180
4 Concrete blocks	20	1,400	0.500	0.400
External surface resistance				0.04
Total resistance R_t (m ² K/W)				0.979
Thermal transmittance $U = R_t^{-1}$ [W/(m ² K)]				1.021



^a Equivalent thermal resistance for hollow bricks

^b Values for unventilated air layers from the EN ISO 6946 Standard

internal and external areas, such as occur at wall/floor/ceiling junctions (EN ISO 10211 Standard).

In general, they are located in any connection between building components or where the building structure changes composition, and in these elements, the hypothesis of mono-dimensional flow is not correct, since they cause two-dimensional or three-dimensional heat flows.

In order to take into account the incidence of a thermal bridge on the whole heat flow, the linear thermal transmittance ψ [W/(m K)] is used; it represents the heat flow rate in steady-state conditions, divided by the length of the junction and by the temperature difference between internal and external surfaces.

In particular, reference values could be used for some standard structures referring to a catalogue of thermal bridges and values of ψ (EN ISO 14683) in relation to some different geometrical dimension, as follows:

- ψ_e : linear thermal transmittance determined according to the external dimensions and measured between the finished external faces of the building external elements;
- ψ_{oi} : linear thermal transmittance determined according to the overall internal dimensions and measured between the finished internal faces of the building external elements including the thickness of internal partitions;
- ψ_i : linear thermal transmittance determined according to the internal dimensions and measured between the finished internal faces of each room in a building excluding the thickness of internal partitions.

Furthermore, if the analysed thermal bridge is not included in the standard catalogue, it is possible to determine its linear thermal transmittance through numerical methods. The EN ISO 10211 Standard provides for the definition of a

geometrical model of a thermal bridge for the numerical calculation of heat flows and surface temperatures considering the following assumptions:

- all physical properties are independent from temperature;
- there are no heat sources within the building element.

Moreover, a thermal coupling coefficient is defined depending both on the heat flows and on the linear thermal transmittance.

In particular, given the geometrical features and the thermal properties of the thermal bridge, it is possible to use a numerical model, whose output is the global heat flows through the element. The coupling coefficient can be determined by the following equation:

$$\varphi_1 = L_{2D} \cdot (\theta_i - \theta_e) \quad (5)$$

where

- θ_i and θ_e represent the internal and the external air temperature;
- φ_1 is the linear thermal flow of the thermal bridge;
- L_{2D} is the coupling thermal coefficient of the thermal bridge, which has to be evaluated

Then, the linear thermal transmittance can be assessed through:

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j l_j \quad (6)$$

where

- U_j is the thermal transmittance of one-dimensional component separating the two environments;
- l_j is the length within the 2D geometrical model over which the value U_j is applied;
- N_j is the number of one-dimensional components.

4.3 Dynamic Thermal Characteristics of the Envelope

The evaluation of the dynamic thermal behaviour of the envelope is based on the definition of transient building simulation models that consider the heat storage in the structure and the time dependence of boundary conditions.

These models should be adopted for the analysis of summer behaviour; in fact, for the heating season, the evaluation by quasi-steady-state methods allows to obtain reliable results. Nevertheless, the quasi-steady-state methods do not represent accurately the thermal behaviour of buildings during the cooling season; therefore, a transient model has to be applied to have accurate results.

Moreover, the European Directive 2020/31/EU highlights that the cooling energy needs have been increased during the last years, and it suggests to focus on strategies which enhance the thermal performances also during summer period, and on the thermal properties that influence the internal overheating, such as heat thermal capacity, specific mass, periodic thermal transmittance, time shift and decrement factor. In particular, the Directive establishes that minimum requirements according to the climatic conditions have to be fixed at national level; therefore, for the countries of the Mediterranean area, dynamic envelope features that reduce the cooling energy needs have to be evaluated.

The EN ISO 13786 Standard defines the dynamic thermal characteristics of the envelope.

One of the significant parameters in this field is the periodic thermal transmittance Y_{ie} [$W/(m^2 K)$], which is defined as the amplitude of the heat flow rate through the component surface adjacent to a zone which is kept at constant temperature, divided by the amplitude of the temperature in the adjacent zone (which also could be the external environment).

Another parameter, which represents the effect of the envelope on the inward heat flow rate, is the decrement factor, which is expressed by the ratio between the periodic thermal transmittance Y_{ie} [$W/(m^2 K)$] and the quasi-steady-state thermal transmittance U [$W/(m^2 K)$]:

$$f = \frac{|Y_{ie}|}{U} \quad (7)$$

The envelope influence on the thermal behaviour is also represented by the time shift Δt , which is defined as the period of time between the maximum amplitude of a cause and the maximum amplitude of its effect.

5 Vapour Transmission Problems

The knowledge of moisture transfer mechanisms, material properties, initial and boundary conditions is often limited.

The building structures are exposed to variable internal and external climatic conditions, as they are usually influenced by outdoor air temperature, relative humidity, solar radiation, rain or are in contact with humid soil. In addition, some building components (concrete, etc.) in the construction process are characterized by high moisture contents that should be dried in short times to avoid the risk of damage to the other components.

The moisture problems that may affect building structures are various: capillary rise of water in the walls, condensation inside building components due to infiltration of indoor air (hot and humid), problems with tightness to rainwater, salts

migration inside materials, etc. and, not less important phenomena, hygrometric surface problems (growth of mould and moisture condensation) and water vapour condensation inside structures.

Therefore, the hygrometric assessment of existing building components presents considerable practical interest and it can be used, for example, to determine whether the operating conditions may lead to a progressive deterioration of the structures.

The constructions can indeed present different degradation levels depending on the types of aggression to which they are subjected: one of the most significant causes is represented by the presence of moisture or liquid water. Some materials, in fact, absorbing water vapour, increase their volume and can generate movements and internal tensions to the structures causing leakages and deformations.

Moreover, the presence of liquid water can cause an increase of thermal conductivity, thus degrading the heat transmission properties. The elimination of the serious damage resulting from the presence of water in the structures may represent a significant item of the costs for the building refurbishment.

The moisture transport and condensation in porous media is very complex, so even today, the degree of knowledge of the interaction between the various transport mechanisms and properties of building materials is unsatisfactory, incomplete and under development.

The International Standard, that gives calculation guidelines to assess of surface mould growth and the interstitial condensation for the prevention of these phenomena, adopts therefore simplified methods. The results of the calculations should be considered an approximation of more complex physical phenomena and therefore characterized by uncertainty. The standardization of simplified methods obviously does not preclude the use of more accurate calculation methods.

The following considered aspects are related only to a part of the hygrometric problems that afflict building structures: in fact, the surface mould growth and the interstitial condensation are considered essentially due to the vapour transport through the wall caused by a difference in partial vapour pressure of the internal/external environment.

The calculations follow the indications provided by the most recent release of the EN ISO 13788 Standard. Therefore, the moisture transfer through a wall is considered purely a function of inside and outside temperature and humidity conditions, and of dimensional and thermo-physical characteristics of its layers.

The diffusion of water vapour through a structure by itself may not cause problems, if it does not cross areas with too low temperature to cause condensation. In particular, two different phenomena can be considered:

- at the wall surface: high values of relative humidity or even, vapour condensation (surface phenomena);
- inside the material layers: vapour condensation as the vapour pressure reaches the saturation pressure (interstitial phenomena).

These phenomena can occur at different times and the distinction between them may not always be clearly defined: the effects of interstitial condensation may arise on the surface and this can happen even after a long time and in zones far from the ones where it took place.

Side effects resulting from these phenomena can produce degradation of buildings and unhealthy environments in the following forms:

- growth of fungal colonies on the inner surface of the building envelope;
- the presence of condensed water on the surface and inside of the walls;
- decay of wooden structures;
- degradation of plaster;
- reduction in the thermal insulation;
- dimensional changes and damage of artefacts;
- migration of salts, efflorescence.

The occurrence of these phenomena, as well as depending on the characteristics of the building and the external climatic conditions, increases with the indoor vapour production and with the reduced air renewal.

5.1 Vapour Diffusion: Basic Parameters

To address the problem of the vapour transfer in walls it is necessary to consider the mechanisms that produce its movement.

Mainly, the vapour flow within a material is determined by a difference between the partial vapour pressures or the vapour concentrations in the air in contact with the two faces of the wall. This phenomenon can be observed commonly in building structures.

Human activities modify the vapour concentration in the internal environment that, therefore, especially in winter, is higher than the one in the external environment. It can be assumed that, at least in the winter season, the moisture transfer is from inside to outside the building.

The thermo-physical parameters of the materials involved in a simplified approach to the problem, in steady-state conditions, are mainly the thermal conductivity λ [W/(m K)], which affects the temperature profile within the layers, and the water vapour permeability δ [kg/(m s Pa)], which determines the greater or lesser capacity of a material to be crossed by the water vapour. For some materials, it is indicated the hygroscopic resistance factor $\mu = \delta_o/\delta$ (-), where δ_o is the water vapour permeability of the air, which assumes, as the reference value, 200×10^{-12} kg/(m s Pa).

To describe in a quantitative way the mass transport by diffusion, the Fick's law can be applied: it relates the vapour flow rate per unit area g'_v through a material (thickness L and vapour permeability δ), with the difference ΔP_v between the

vapour pressures of the air on its surfaces. Assuming steady-state conditions, g'_v [kg/(m² s)] can be expressed as

$$g'_v = \delta \Delta P_v / L \quad (8)$$

It remains constant if there are not condensation phenomena in the internal layers. They may occur if the internal temperatures are low enough to cause low values of saturation vapour pressure: local vapour pressure can reach easily the maximum value of saturation.

The expression often refers to the equivalent thickness s_d [m]:

$$s_d = L \delta_o / \delta = L \mu \quad (9)$$

where

$\mu = \delta_o / \delta$ Hygroscopic resistance factor
 δ_o Vapour permeability of air = 193×10^{-12} kg/(m s Pa), approximated in the calculations to 200×10^{-12} kg/(m s Pa)

Therefore, the vapour flow rate g'_v [kg/(m² s)] can be written as

$$g'_v = \delta \Delta P_v / L = \delta_o \Delta P_v / s_d \quad (10)$$

5.2 The Assessment of the Risk of Interstitial Condensation Due to Water Vapour Diffusion

The Glaser method allows to verify the risk of interstitial condensation in a building wall through a graphical representation.

It compares the vapour pressure values with the saturation pressure ones, calculated as a function of the temperature distribution within the different layers of the wall. From the graphical comparison of the two trends, it is possible to put in evidence the condition in which there is condensation of the vapour, which occurs if the vapour pressure reaches the value of the saturation.

The wall passes the test if two criteria are met:

- the calculation (usually on a monthly basis) demonstrates that any condensation can be completely dried throughout the year.
- the condensation in a layer does not exceed the limit values of the materials involved.

Although the Glaser method is the reference for the evaluation of the vapour condensation risk in building structures, the method has limitations that can lead to mistakes.

Indeed, the thermo-physical characteristics of the materials, such as thermal conductivity, depend on the moisture content of the materials, which is influenced

by the capillary absorption, by the liquid water transfer, or even by the movements of air through cavities or by the superficial absorption of rain.

The method considers the built-in water dried out and it neglects some effects:

- the variation of material properties with moisture content;
- the capillary suction and the liquid water transport within the material;
- the air movement through cavities or air spaces;
- the hygroscopic moisture capacity of materials.

The evaporation and condensation processes that may occur in the materials also involve thermal energy exchanges that modify the temperatures distribution and the corresponding saturation pressures. Moreover, the effects of the solar radiation can contribute to change the distribution of the temperature in the outer layers.

In addition, neglecting the effects listed above, the analysis based on the Glaser method is carried out considering the mono-dimensional moisture transport and assuming constant boundary conditions.

The interstitial condensation assessment is developed referring to the monthly mean values of the climatic data. The verification process can be summarized in the following steps.

Step 1 Boundary conditions

(a) Material properties and geometrical dimensions (thickness).

Thermal conductivity or thermal resistance or conductance and vapour permeability of the layers are the main information needed.

For new buildings, the necessary data can be found in the technical specifications, while for existing buildings, some indications provided by international/national standards can be considered as reference values. For example, EN ISO 10456:2008 “Materials and products for buildings—Hygrothermal properties, tabulated design values and procedures for determining declared and design thermal values” can be a reference for some materials.

Some indications (by EN ISO 13788) should be taken into account:

- elements with a thermal resistance greater than $0.25 \text{ m}^2 \text{ K/W}$ should be subdivided into a number of notional layers, each one with thermal resistance $\leq 0.25 \text{ m}^2 \text{ K/W}$; these subdivisions are treated as separate material layers with interfaces between them in all calculations;
- if the wall presents a ventilated cavity, the presence of materials between this and the outside is ignored;
- some materials, such as aluminium foil, effectively prevent vapour transmission: their water vapour resistance factor is practically infinite. However, since for the calculation procedure is required a finite value, for these materials it is assumed $\mu = 100,000$. This can lead to predict small quantities of condensed water that should be neglected.

Table 3 Surface thermal resistance for the interstitial condensation calculations

Heat flow direction	Internal thermal resistance R_i ($\text{m}^2 \text{K/W}$)
Upwards	0.10
Horizontal	0.13
Downwards	0.17
All	External thermal resistance R_e ($\text{m}^2 \text{K/W}$) 0.04

- (b) Surface thermal resistance. To calculate the surface thermal resistance, the reference standard is EN ISO 6946 (Table 3), as well as for the thermal resistance of cavities. For air layers, the equivalent thickness s_d is considered to be equal to 0.01 m, regardless of their real thickness and position (vertical/horizontal).
- (c) External boundary conditions: monthly mean temperature and vapour pressure values are considered.
- (d) Internal boundary conditions: air temperature. The indoor air temperature is assumed according to the expected use of the building. For residential buildings, in the absence of specific information, the following values may be considered (ref. Italian regulations):
- $t_i = 20 \text{ }^\circ\text{C}$ in the heating period (heating system is on);
 - $t_i = 18 \text{ }^\circ\text{C}$ out of the heating period, when the monthly average outdoor temperature is $t_e < 18 \text{ }^\circ\text{C}$;
 - $t_i = t_e$ when the monthly average outdoor temperature is $\geq 18 \text{ }^\circ\text{C}$.
- (e) Internal boundary conditions: vapour pressure. If there is a HVAC system, relative humidity and internal temperature are imposed and the corresponding vapour pressure can be calculated. In the absence of a relative humidity control system, the data should be obtained by a hygrometrical balance of the environment.

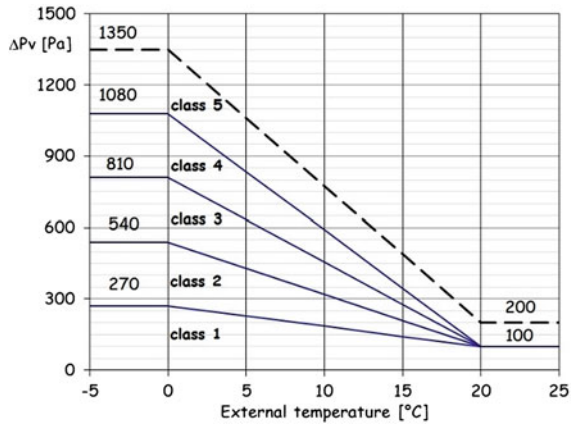
Alternatively, for maritime-mild climates, in the absence of detailed information on the building use, and of a RH control system, the information provided by the graph in Fig. 4 may be useful.

The horizontal axis represents the external monthly mean temperature. Month-to-month, the difference between internal and external vapour pressure ΔP_v can be determined, rising up from the temperature to meet the upper line of the chosen class. The upper lines are the reference for each class. In principle, residential buildings refer to class 3.

Step 2 Starting month

The climatic conditions of the starting month correspond to the first month in which condensation occurs (if there is). In principle, as a first attempt, the climatic conditions of a month at the end of the autumn can be considered. Once the starting month is individuated, the monthly mean external climatic conditions (temperature and relative humidity or vapour pressure) are used to calculate the amount of condensed/evaporated water (if any) month by month to complete the annual cycle.

Fig. 4 $P_{vi} - P_{ve}$ as function of humidity classes. Legend: *Class 1* unoccupied buildings, storage of dry goods. *Class 2* offices, dwellings with normal occupancy and ventilation. *Class 3* buildings with unknown occupancy. *Class 4* Sports halls, kitchens, canteens. *Class 5* Special buildings, e.g. laundry, brewery, swimming pool



Step 3 Calculation of the temperature and saturation pressure distribution inside the wall.

All data are referred to interfaces between layers. The temperatures at each interface between layers are calculated, as function of the thermal resistances and the temperatures of the indoor–outdoor environments.

The saturation pressure P_s (Pa) is calculated as a function of temperature. The following expressions can be used:

$$t \geq 0^\circ\text{C} \quad P_s = 610.5 e^{\frac{17.269 \cdot t}{237.3 + t}} \quad (11)$$

$$t < 0^\circ\text{C} \quad P_s = 610.5 e^{\frac{21.875 \cdot t}{265.5 + t}} \quad (12)$$

Step 4 Vapour pressure distribution. Graphical comparison between vapour pressure and saturation pressure values, as a function of the equivalent thickness s_d , allows to verify whether there is condensation. It occurs if the vapour pressure reaches the saturation pressure.

Step 5 In case of the presence of condensation in the trial month conditions: the calculation must be performed for the external climatic conditions of the previous month. The procedure is repeated backwards until it is individuated the first month in which no condensation occurs. Starting from this one, the amount of condensation the next months is calculated.

Step 6 In case of no condensation in the wall: the wall is checked with the climatic conditions of the following month. If there is no condensation in all the 12 months of the year, the structure is free of interstitial condensation. If condensation occurs in a following month, this is considered the starting month for the calculation of the amount of condensation.

Step 7 The presence of condensation during some months. The condensation can evaporate in some other months of the year. In the first month in which the calculation does not show condensation, it is assumed $P_v = P_s$ in the wet

layer of the previous month, to calculate the amount of evaporated water. In the following months, the same principle is applied, until all the condensation is progressively dried.

- Step 8 Add up all positive (condensation) and negative (evaporation) quantities and verify that the sum of the positive contributions can be balanced by the negative ones over the year.
- Step 9 The total amount of accumulated condensate is compared with the maximum values allowed for the different types of materials.

In the EN ISO 13788 standard, the risk of run-off from non-absorbent materials is considered very high over 200 g/m² of condensate. In other cases (i.e. Italian regulations), for example, the maximum amount of condensate accumulated in a layer is $M_{c,amm} = 500 \text{ g/m}^2$. For some materials, lower values are taken into account, in function of thickness L (m), density ρ (kg/m³) and conductivity λ [W/(m K)]:

- Wood ($\rho = 500 - 800 \text{ kg/m}^3$) : $M_{c,amm} \leq 30 \rho L$
- Plaster and mortar ($\rho = 600 - 2,000 \text{ kg/m}^3$) : $M_{c,amm} \leq 30 \rho L$
- Mineral wool ($\rho = 10 - 150 \text{ kg/m}^3$) : $M_{c,amm} \leq 5,000 \rho L [\lambda/(1 - 1,7\lambda)]$
- Cellular plastic materials ($\rho = 10 - 80 \text{ kg/m}^3$) : $M_{c,amm} \leq 5,000 \rho L [\lambda/(1 - 1,7\lambda)]$

- Step 10 The assessment is positive if both conditions referred to in Steps 8 and 9 are satisfied.

5.2.1 Example: Interstitial Condensation Calculation

To illustrate the calculation procedure for the verification of interstitial condensation problems, a wall with the geometrical and thermal characteristics described in the following has been considered.

- Step 1 (1a, 1b)—the geometrical structure and thermal parameters are summarized in Table 4. The climatic conditions (1c, 1d) are reported in Table 5. The indoor vapour production (1e) is assumed corresponding to class 3 (Fig. 4); therefore, the internal vapour pressure can be calculated by means of the slope of the corresponding lane, analytically expressed as:

$$P_{vi} = P_{ve} + 100 + [(810 - 100)/20] (20 - t_e) \quad (13)$$

The P_{vi} values are resumed in Table 5, as well as the internal temperature of the environment, based on the criteria reported in Step 1 of the procedure. For each layer is calculated also the equivalent thickness for vapour diffusion $s_d = L\delta_o/\delta(m)$ (Table 6).

- Step 2 The calculations start with the conditions of the trial month: it is established (arbitrarily) to be October. The corresponding monthly mean values of temperature and vapour pressure are considered. Depending on the

Table 4 Thermal properties of the wall

Concrete insulated precast wall					
Layer	<i>L</i> (cm)	ρ (kg/m ³)	<i>c</i> [J/(kg K)]	λ [W/(m K)]	<i>R</i> (m ² K/W)
1 Internal plaster	1	1,400	1,000	0.700	0.014
2 Concrete panel	1	1,400	1,000	0.580	0.017
3 Mineral wall panel	3	30	670	0.040	0.750
4 Concrete panel	10	1,400	1,000	0.580	0.172
5 External plaster	2	1,800	1,000	0.900	0.022
<i>U</i> [W/(m ² K)]	0.873			<i>R_i</i> (m ² K/W)	0.13
<i>M_s</i> (kg/m ²)	205			<i>R_e</i> (m ² K/W)	0.04
κ_i [kJ/(m ² K)]	33.1			<i>R_{tot}</i> (m ² K/W)	1.146
<i>Y_{ie}</i> [W/(m ² K)]	0.555				
<i>S</i> (h)	5.35				
<i>f_a</i>	0.635				

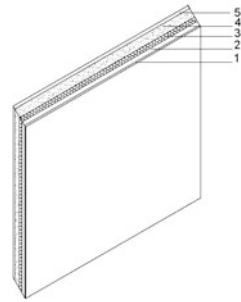


Table 5 Internal and external climatic conditions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>t_e</i> (°C)	1.5	4.2	9.3	13.5	17.7	22.0	24.4	23.7	19.9	14.0	7.8	3.5
<i>P_{ve}</i> (Pa)	661	685	783	1,046	1467	1,625	1,910	2,036	1622	1,246	896	582
<i>P_{vi}</i> (Pa)	1,418	1,346	1,263	1,377	1,649	1,654	1,854	2,005	1,726	1,559	1,429	1,268
<i>t_i</i> (°C)	20	20	20	20	18	22	24.4	24	19.9	20	20	20

climatic conditions, it is possible that condensation will not occur in October and it will not be necessary to proceed backwards with the search of the first month of the condensation.

Step 3 The temperatures at different interfaces are calculated, based on the outside temperature and on the relationship:

$$t_x = t_{x-1} - (t_i - t_e)R_x / R_T \tag{14}$$

and they are applied for each x-interface:

Table 6 Calculation details for the wall

Layer	L	λ	R	δ	s_d	ΣR_i	Σs_d	Interf
Internal thermal resistance R_i			0.13		0.00	0.130	0	0-1
1 Internal plaster	1	0.700	0.014	18	0.11	0.144	0.11	1-2
2 Concrete panel	1	0.580	0.017	4	0.50	0.161	0.61	2-3a
3a Mineral wall panel	1	0.040	0.250	150	0.013	0.411	0.62	3a-3b
3b Mineral wall panel	1	0.040	0.250	150	0.013	0.661	0.64	3b-3c
3c Mineral wall panel	1	0.040	0.250	150	0.013	0.911	0.65	3c-4
4 Concrete panel	10	0.580	0.172	4	5.00	1.084	5.65	4-5
5 External plaster	2	0.900	0.022	18	0.22	1.106	5.87	5-0
External thermal resistance R_e			0.04			1.146		

Note The thermal resistance of the glass fibre layer is higher than the limit value of $0.25 \text{ m}^2 \text{ K/W}$, and therefore, it is divided into three sublayers, each characterized by a thermal resistance of $0.25 \text{ m}^2 \text{ K/W}$

$$t_1 = t_0 - (t_i - t_e) R_1 / R_T = 20 - 0.13(20 - 14) / 1.146 = 19.3^\circ\text{C}$$

$$t_2 = t_1 - (t_i - t_e) R_2 / R_T = 19.3 - 0.014(20 - 14) / 1.146 = 19.2^\circ\text{C}$$

and so on for all the layers. All the values are reported in the third column of Table 7. From them, it is possible to calculate the corresponding values of the saturation pressure.

Step 4 To calculate the vapour pressure in each interface, the vapour resistance surface coefficients are neglected, and therefore, the vapour pressures on the two wall surfaces coincide with the corresponding environmental ones:

$$P_{vi} = P_{v1} \text{ and } P_{ve} = P_{v5} \quad (15)$$

Starting from the assumption that there is not condensation and therefore the vapour flow rate through the wall is constant, the two surface values can be connected by a straight-line segment in a plot P_v versus s_d . Analytically, the vapour pressure of each interface is calculated according to Fick's law:

$$g_v' = \delta_o(P_{vi} - P_{ve})/s_{dtot} = \delta_o(P_{v1} - P_{v2})/s_{d1-2} \quad (16)$$

and therefore

$$P_{v2} = P_{v1} - s_{d1}(P_{vi} - P_{ve})/s_{dtot} = 1,459 - 0.11(1,459 - 1,246)/5.87 = 1,455 \text{ Pa}$$

and similarly, applying the same relation to all the following layers:

$$P_{vx} = P_{v,x-1} - s_{d,x}(P_{vi} - P_{ve})/s_{dtot} \quad (17)$$

from which

$$P_{v3} = P_{v2} - s_{d2}(P_{vi} - P_{ve})/s_{dtot} = 1,455 - 0.5(1,459 - 1,246)/5.87 = 1,437 \text{ Pa}$$

Table 7 a. Temperature, saturation and vapour pressure in the wall (October–January); b. Temperature, saturation and vapour pressure in the wall (February–April)

Interf	R	s _d	October			November			December			January		
			t	P _s	P _v	T	P _s	P _v	t	P _s	P _v	t	P _s	P _v
(a)														
0-1	0.13	0	20	2,337	1,559	20	2,337	1,429	20	2,337	1,268	20	2,337	1,418
1-2	0.014	0.11	19.3	2,240	1,559	18.6	2,144	1,429	18.1	2,080	1,268	17.9	2,050	1,418
2-3a	0.017	0.5	19.2	2230	1,526	18.5	2124	1,419	17.9	2,053	1,255	17.7	2,021	1,403
3a-3b	0.250	0.013	17.8	2043	1,526	15.6	1774	1,374	14.1	1,606	1,195	13.4	1,532	1,337
3b-3c	0.250	0.013	16.5	1881	1,525	13.0	1493	1,371	10.5	1,267	1,193	9.3	1,173	1,336
3c-4	0.250	0.013	15.2	1730	1,524	10.3	1252	1,370	6.9	993	1,192	5.3	890	1,334
4-5	0.172	5.0	14.3	1632	1,258	8.5	1106	916	4.4	836	608	2.5	731	690
5-0	0.022	0.22	14.2	1620	1,246	8.2	1089	896	4.1	817	582	2.2	713	661
0.04	0.04		14.0	1598	1,246	7.8	1058	896	3.5	785	582	1.5	680	661
(b)														
Interf	R	s _d	February			March			April					
			t	P _s	P _v	t	P _s	P _v	t	P _s	P _v			
0-1	0.13	0	20	2,337	1,346	20	2,337	1263	20	2,337	1263	20	2,337	1,377
1-2	0.014	0.11	18.2	2,090	1,346	18.8	2,167	1263	19.3	2,232	1,377	19.2	2,221	1,370
2-3a	0.017	0.5	17.8	2,034	1,277	18.5	2,128	1213	19.1	2,208	1,342	17.7	2,020	1,342
3a-3b	0.250	0.013	14.3	1,632	1,276	16.2	1,836	1212	16.2	1,846	1,341	14.8	1,686	1,340
3b-3c	0.250	0.013	10.9	1,302	1,274	13.8	1,580	1211	13.9	1,583	1,059	13.7	1,570	1,046
3c-4	0.250	0.013	7.4	1,032	1,273	11.5	1,355	1210	9.9	1,218	801	8.3	783	1,046
4-5	0.172	5.0	5.1	875	710	9.9	1,201	783	9.7	1,201	783	13.5	1,547	1,046
5-0	0.022	0.22	4.8	857	685	9.7	1,171	783	9.3	1,171	783			
0.04	0.04		4.2	824	685	9.3	1,171	783						

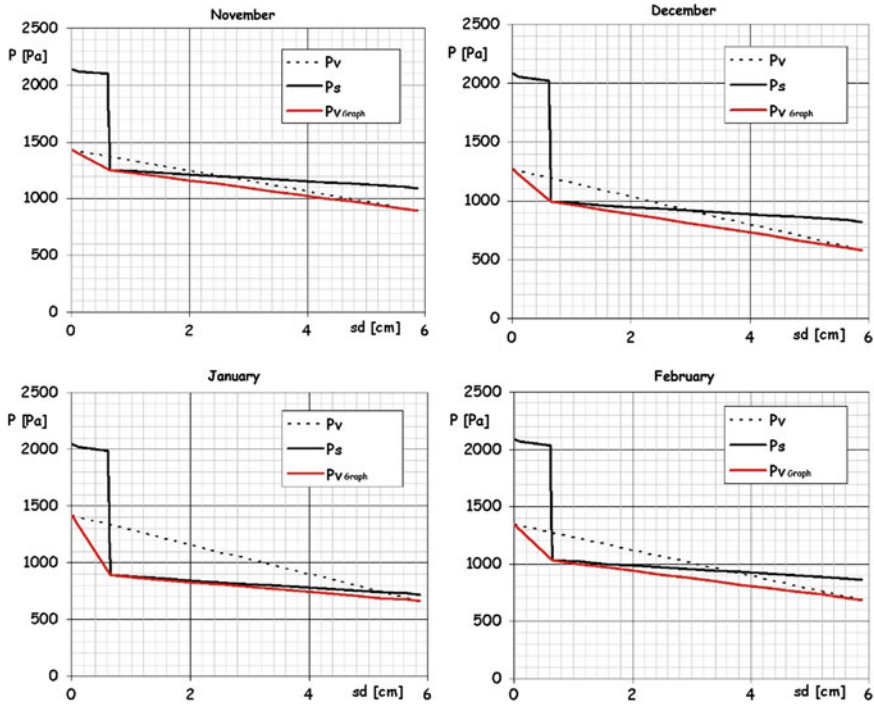


Fig. 5 Glaser diagrams (condensation) for a November, b December, c January, d February

and so on for the other layers.

The vapour pressure values in the different interfaces are reported in Table 7.

The calculations for October show that all values of the saturation pressure are higher than the vapour pressure in each interface and therefore no condensation occurs for the conditions of this month. Step 5 can be skipped.

Step 6 The calculations are developed for the 12 months (Table 7) with the input data in Tables 4 and 5. The difference between saturation and vapour pressure in November can be put in evidence: in the interface 3c-4, it can be observed that $P_v > P_s$. The diagrams in Fig. 5 highlight the occurrence.

Then, the month of November is the starting month for the calculation of the amount of condensation that forms at the interface between the two layers.

P_v is plotted as a straight line between the surface values and the P_s lower value (in this case at the interface 3c-4). The difference between the two slopes represents the rate of condensed water.

Step 7 The calculations proceed with the climatic conditions of the subsequent months, to determine the amount of condensate accumulated in the interface for each month. The condition $P_v > P_s$ is observed until February and the same procedure of November is applied. Note that for January, the

Table 8 Amounts of condensation/evaporation quantities

Month	M_c (g/m ²)	Sum (g/m ²)
October	0.0	0.0
November	105.6	105.6
December	183.9	289.5
January	411.1	700.7
February	201.4	902.1
March	-134.9	767.2
April	-309.7	457.5
May	-373.4	84.1
June	-887.9	0.0
July	0.0	0.0

comparison between P_v and P_s shows that $P_v > P_s$, also the interface 3b-3c. From the graph (Fig. 5c), however, it is observed that the minimum P_s corresponds to the interface 3c-4.

For example, the condensate for November is detailed (g_{H_2O} in [kg/(m² s)]):

$$\begin{aligned}
 g_{H_2O} &= g'_{v\ in} - g'_{v\ out} \\
 &= \delta_o(P_{vi} - P_{s3c-4}) / (s_{d3c-4}) \\
 &\quad - \delta_o(P_{s3c-4} - P_{ve}) / (s_{dtot} - s_{d3c-4})
 \end{aligned} \tag{18}$$

$$g_{H_2O} = 200 \times 10^{-12} [(1,429 - 1,252) / (0.11 + 0.5 + 0.013 + 0.013 + 0.013) + (1,252 - 896) / (5.0 + 0.22)]$$

$$g_{H_2O} = 200 \times 10^{-12} [272 - 68.2] = 4.09 \times 10^{-8} \text{ kg}/(\text{m}^2 \text{ s}) = 3.53 \text{ g}/(\text{m}^2 \text{ day})$$

The water condensate in the whole month will be

$$M_c = 3.53 \text{ g}/(\text{m}^2 \text{ day}) 30 \text{ days} = 106 \text{ g}/\text{m}^2$$

The calculation of the amount of condensed water is performed for all months until February: the quantities are indicated in Table 8.

In March, all interfaces present $P_v < P_s$; therefore, the amount of evaporated water is calculated assuming that $P_v = P_s$ in the 3c-4 interface, where the condensate remains concentrated until complete evaporation.

On a graph (Fig. 6), the trends of the saturation and vapour pressure are shown; the mass of evaporated water in the period can be calculated as

$$\begin{aligned}
 g'_{v\ in} &= \delta_o(P_{v1} - P_{s3c-4}) / (\sum s_d)_{1-3c} \\
 g'_{v\ in} &= 200 \times 10^{-12} (1,263 - 1,355) / 0.65 = -2.83 \times 10^{-8} \text{ kg}/(\text{m}^2 \text{ s})
 \end{aligned} \tag{19a}$$

Due to the positive direction of the x -axis from inside to outside, the negative sign indicates that the vapour flow is directed from the interface to the indoor

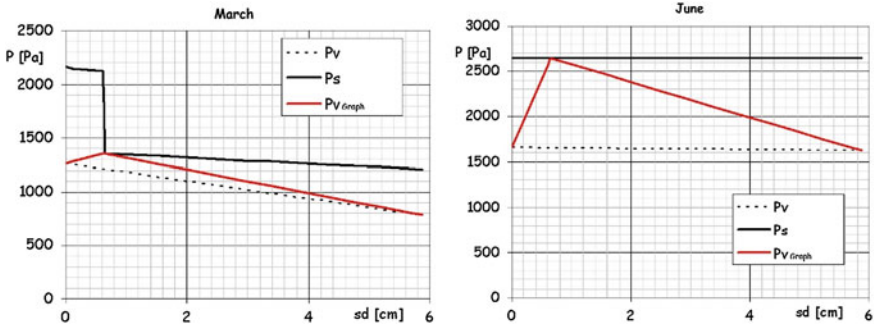


Fig. 6 Example of Glaser diagrams for evaporation: **a** March, **b** June

environment. The vapour flow from the interface 3c -4 to outside can be expressed as

$$g'_{v\ out} = \delta_o(P_{s3c-4} - P_{v4})/[s_{dtot} - (\sum s_d)_{1-3c}] \tag{19b}$$

$$g'_{v\ out} = 200 \times 10^{-12}(1,355 - 783)/(5.87 - 0.65) = 2.19 \times 10^{-8}$$

In this case, the positive sign indicates that the vapour flow is directed to outside. The two calculated flow rates show that the vapour transfer occurs from the interface where it condensed in the previous months both to the internal and external environments.

The total amount of evaporated water in March will be

$$g'_{H_2O} = g'_{v\ in} - g'_{v\ out} = -2.83 \times 10^{-8} - 2.19 \times 10^{-8} = -5.02 \times 10^{-8} \text{kg}/(\text{m}^2 \text{s})$$

$$g'_{H_2O} = -5.02 \times 10^{-8} \text{kg}/(\text{m}^2 \text{s}) = -5.02 \times 10^{-8} 86,400 \times 10^3 \text{g}/(\text{m}^2 \text{day}) = -4.34 \text{ g}/(\text{m}^2 \text{day})$$

$$M_c = g'_{H_2O} \Delta\tau = [-4.34.0 \text{ g}/(\text{m}^2 \text{day})] 31 \text{ days} = -134.5 \text{ g}/\text{m}^2$$

The calculation goes on under the climatic conditions of the subsequent months, starting from the hypothesis $(P_v = P_s)_{3c-4}$ until the total amount of condensate is dried. The results, obtained with the same procedure, are in Table 8.

Step 8 The progressive sum of condensate (Table 8) grows from November to February and then decreases until June, due to evaporation. In the following months, the wall is dry.

Step 9 Assuming the limits for the condensation in mineral wool panels as indicated in the previous paragraph, the maximum level should be

$$M_{c.amm} \leq 5,000 \rho L [\lambda/(1 - 1.7 \lambda)] = 5,000 \times 30 \times 0.03[0.04/(1 - 1.70.04)]$$

$$= 193 \text{ g}/\text{m}^2$$

The values in Table 8 show that the sum of the condensate at the end of January would exceed the limit for mineral wool.

Step 10 The assessment is negative, as the condition referred to in Step 8 is satisfied, but not the one in Step 9.

6 Common Typologies of Walls and Their Characteristics: A Wall Database

Considering the method and the results of the projects INVESTIMMO and TABULA, a wall database, which integrates information related both to energy performance (i.e. thermal conductivity, transmittance and dynamic properties) and to hygrothermal behaviour (interstitial condensation assessment) was developed.

The database collects a large number of walls, which represent the constructive typologies of post-World War II buildings all over Europe.

In particular, the database includes information related to:

- thermal parameters: thermal transmittance, thermal mass, areal thermal capacitance;
- dynamic parameters: periodic thermal transmittance, time shift and decrement factor.

The control of moisture problems, such as the interstitial condensation risk, must be analysed basing on specific climatic conditions.

In Table 9 are reported the wall typologies and their parameters. For the calculations, surface thermal resistances of Table 3 are applied.

7 Thermo-Hygrometric Problems: Introduction to Energy Refurbishment

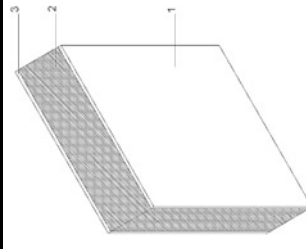
The overall energy consumption of a building is determined by numerous factors, and some of them cannot be changed under renovation. In fact, the geometry, the orientation, the relationship between opaque and transparent surfaces, and the location in urban area represent some of the constraints to the improvement of building energy performance.

In order to reduce energy consumption in existing buildings, the possibilities offered by synergistic actions on elements of the building envelope and plant components have to be assessed.

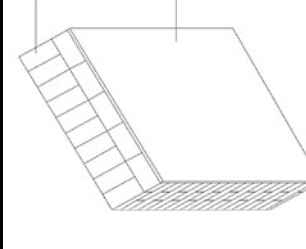
The HVAC system can be, at least partially, replaced or made more efficient with non-invasive interventions, while the renovation of the envelope can cause more inconveniences to the occupants. Nevertheless, the insulation of the envelope allows to reduce the transmission losses and the energy needs of buildings.

Table 9 Building walls database

01 BM—brick masonry						
<i>Layer</i>	<i>L</i>	ρ	λ	<i>R</i>		
1 Internal plaster	2	1,400	0.700	0.028		
2 Brick	38	1,800	0.720	0.528		
3 External plaster	2	1,800	0.900	0.022		
<i>U</i>	<i>M_s</i>	κ_i	Y_{fe}	<i>S</i>	f_a	
1.336	748	63.1	0.136	14.59	0.102	

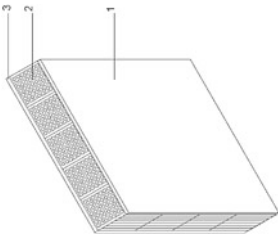


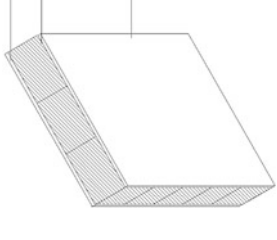
02 BM—masonry face brick						
<i>Layer</i>	<i>L</i>	ρ	λ	<i>R</i>		
1 Internal plaster	1.5	1,400	0.700	0.021		
2 Brick	51	1,800	0.720	0.708		
<i>U</i>	<i>M_s</i>	κ_i	Y_{fe}	<i>S</i>	f_a	
1.112	939	62.2	0.048	18.5	0.04	



(continued)

Table 9 (continued)

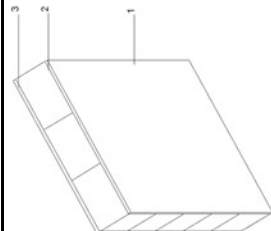
03 BM—cellular brick masonry						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Brick block	30	1,000	—	0.890 ^a		
3 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{ie}	S	f_a	
0.900	364	53.7	0.197	11.94	0.22	

04 SM—stone masonry						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Stone blocks	80	2,500	2.400	0.333		
3 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{ie}	S	f_a	
1.805	2,064	72.3	0.033	20.4	0.018	

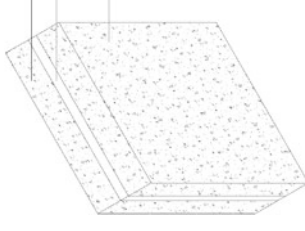
(continued)

Table 9 (continued)

05 SM—tuff stone masonry						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Tuff stone blocks	50	1,600	0.550	0.909		
3 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{fe}	S	f_a	
0.885	864	58.7	0.029	20.18	0.033	



06 SM—stone masonry with air layer						
Layer	L	ρ	λ	R		
1 Stone masonry	25	2,500	2.400	0.104		
2 Air layer	2.5/30	1.2	—	0.180 ^b		
3 Stone masonry	25	2,500	2.400	0.104		
U	M_s	κ_i	Y_{fe}	S	f_a	
1.791	1,250	84.8	0.121	14.41	0.067	



(continued)

Table 9 (continued)

07 SM—stone masonry with insulated layer						
Layer	L	ρ	λ	R		
1 Stone masonry	25	2500	2.400	0.104		
2 Insulation	4	30	0.110	0.364		
3 Stone masonry	25	2500	2.400	0.104		
U	1.348	κ_i	Y_{fe}	S	f_a	0.052
		84.4	0.070	14.88		
08 CM—brick and stone masonry						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1400	0.700	0.028		
2 Brick and stones	50	1500	0.900	0.556		
3 External plaster	2	1800	0.900	0.022		
U	1.288	κ_i	Y_{fe}	S	f_a	0.081
		62.8	0.104	15.646		

(continued)

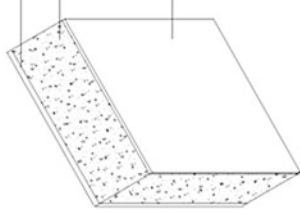
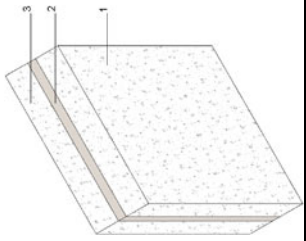


Table 9 (continued)

09 CM—masonry with air layer									
Layer	L	ρ	λ	R					
1 Internal plaster	2	1,400	0.700	0.028					
2 Hollow bricks	8	800	—	0.200 ^a					
3 Filler	10	1,500	0.700	0.143					
4 Bricks	25	1,800	0.720	0.347					
5 External plaster	2	1,800	0.900	0.022					
U	M_s	κ_i	Y_{fe}	S	f_a				
1.098	728	49.4	0.093	15.53	0.084				
10 CM—hollow concrete block masonry (1)									
Layer	L	ρ	λ	R					
1 Internal plaster	2	1,400	0.700	0.028					
2 Hollow concrete blocks	20	1,400	0.500	0.40					
3 External plaster	2	1,800	0.900	0.022					
U	M_s	κ_i	Y_{fe}	S	f_a				
1.611	344	65.1	0.656	8.12	0.407				

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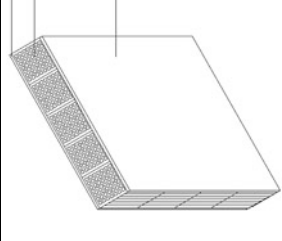
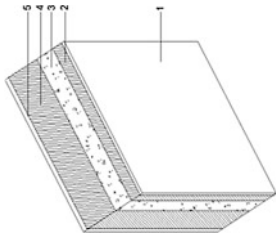
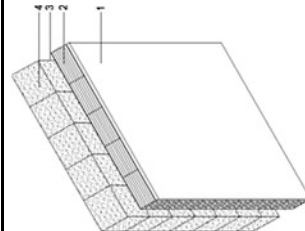
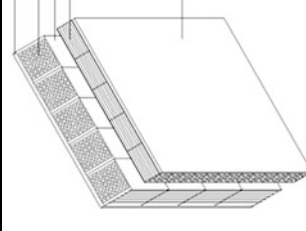


Table 9 (continued)

11 CM—hollow concrete block masonry (2)						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.029		
2 Hollow bricks	8	800	—	0.200 ^a		
3 Air layer	2.5/30	1.2	—	0.180 ^b		
4 Concrete blocks	20	1,400	0.500	0.40		
U	M_s	κ_i	Y_{te}	S	f_a	0.252
1.022	372	53.3	0.258	10.8		



12 HB—hollow brick masonry (1)						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	8	800	—	0.200 ^a		
3 Air layer	2.5/30	1.2	—	0.180 ^b		
4 Hollow bricks	12	800	—	0.310 ^a		
5 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{te}	S	f_a	0.541
1.098	224	57.9	0.594	7.268		



(continued)

Table 9 (continued)

13 HB—air layer brick masonry (1)						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	8	800	—	0.200 ^a		
3 Air layer	2.5/ 30	1.2	—	0.180 ^b		
4 Bricks	25	1,800	0.720	0.347		
5 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{fe}	S	f_a	
1.055	578	50.6	0.152	13.12	0.144	
14 HB—air layer brick masonry (2)						
Layer	L	ρ	λ	R		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	8	800	—	0.200 ^a		
3 Polystyrene	4	15	0.045	0.889		
4 Bricks	25	1,800	0.720	0.347		
5 External plaster	2	1,800	0.900	0.022		
U	M_s	κ_i	Y_{fe}	S	f_a	
0.604	578	53.5	0.063	14.22	0.105	

(continued)

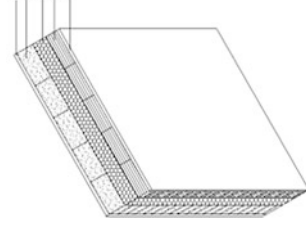
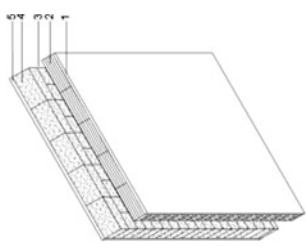


Table 9 (continued)

15 HB—air layer brick masonry (3)						
Layer	<i>L</i>	ρ	λ	<i>R</i>		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	12	800	—	0.310 ^a		
3 Air layer	2.5/ 30	1.2	—	0.180 ^b		
4 Hollow bricks	12	1,200	—	0.310 ^a		
<i>U</i>	<i>M_s</i>	κ_i	<i>Y_{ie}</i>	<i>S</i>	<i>f_a</i>	
1.001	268	56.7	0.379	9.15	0.378	
16 HB—air layer brick masonry (4)						
Layer	<i>L</i>	ρ	λ	<i>R</i>		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	12	800	—	0.310 ^a		
3 Air layer	2.5/30	1.2	—	0.180 ^b		
4 Bricks	12	1,800	0.720	0.720		
<i>U</i>	<i>M_s</i>	κ_i	<i>Y_{ie}</i>	<i>S</i>	<i>f_a</i>	
1.169	340	57.0	0.45	9.05	0.385	

(continued)

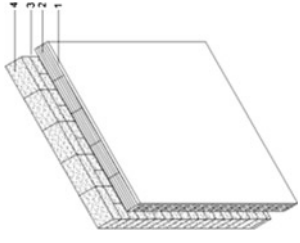
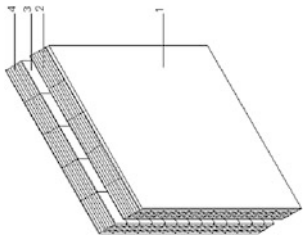
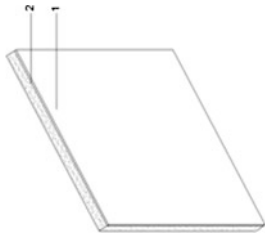


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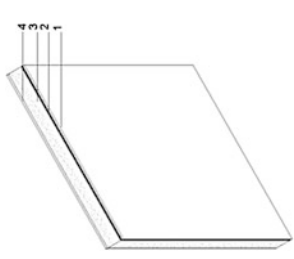
17 PC—concrete wall							
Layer	L	ρ	λ	R			
1 Internal plaster	1	1,400	0.700	0.028			
2 Concrete wall	25	1,400	0.720	0.528			
U	M_s	κ_i	Y_{te}	S	f_a		
1.837	364	64.7	0.599	8.46	0.367		



(continued)

Table 9 (continued)

1.8 PC—concrete insulated wall (2)					
Layer	<i>L</i>	ρ	λ	<i>R</i>	
1 Internal plaster	1	1,400	0.700	0.014	
2 Mineral wall panel	2	30	0.040	0.50	
3 Concrete panel	25	1,400	0.580	0.431	
4 External plaster	2	1,800	0.900	0.022	
<i>U</i>	<i>M_s</i>	κ_i	<i>Y_{ie}</i>	<i>S</i>	<i>f_a</i>
0.879	400	25.6	0.181	10.25	0.206



- L* Thickness (cm)
- ρ Density (kg/m³)
- λ Thermal conductivity [W/(m K)]
- R* Thermal resistance (m² K/W)
- U* Thermal transmittance [W/(m² K)]
- M_s* Specific mass (kg/m²)
- κ_i Arei thermal capacity. [kJ/(m² K)]
- Y_{ie}* Dynamic thermal transmittance [W/(m² K)]
- S* Time shift (h)
- f_a* Decrement factor (-)

^a Estimated values of thermal equivalent resistance for hollow bricks

^b Values for unventilated air layers from the Standard EN ISO 6946

The building energy performance assessment requires also the analysis of HVAC systems, in order to verify whether the plants can efficiently operate even with a low energy demand. On the other hand, reducing the amount of energy allows to consider alternative system solutions that include the exploitation of renewable sources. The refurbishment of the opaque elements of existing buildings means, in general, using thermal insulation materials to decrease the transmittance and therefore the energy losses through the walls facing towards the external environment. The consequences of the insulation can be summarized with the following considerations.

Increasing insulation of external structures allows the reduction of winter heat losses and of summer loads, with the reduction of global energy consumption.

Moreover, a careful design and verification of glazed surfaces and their solar shading is necessary. In fact, incorrect evaluation of the transparent elements influence in summer could cause overheating and greenhouse effects in the indoor environment. In this case, a high thermal insulation level would reduce the heat loss through the walls from inside to outside, maintaining a high temperature, not desired, in the indoor environments, in summer.

Insulating the external envelope can improve the indoor comfort as if the wall surface temperature is closer to the air one, the heat exchange by radiation between the human body and the different surfaces is reduced.

There are three main solutions for thermal insulation:

- external insulation;
- internal insulation;
- air layer insulation.

The most effective one is the external insulation, even if it is also the most expensive. Moreover, it is not always feasible, since, for the application, the facade must be free of ornaments. This solution is interesting if the installation cost of scaffolding and other works is considered in association with the other renovation actions already planned and if there is not a large number of overhang elements in the external surface.

With the installation of a ventilated facade, good results can be reached, even if with rather high costs. The intervention with insulating plaster could be useful, if considered synergistically with other actions, due to the low thickness of the layer. In fact, even if insulating plaster is characterized by a low thermal conductivity, it could lead to results that do not comply the minimum requirements for the envelope.

The air layer insulation can be interesting for many buildings built between the 1960s and 1970s, since they often have empty cavity in the envelope layers, which can be filled by melted materials. The results can be effective: it is possible to apply the insulation from external holes in the façade or from inside without high costs.

However, the thermal properties of the insulation (foam or melted material) have to be defined. Moreover, before performing this kind of action, it would be appropriate to have information on the effective period in which the properties are guaranteed; otherwise, it will be necessary a second application after a period in

Table 10 Hygrothermal properties of insulation materials

Type	λ [W/(m K)]	δ [kg/(m s Pa)]	ρ (kg/m ³)
<i>Internal or external insulation</i>			
Mineral wall (MW)	0.036	193×10^{-12}	40
Wooden fibreboard (WF)	0.040	97×10^{-12}	110
Polystyrene (PY)	0.033	1.3×10^{-12}	35
<i>Air layer insulation</i>			
Cellulose	0.038	1×10^{-12}	35
Polyurethane foam	0.030	3.8×10^{-12}	30

dependence of the degeneration and the maintained uniformity of the filling material.

The internal insulation may be less difficult, since it regards single dwellings and it does not involve actions on the facade, the use of scaffolding, etc. Nevertheless, this intervention could reduce the internal surface of the living spaces; therefore, it has to be correctly designed and planned. In fact, while the insulation in the cavity presents physical limits due to the width of the air layer, the application of insulating panels becomes effective for thicknesses generally higher than 4–6 cm, especially in the continental climatic conditions.

Regarding the dynamic thermal performance of the walls, the position of the insulation greatly influences the thermal inertia of the structure. The heat storage is determined by the properties of materials, which are involved in the heating transmission of the envelope, In general, the external insulation provides better results.

As regards hygrometric properties, a higher thermal insulation undoubtedly involves a good improvement in terms of surface moisture problems. Nevertheless, the situation should be carefully assessed in terms of risk of interstitial condensation, especially when the insulating layer is located close to the internal side of the wall.

7.1 Evaluation of Insulation Intervention: Practical Examples

As reference for the thermal transmittance reductions of building walls, the effects of the thermal insulation of the structures of the database (Table 9) are calculated, considering two kind of installation, on the internal or the external side. As an alternative, for air layer masonry, the effect of the cavity insulation is also considered.

For each structure, three different kinds of insulated materials widely used in building refurbishment are considered (Table 10). Their properties are gathered from the technical files of commercial products.

Moreover, for the evaluation of the periodic thermal transmittance, it is also taken into account the position of the insulating layer (external or internal). An additional layer of external plaster is added in case of external insulation.

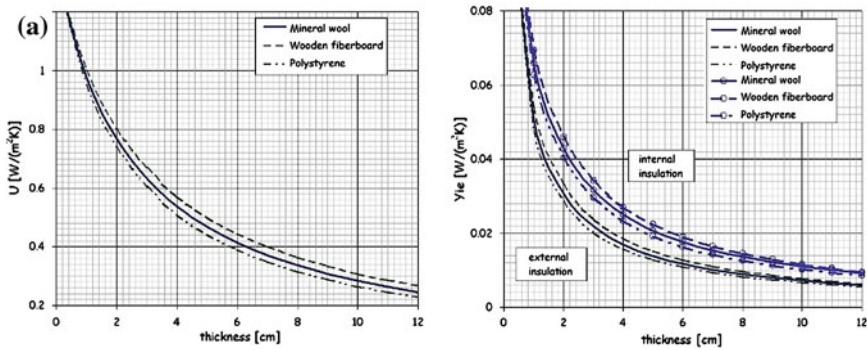


Fig. 7 U and Y_{ie} values versus insulation thickness. **a** 01 BM—brick masonry. **b** 02 BM—masonry face brick. **c** 03 BM—cellular brick masonry. **d** 04 SM—stone masonry. **e** 05 SM—tuff stone masonry. **f** 06 SM—stone masonry with air layer. **g** 06 SM—stone masonry with air layer—cavity insulation. **h** 07 SM—stone masonry with insulated layer. **i** 08 CM—brick and stone masonry. **j** 09 CM—masonry with air layer. **k** 10 CM—hollow concrete block masonry (1). **l** 11 CM—hollow concrete block masonry (2). **m** 11 CM—hollow concrete block masonry (2)—cavity insulation. **n** 12 HB—hollow brick masonry (1). **o** 12 HB—hollow brick masonry (1)—cavity insulation. **p** 13 HB—air layer brick masonry (1). **q** 13 HB—air layer brick masonry (1)—cavity insulation. **r** 14 HB—air layer brick masonry (2). **s** 15 HB—air layer brick masonry (3). **t** 15 HB—air layer brick masonry (3)—cavity insulation. **u** 16 HB—air layer brick masonry (4). **v** 16 HB—air layer brick masonry (4)—cavity insulation. **w** 17 PC—concrete wall. **x** 18 PC—concrete insulated wall (2)

The following graphs (Fig. 7a–x) allow to check the insulation thickness needed to improve the performances indicated by local requirements or limits of the thermal transmittance U and periodic thermal transmittance Y_{ie} . In addition, cavity filling is evaluated, where applicable.

8 Interstitial Condensation Evaluation: Maximum Insulating Thickness Allowed in the Refurbishment for Some Wall Structures

It is important to associate the choice of insulation, in relation to the limits for the energy refurbishment, to the corresponding hygrometric assessment. Sometime, for particular climatic conditions and building structures, an optimal choice in terms of energy saving may not be suitable in relation to the risk of interstitial condensation.

Following the steps of the procedure for the interstitial condensation assessment, the previously described walls are considered in the following calculations, to determine the insulating layer thicknesses for a positive assessment (Step 10). As reference, only the structure number is indicated, from 01 to 18.

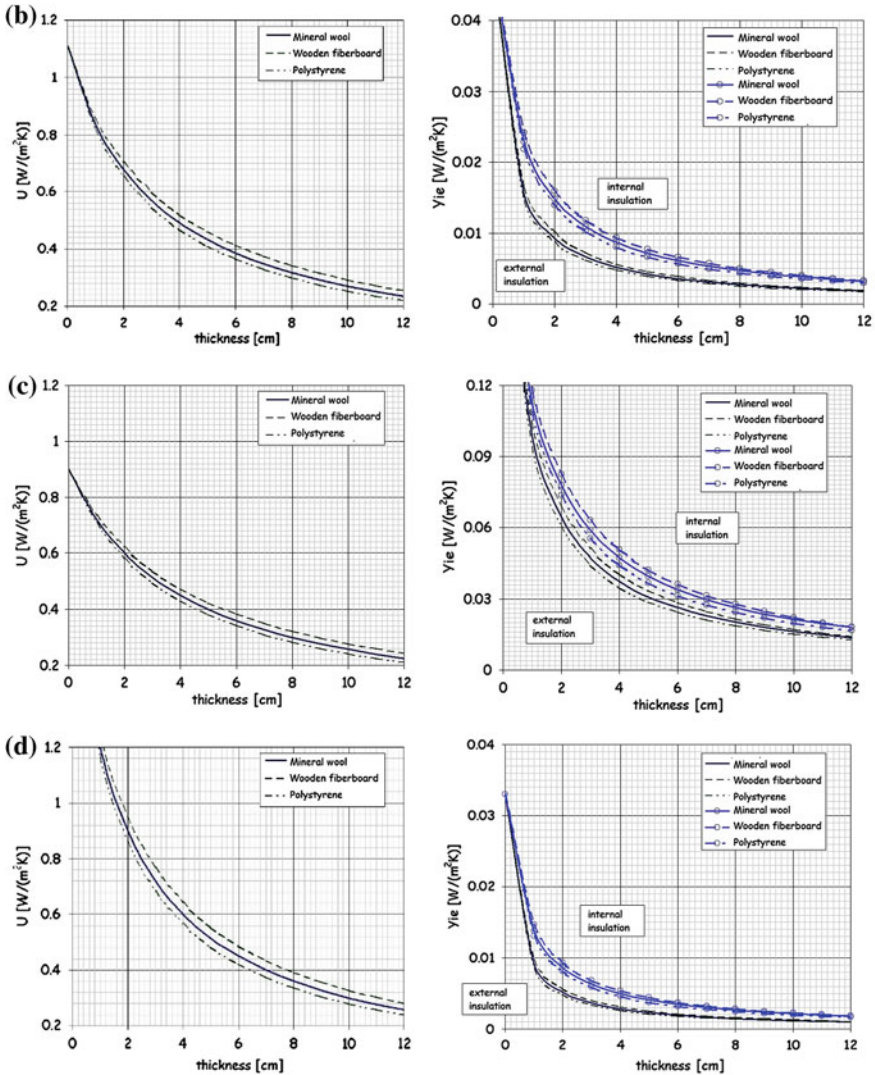


Fig. 7 continued

As before, for the thermal calculations, various insulating materials, thicknesses (from 1 to 12 cm), position (outside, inside, filling the air layer) have been considered with their hygrothermal parameters.

The indoor moisture production was referred to humidity class 3 (buildings with unknown occupancy, Fig. 4). The climatic data of six different regions in Europe are resumed in Table 11 [t_e in (°C), P_{ve} in (Pa)].

The upper limits of condensation in the annual cycle for different materials have been calculated in function of thickness L (m), density ρ (kg/m³) and conductivity

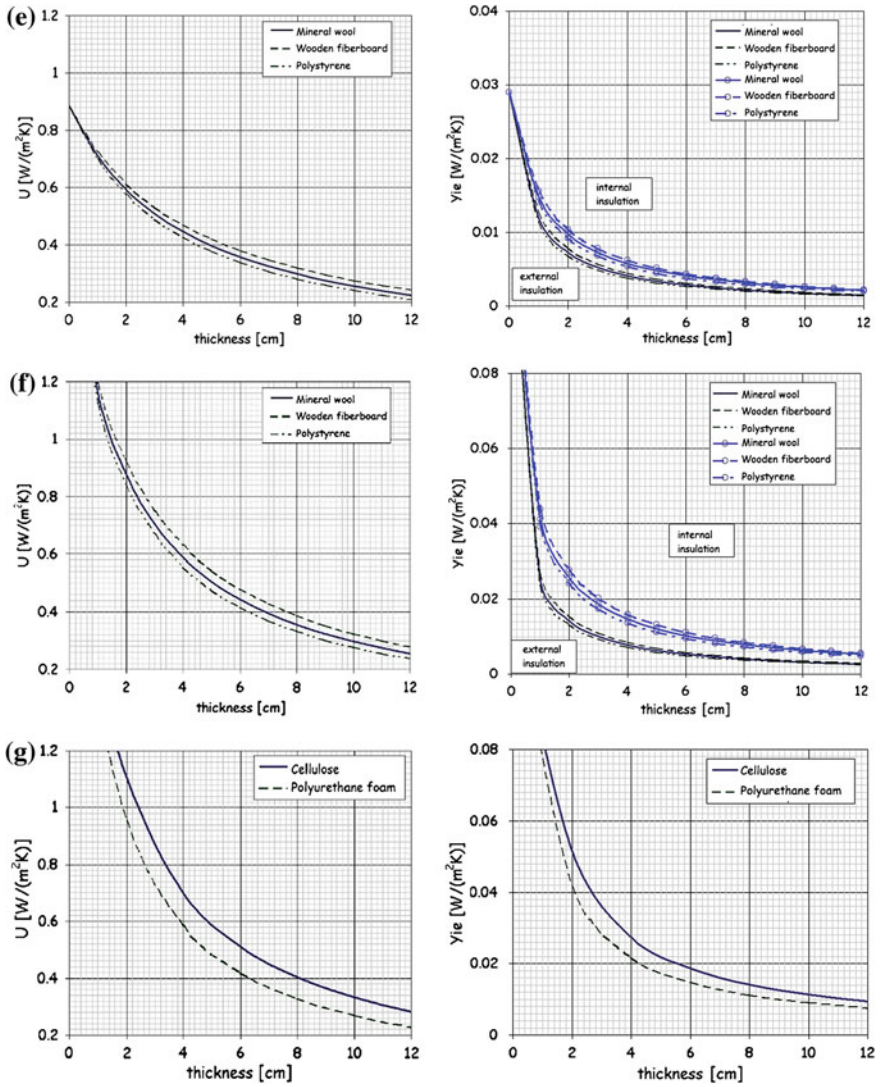


Fig. 7 continued

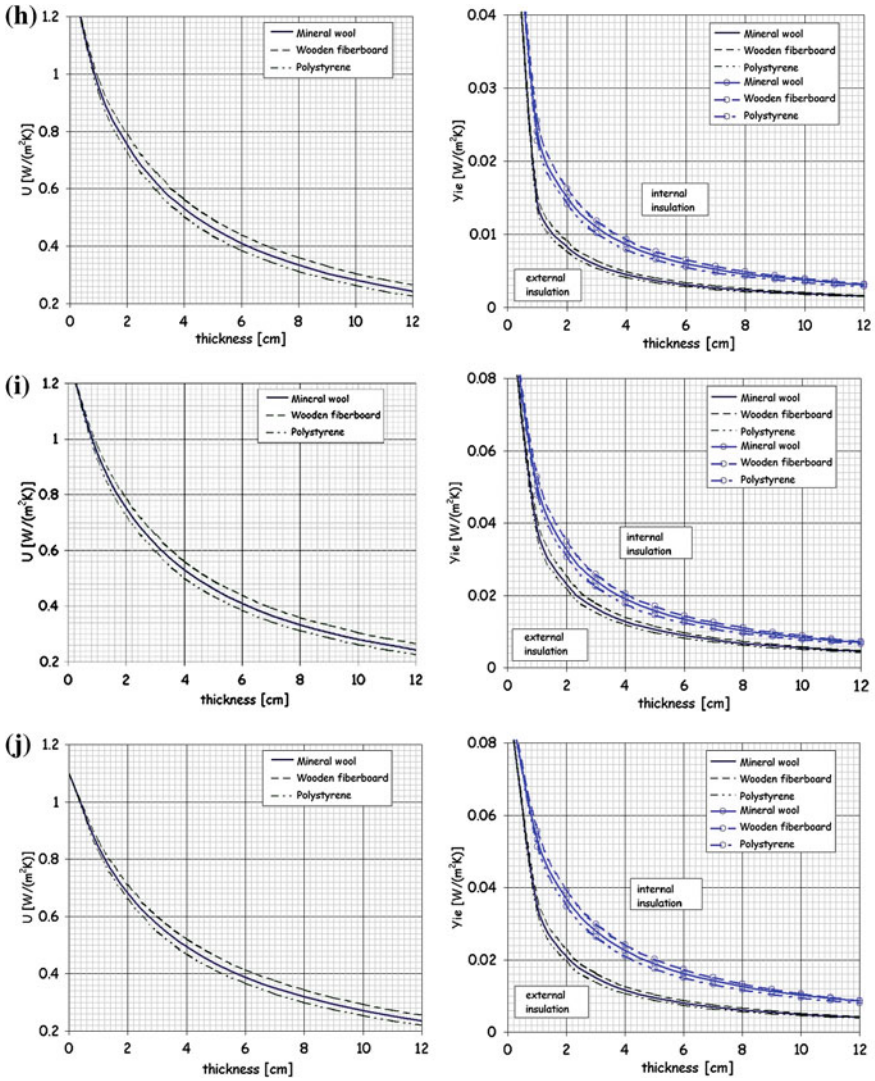


Fig. 7 continued

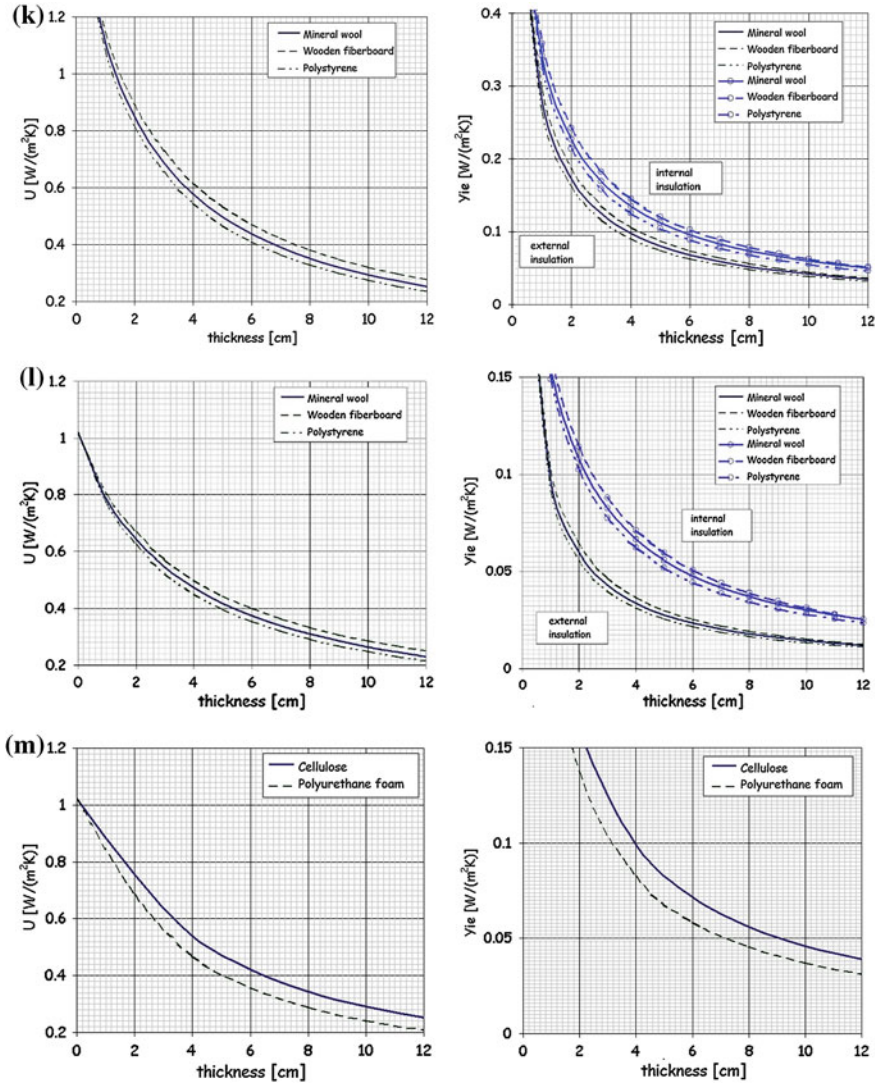


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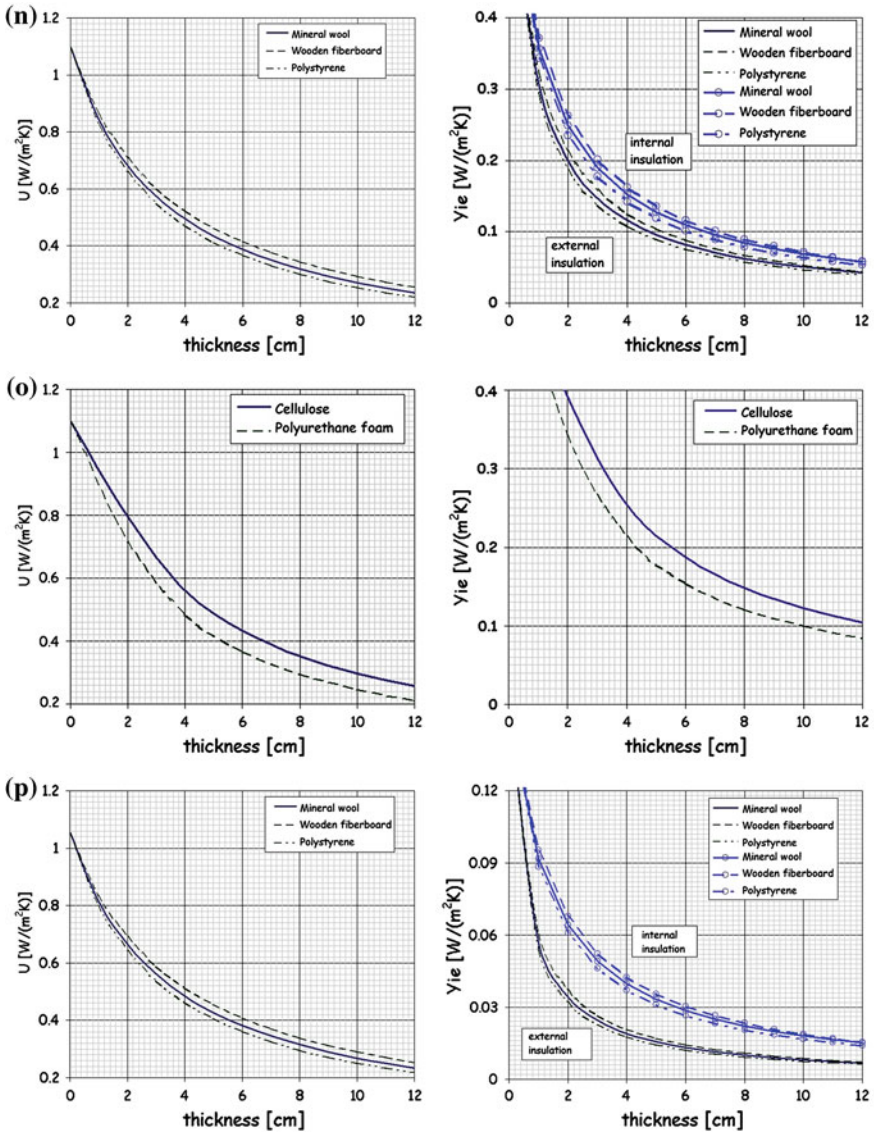


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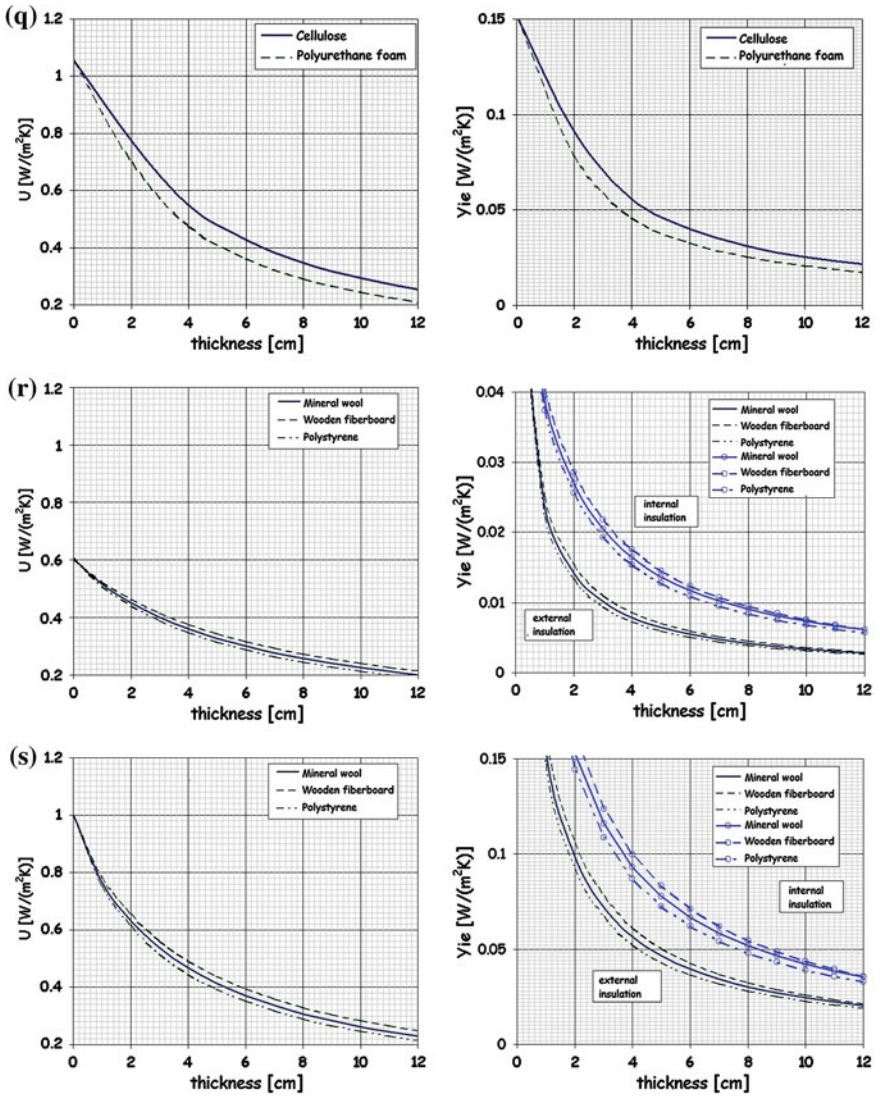


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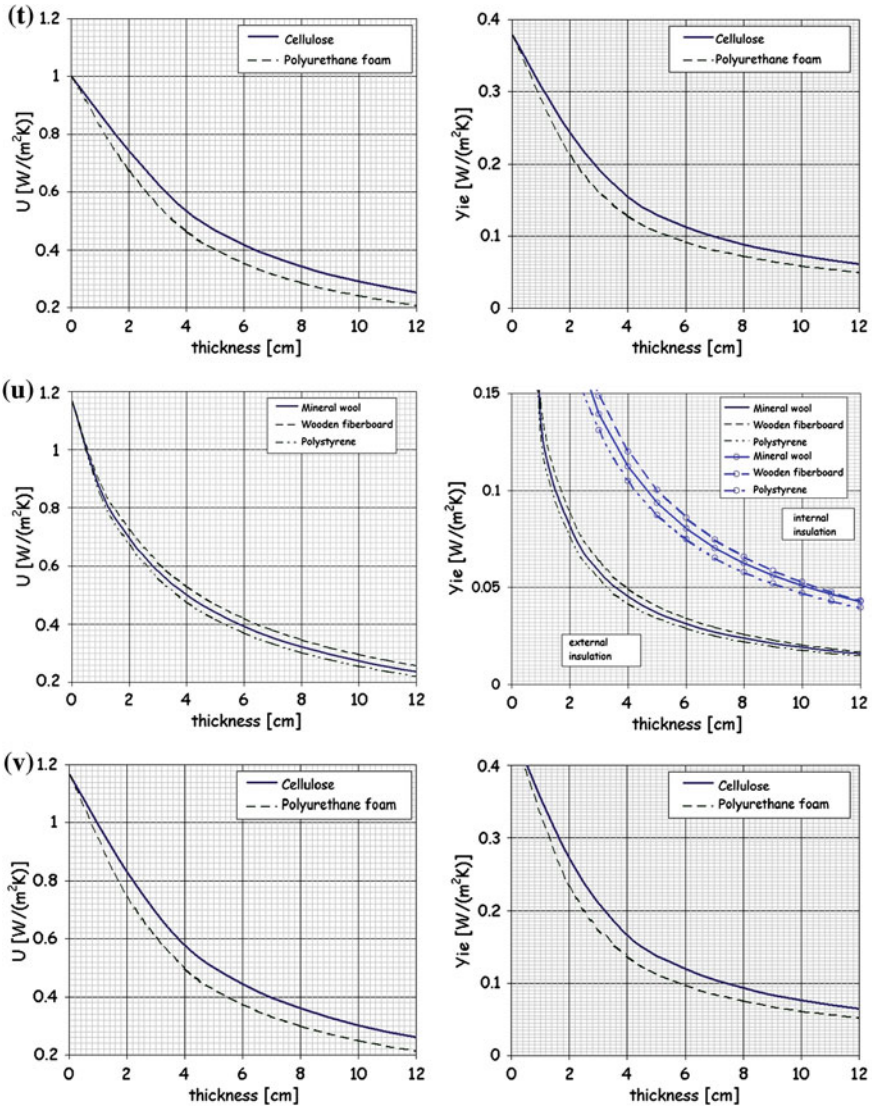


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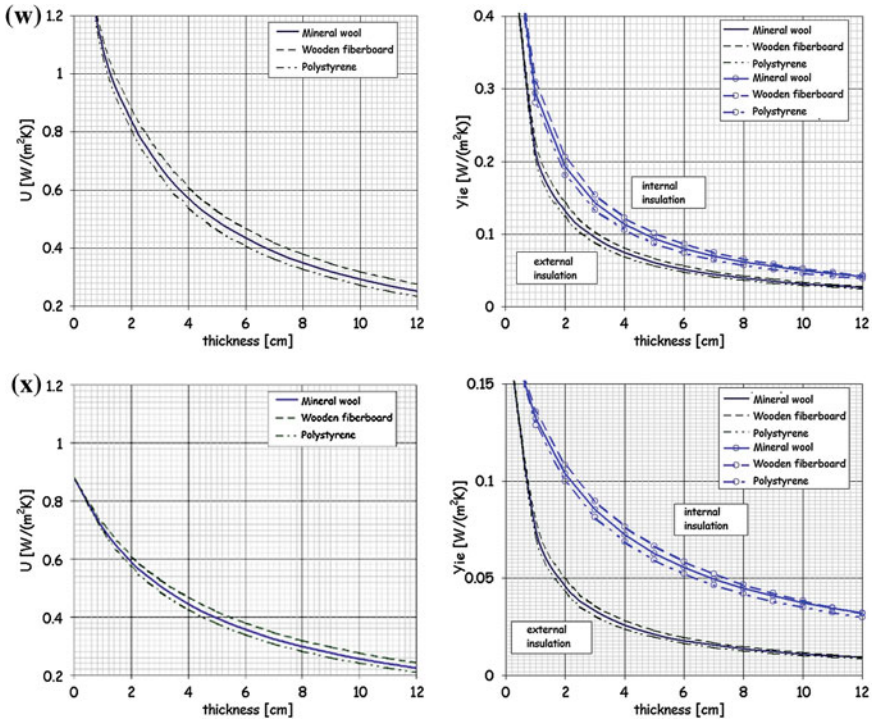


Fig. 7 continued

λ [$W/(m K)$] of the chosen materials, in agreement with the indications described in Sect. 5 (Table 12).

8.1 Existing Walls

Condensation occurs in the following existing structures:

- Wall 06, in the climatic conditions of Milan and Hamburg ($<2 g/m^2$).
- Wall 07, in the climatic conditions of Milan, Paris, Brussels ($<3 g/m^2$) and Hamburg ($<6 g/m^2$).
- Wall 11 and 18, in the climatic conditions of Milan (<110 and $<350 g/m^2$, respectively), Hamburg (<200 and $<2,000 g/m^2$), Paris and Brussels (<35 and $<720 g/m^2$).
- Wall 14 and 16, in the climatic conditions of Milan (<20 and $<4 g/m^2$, respectively).

Table 11 Climatic conditions considered in the calculations

Climatic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rome	t_e 8.3	9.0	10.6	13.3	17.6	21.2	24.2	24.4	21.5	17.0	12.8	9.4
	P_{ve} 833.0	932.7	1042.1	1167.5	1523.9	1915.8	2354.7	2263.8	1962.0	1500.3	1153.5	953.3
Milan	t_e 0.3	2.2	7.5	10.9	16.3	19.7	23.1	22.2	17.6	12.5	6.5	2.2
	P_{ve} 556.8	479.4	698.1	885.2	1285.3	1857.4	1820.5	1817.2	1609.6	1300.7	803.6	523.3
Paris	t_e 3.9	4.2	7.0	10.0	14.3	16.8	19.4	19.7	15.7	11.3	6.4	4.5
	P_{ve} 735.4	558.7	754.7	891.2	1081.4	1486.4	1469.5	1555.8	1387.2	1090.8	859.3	754.3
Madrid	t_e 5.6	6.9	10.0	11.7	16.9	20.6	25.5	24.7	20.1	14.2	9.4	5.9
	P_{ve} 656.5	690.5	744.7	762.5	1151.7	1257.8	1293.8	1407.5	1339.6	1133.4	884.9	773.6
Brussels	t_e 3.1	3.2	6.4	8.9	12.9	15.6	18.4	17.4	14.5	10.9	6.6	4.9
	P_{ve} 644.6	663.8	804.8	868.6	1141.3	1320.4	1640.9	1492.9	1333.7	1047.6	817.6	754.7
Hamburg	t_e 2.0	0.2	4.4	6.9	12.8	15.8	16.9	17.4	13.5	9.8	5.2	2.6
	P_{ve} 630.9	506.3	682.6	737.9	1042.3	1328.1	1393.2	1511.5	1255.4	988.0	726.8	658.1

Table 12 Vapour condensation upper limits for some building materials

Thickness	ρ (kg/m ³)	L (cm) = λ [W/(mK)]	1	2	3	4	5	6	7	8	9	10	11	12
			Q_{amm} (g/m ²)											
Brick			500	500	500	500	500	500	500	500	500	500	500	500
Concrete			500	500	500	500	500	500	500	500	500	500	500	500
Timber	100	0.040	30	60	90	120	150	180	210	240	270	300	330	360
Plaster and mortar	1,400	0.700	420	500	500	500	500	500	500	500	500	500	500	500
Organic fibre														
water-resistant adhesive	100	0.040	20	40	60	80	100	120	140	160	180	200	220	240
not water-resistant adhesive	100	0.040	5	10	15	20	25	30	35	40	45	50	55	60
Mineral fibre	40	0.036	77	153	230	307	383	460	500	500	500	500	500	500
Cellular plastic materials	35	0.033	61	122	184	245	306	367	428	489	500	500	500	500

8.2 External Insulation

The results of the assessment of condensation in the case of external insulation show that sometime condensation may occur before the external plaster layer with moderate quantities.

Walls 1–2, 4–11 and 13: no condensation occurs for any climatic conditions.

Wall 3: 1 cm PY produces condensation in the climatic conditions of Milan ($<30 \text{ g/m}^2$) and Hamburg ($<15 \text{ g/m}^2$).

Wall 12 presents condensation in the climatic conditions of Milan, for MW and WF (thickness $>2 \text{ cm}$), and of Hamburg for MW ($>5 \text{ cm}$). In the same climatic conditions, 1 cm PY produces, respectively, <35 and $<15 \text{ g/m}^2$ of condensation in the annual cycle. In any case, the amount of condensation is moderate and lower than the maximum values for the materials involved.

Wall 14, affected by interstitial condensation in the existing conditions and climate of Milan, becomes free of condensation for the same climate, if MW or WF is used. For PY, the amount of assessed condensation reduces gradually to zero, but it occurs for 1–2 cm.

Walls 15, 16 and 17 present condensation for MW (for thickness >4 , >5 and $>4 \text{ cm}$, respectively), for WF (>7 , >8 , $>5 \text{ cm}$) and for PY (1 cm only for 15 and 16) in the climatic conditions of Milan. Wall 15 presents condensation also for Hamburg only for 1 cm thickness PY ($<20 \text{ g/m}^2$). In any case, the amount of condensation is small and lower than the maximum values for the materials involved.

Wall 18: the problem of condensation, found for Paris and Brussels in the existing conditions, disappears with any insulating material and thickness, while for Milan remains also with 1 cm of MW, WF and PY. For the climatic conditions of Hamburg, condensation occurs only for 1 cm PY.

8.3 Internal Insulation

Generally, significant problems of condensation emerge for internal insulation, even if sometimes it is an easier refurbishment solution, mostly in the case of articulated, painted, decorated façades. The calculation results are summarized in Table 13: for each wall (01–18) and the three insulating materials, the thickness that corresponds to the absence of condensation is in brackets, the positive assessment is pointed out as X, on the contrary the number indicates the maximum thickness that allows a positive assessment.

Table 13 Maximum thickness (cm) of insulating layer that satisfies the two criteria for interstitial condensation (acceptable maximum condensate quantity and complete evaporation)-Internal insulation

	Rome	Milan	Paris	Madrid	Brussels	Hamburg
01	MW WF PY X	1(1) 1(1) X	2(1) 2(2) X	7(3) 4(3) X	2(2) 2(2) X	1(1) 1(1) X
02	MW WF PY X	2(1) 2(1) X	2(2) 2(2) X	7(3) 5(4) X	2(2) 3(2) X	2(1) 2(2) X
03	MW WF PY X	4(1) 3(2) X	5(3) 4(3) X	X(5) X(6) X	5(3) 5(4) X	3(2) 3(3) X
04	MW ^a WF ^a PY ^a X	0(0) 0(0) X(0)	0(0) 0(0) X(0)	2(1) 1(1) X(1)	0(0) 1(0) X(0)	0(0) 0(0) 1-2 only(0)
05	MW WF PY X	3(1) 2(2) X	4(3) 3(3) X	10(4) 8(5) X	4(3) 3(3) X	2(2) 3(2) X
06	MW ^a WF ^a PY ^a X	0 0 X(0)	1(0) 1(0) X(0)	2(1) 1(1) X(1)	1(0) 1(0) X(0)	0(0) 0(0) 2 only(0)
07	MW ^a WF ^a PY ^a X	0(0) 0(0) X(0)	1(0) 1(0) X(0)	4(0) 3(0) X(0)	1(0) 1(0) X(0)	1(0) 1(0) X(0)
08	MW WF PY X	1(1) 1(1) X	2(1) 2(2) X	7(3) 4(3) X	2(2) 2(2) X	1(1) 1(1) X
09	MW X(8)	3(0)	3(1)	10(3)	3(2)	1(1)

(continued)

Table 13 (continued)

	Rome	Milan	Paris	Madrid	Brussels	Hamburg
	WF	1(1)	2(1)	7(4)	2(2)	2(1)
	PY	X	X	X	X	X
10	MW	0	1	2(1)	1(1)	1
	WF	0	1	2(2)	1(1)	1
	PY	X	X(1)	X	X(2)	X(3)
11	MW	X(2)	0(0)	X(0)	0(0)	0(0)
	WF	6(3)	0(0)	1(0)	0(0)	0(0)
	PY	X	X(0)	X	X(0)	1 only(0)
12	MW	X(10)	3(1)	X(4)	3(2)	1(1)
	WF	X	2(1)	X(5)	3(2)	1(1)
	PY	X	X	X	X	X
13	MW	X(8)	1(0)	X(2)	1(1)	0(0)
	WF	X(11)	1(0)	8(2)	1(1)	0(0)
	PY	X	X	X	X	X
14	MW ^a	X	8(0)	X(6)	8(1)	6(0)
	WF ^a	X	8(0)	X(8)	8(1)	0(0)
	PY ^a	X	X	X	X	X
15	MW	X(11)	4(2)	X(5)	4(3)	3(2)
	WF	X	4(3)	X(6)	4(4)	3(2)
	PY	X	X	X	X	X
16	MW	X(9)	3(0)	X(4)	3(1)	0(0)
	WF	X	1(0)	X(5)	2(1)	0(0)
	PY	X	X	X	X	X
17	MW	6(3)	1(1)	2(1)	1(1)	0(0)
	WF	6(4)	1(1)	2(2)	1(1)	0(0)
	PY	X	X	X	X	X

(continued)

Table 13 (continued)

	Rome	Milan	Paris	Madrid	Brussels	Hamburg
18	MW 3(2)	0(0)	0(0)	0(0)	0(0)	0(0)
	WF 3(2)	0(0)	0(0)	0(0)	0(0)	0(0)
	PY X	X > 2	X > 2	X(0)	X(0)	X(0)

X maximum limit verified for thickness up to 12 cm (no condensation at all), MW mineral wool, WF wooden fibreboard, PY polystyrene panels
 In brackets, maximum thickness (cm) without any condensation all over the year

only condensation occurs only in the case of one or two thicknesses and not for other ones
^a condensation occurs also on the external face of the existing insulating layer

Table 14 Maximum amount of interstitial condensation (g/m^2), and in brackets, the corresponding air layer thickness (cm)

		Rome	Milan	Paris	Madrid	Brussels	Hamburg
06	Cell	0.0	6.7(7–8)	7.4(7–9)	1.0(7–12)	8.3(8)	12.6(7)
	Foam	0.0	11.3(12–14)	11.2(11–15)	2.2(11–20)	13.7(11–15)	18.5(10–14)
11	Cell	0.0	15.6(3)	7.3(3)	0.0	3.6(3)	27.5(3)
	Foam	0.0	189.3(3)	164.7(3)	34.9(5)	200.2(3)	298.7(3)

8.4 Air Cavity Insulation

In the case of cavity insulation, the risk of condensation is estimated for 3–30 cm air layer thickness and for cellulose or polyurethane foam filling. Through the calculations, 12, 13 and 15 walls are free of condensation for all the climatic conditions considered (Table 11), even if 13 wall presents condensation for 3–11 cm cavity thickness with PY foam, in the climatic conditions of Milan. Condensation results in 06 and 11 walls are resumed in Table 14.

8.5 Refurbishment Example: How to Evaluate the Intervention

Considering the wall described in Table 15 (taken from Table 9), it is shown how to calculate the appropriate thickness of mineral wool, to reach the value of thermal transmittance $U = 0.30 \text{ W}/(\text{m}^2 \text{ K})$ and the dynamic thermal transmittance $Y_{ic} = 0.12 \text{ W}/(\text{m}^2 \text{ K})$. Interstitial condensation assessment is also performed.

Starting from the thermal properties of the analysed wall, the minimum thickness of insulation which allows to reach the imposed transmittance values is determined through the diagrams in Fig. 8a and b.

To reach the U -value of $0.30 \text{ W}/(\text{m}^2 \text{ K})$, 7 cm insulation thickness is necessary both for the internal and the external insulation layer.

For the dynamic thermal transmittance, 4 cm thickness has to be applied for the external layer and 5.5–6 cm is needed if the intervention is on the internal layer.

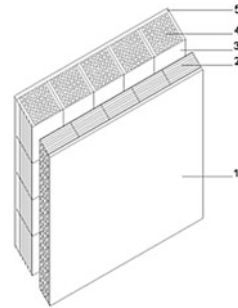
This last information is useful to define the optimal position of the insulation layer (internal or external), even if in this case the most strict condition is determined by the thermal transmittance (Table 16).

Moreover, an intervention of air layer insulation is also evaluated (Fig. 9). If the air cavity thickness is greater than 10 cm, the target U -value is reached both with cellulose or polyurethane foam filling. The same result is obtained for the dynamic thermal transmittance limit.

Referring to the climatic conditions in Table 11, the application of 7 cm mineral wool insulating layer causes interstitial condensation. For the external insulation, it occurs in the climatic conditions of Milan and of Hamburg. In any

Table 15 Thermal properties of the wall

12 HB—Hollow brick masonry (1)						
Layer	L (cm)	ρ (kg/m^3)	λ (W/m K)	R ($m^2 K/W$)		
1 Internal plaster	2	1,400	0.700	0.028		
2 Hollow bricks	8	800	—	0.200 ^a		
3 Air layer	2.5/30	1.2	—	0.180 ^b		
4 Hollow bricks	12	800	—	0.310 ^a		
5 External plaster	2	1800	0.900	0.022		
U [$W/(m^2 K)$]	M_s (kg/m^2)	κ_i [$kJ/(m^2 K)$]	Y_{ie} [$W/(m^2 K)$]	S (h)	f_a (-)	
1.098	224	57.9	0.594	7.268	0.541	



^a Equivalent thermal resistance for hollow bricks

^b Thermal resistance for unventilated air layer EN ISO 6946

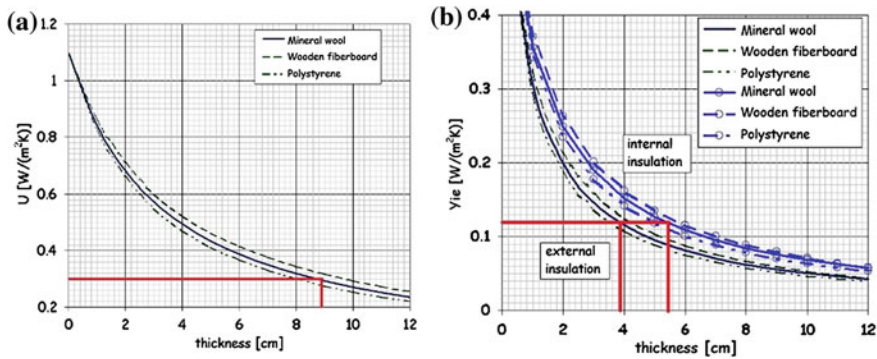


Fig. 8 a Thermal transmittance U . b Dynamic transmittance Y_{ie} according to the insulation thickness (internal and external insulation layer)

Table 16 Insulation thickness (external/internal)

Defined value	External insulation (cm)	Internal insulation (cm)
$U = 0.30$ W/(m ² K)	7	7
$Y_{ie} = 0.12$ W/(m ² K)	4	6

case, the amount of condensation is moderate and lower than the maximum values for the materials involved. In case of internal insulation, the climatic conditions of Rome do not cause condensation at all; in Madrid, condensation occurs, but it satisfies the two criteria for interstitial condensation (acceptable maximum

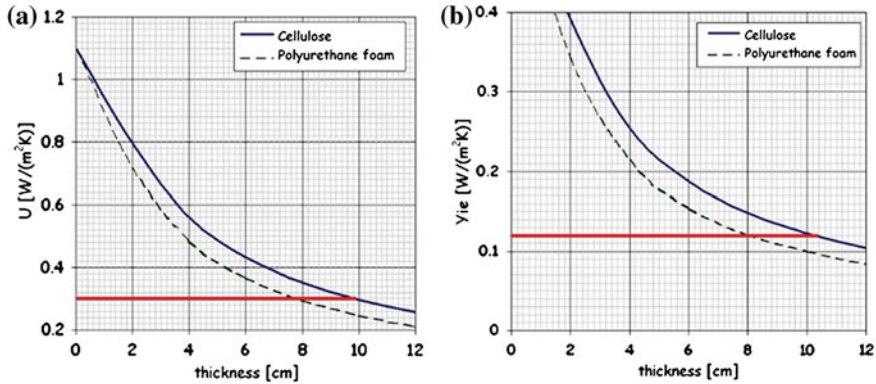


Fig. 9 a Thermal transmittance U . b Dynamic transmittance Y_{ie} according to the insulation thickness (air layer)

condensate quantity and complete evaporation). In the other climatic conditions (Milan, Paris, Brussels, and Hamburg), the wall is not verified.

The calculations show that the wall is free of condensation for all the climatic conditions considered, if the air cavity is filled with cellulose or polyurethane foam.

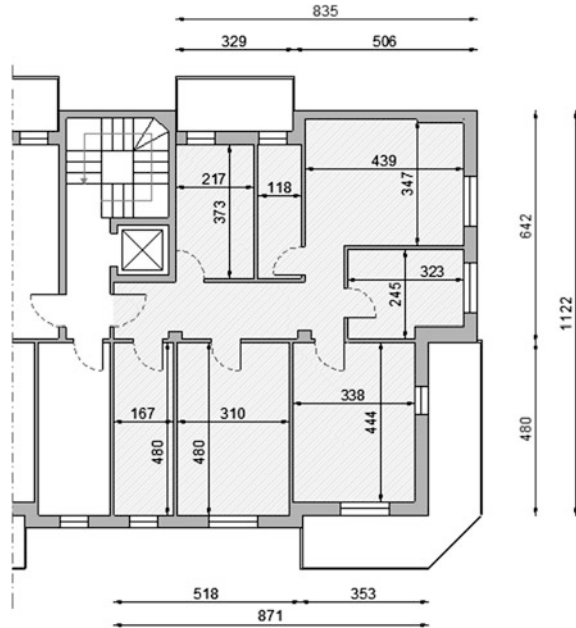
9 Case Study: Evaluation of the Envelope Incidence in Terms of Energy Performance

In order to estimate the importance of the envelope in building refurbishment, a set of simulations is carried out considering a case study. In particular, one flat of a typical construction built in the 1970s is adopted (Fig. 10).

The case study is a single dwelling in an intermediate level (adiabatic floor and ceiling). The main geometrical features are reported in Table 17.

The single glass windows have a wooden frame and a thermal transmittance of 3.44 W/(m² K). In order to investigate the different hygrothermal behaviours of some representative wall typologies described in Sect. 6, three opaque envelope hypotheses were defined according to the age of the analysed construction, as reported in Table 18.

The energy performance of the base case (without thermal insulation) was assessed according to the quasi-steady-state method presented in Sect. 6, referring to three different climatic conditions (Hamburg, Madrid, Milan).

Fig. 10 Case study—general plan**Table 17** Building features

Internal floor area (m ²)	61.49
Overall conditioned volume (m ³)	260.12
Envelope surface/conditioned volume ratio (m ⁻¹)	0.46
Opaque envelope (m ²)	64.60
Transparent/opaque envelope ratio	0.21

Table 18 Case study—wall types and corresponding envelope winter energy needs

Wall type	U [W/(m ² K)]	Y_{ic} [W/(m ² K)]	$EP_{H,env}$ [kWh/(m ² year)]		
			Hamburg	Madrid	Milan
10	1.16	0.656	185.58	97.74	157.47
12	1.098	0.594	152.53	76.49	127.88
17	1.626	0.599	200.16	107.14	170.52

9.1 Refurbishment Interventions

According to each building typology, a set of envelope renewal interventions is defined in order to evaluate the improvement of the energy performance. In particular, the four insulation materials reported in Table 19 are adopted, considering three different thicknesses (4–8–12 cm).

Table 19 Hygrothermal properties of the applied insulations

Material	[W/(m K)]	[kg/(m s Pa)]	ρ (kg/m ³)
Mineral wall	0.036	193×10^{-12}	40
Wooden fibreboard	0.040	97×10^{-12}	110
Polystyrene	0.033	1.3×10^{-12}	35
High-performance polyurethane	0.027	10.6×10^{-12}	35

Table 20 Percentage of improvement with the insulated walls

L (cm)		Mineral wool			Wooden fibreboard			Polystyrene			Polyurethane		
		4	8	12	4	8	12	4	8	12	4	8	12
10	Hamburg	35.9	43.7	47.1	34.5	42.7	46.3	37.0	44.5	47.8	41.2	47.5	50.0
	Madrid	43.5	52.8	56.8	41.9	51.6	55.9	44.8	53.7	57.5	49.5	56.8	59.8
	Milan	37.8	46.0	49.6	36.4	45.0	48.8	39.0	46.9	50.3	43.4	50.0	52.6
12	Hamburg	25.5	32.9	36.4	24.3	31.9	35.6	26.5	33.7	37.1	30.4	36.7	39.5
	Madrid	32.2	41.4	45.7	30.7	40.1	44.7	33.5	42.4	46.6	38.4	46.1	49.5
	Milan	27.1	35.0	38.8	25.9	33.9	37.9	28.2	35.9	39.5	32.4	39.1	42.0
17	Hamburg	39.7	47.5	50.8	38.3	46.5	50.0	40.8	48.2	51.4	45.0	51.1	53.5
	Madrid	47.5	56.6	60.4	45.4	55.0	59.1	48.8	57.5	61.1	53.7	60.8	63.5
	Milan	41.7	49.9	53.3	40.1	48.7	52.4	42.9	50.7	54.0	47.3	53.6	56.2

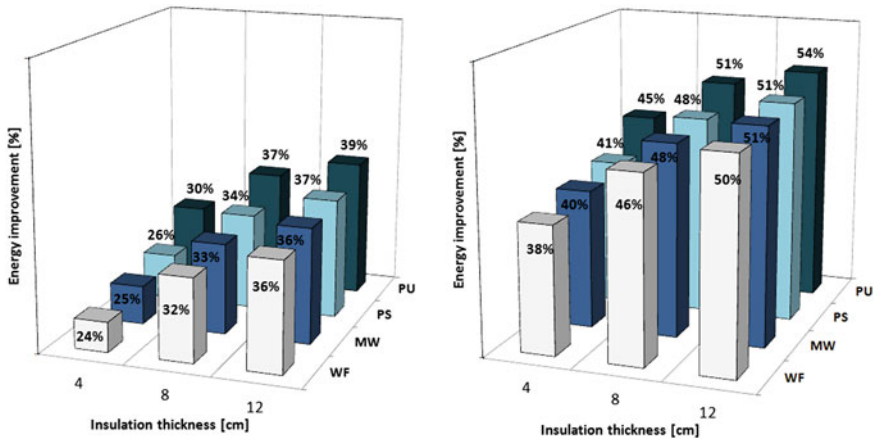


Fig. 11 Results for 12 and 17 walls (Hamburg). WF = wooden fibreboard. MW = mineral wool. PS = Polystyrene. PU = Polyurethane

In Table 20, the comparison of the improvement percentage in terms of envelope energy performance is presented, according to the kind of insulation and its thickness *L*, the climatic conditions, and the wall type that is investigated.

In general, it is possible to reach an average reduction, which accounts for 30–40 %, in comparison with the initial energy needs for the envelope, even with

4 cm of insulation. These values increase for the high-performance polyurethane, as it is expected, since it has a lower value of thermal conductivity.

It is apparent that for the wall 12, which presents the lowest value of thermal transmittance, the effect of the energy conservation measures is less significant than for 10 and 17 walls.

In particular, in Fig. 11, the percentage values for the wall types 12 and 17 are shown for the Hamburg climatic conditions. The differences related to the insulation types are negligible, except for the high-performance polyurethane, which is more effective than other materials. The main differences between the energy improvements are mainly related to the initial high thermal transmittance.

In fact, the energy refurbishment of low-performance buildings is more effective than in other cases. On the other hand, the less are the initial energy needs of the building, the more difficult is increasing the energy saving.

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