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# Energy Improvement in the Building Sector: An Economic Analysis Relating to the Most Common Italian Masonry

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**Abstracts.** The construction sector is a major contributor to total energy consumption, therefore, it is crucial to adopt energy efficiency strategies capable of reducing energy impact in buildings. Among these strategies, exterior wall insulation is one of the most cost-effective options to achieve energy savings for both newly constructed and renovated buildings. In this paper, based on an economic analysis, we aim to determine the economically optimal thickness of insulation material to be used for retrofit interventions of masonry structures. The study analyzes 10 different insulating materials and 5 masonry structures widespread in Italy. The results show that each masonry structure requires a careful evaluation of the thickness of the insulating material to be applied in retrofit operations. Moreover, varying the type of insulating material used, even if applied to the same wall structure, there are different levels of thickness to be applied in order to optimize the performance of the structure.

## Introduction

According to recent studies, buildings consume 40% of total energy, specifically 80% of energy from fossil fuels is used for heating, cooling and lighting in commercial and residential buildings [1]. In addition, energy production from non-renewable sources has a significant weight in the emission of carbon dioxide and other harmful gases that negatively impact human health, environmental pollution, and climate change [2]. For these reasons, it becomes increasingly essential to adopt energy efficiency strategies in the construction sector. According to Zhu et al. [3], energy efficiency indicates a set of technologies or approaches used to produce the same output using less energy. International Energy Agency (IEA) also gave a definition to the construct "energy efficiency" and defined it as "away of managing and restraining the growth in energy consumption".

Since the link between energy use in buildings and total energy use is well known, more and more scholars are pushing for the use of renewable energy resources. In addition, there is a growing trend towards sustainable construction and retrofitting of existing buildings. The energy efficiency of existing buildings is a topic of particular importance since it is predicted that 60% of the current building stock will still be in use in 2050 [4]. In addition, energy efficiency retrofits in buildings lead to improved health and well-being of the occupants themselves [5].

Proper building envelope design can contribute to energy savings: exterior wall insulation is one of the most cost-effective options for achieving energy savings in buildings and reducing greenhouse gas emissions for both new and retrofitted walls [6]. However, while building insulation helps reduce space heating and cooling costs, a retrofit involves an initial outlay. For this reason, it is necessary to optimize the insulation thickness, i.e., to identify an optimal insulation thickness that will minimize total costs. Clearly, many variables are involved in the definition of the optimal thickness such as: type of wall, its exposure, climatic conditions, energy sources [7]. In addition, the choice of insulation material also has consequences on the optimal thickness. It is necessary to identify an insulator that has a low cost but, at the same time, a high thermal resistance. The thermal resistance of a material can be improved by increasing its thickness which will lead to an increase in the cost of the material. For these reasons, identifying the insulation thickness that will increase the thermal performance of the building and minimize total costs is a significant step that can have both economic, building performance, and environmental consequences.

This issue is analyzed in the literature. For example, the optimal insulation thickness applied in 16 Turkish cities varies from 2 cm to 17 cm [8]. The thickness variation depended on the extreme differences in climatic conditions. In fact, it is confirmed that the optimal insulation thickness varies for each region analyzed demonstrating how energy efficiency strategies must be weighted according to the specific conditions of the site [9]. In this regard, some authors analyze the effects of building insulation on annual heating and cooling loads in Palestine considering 2 different insulation materials [10]. A multidisciplinary approach compares the optimal thickness calculated both through transmittance values of historical walls measured in situ and those provided in the literature [11]. In addition, the optimal envelope insulation considering both exterior walls and roof is evaluated in four Turkish cities [12] and the optimal thickness is influenced by wall orientation and surface colour [13].

It is also interesting to see how optimizing insulation can help reduce $CO_2$ and $SO_2$ emissions. The literature provides some studies for this aspect as well. Insulation led to the reduction of about 42% of $CO_2$ and $SO_2$ emissions [14] and $CO_2$ emissions were reduced by 50% following optimal insulation and other energy saving measures [15]. Other authors point out that compared to a wall without insulation or air gaps, an emission reduction of 60% can be achieved [16].

This study aims to determine the economically optimal thickness of 10 insulating materials used for retrofit interventions of 5 typical masonry structures in Italy through the use of an economic model. This model is the right tool to determine the economically optimal thickness of the insulation material because if on one hand the insulation of buildings helps to reduce heat transmission through the envelope and thus improve energy savings, on the other hand it involves an additional cost of installing the insulation.

## Methodology

This section aims to illustrate the methodology used to calculate the economically optimal thickness of the insulating material used for retrofit interventions of masonry structures through thermal insulation. In detail, this study uses an economic model to identify the optimal solution of the energy retrofit intervention. This economic tool allows estimating part of the total cost of a product [17]. For the retrofit of masonry structures through thermal insulation, the following cost items were considered: investment cost, energy costs for heating and cooling. Operating costs, maintenance costs, and salvage value are excluded from the analysis [11].

The use of Present Worth Factor (PWF) can be a useful approach for estimating cost of heating and cooling over the life of the insulation material because it is often used to estimate the current worth of a sum of money that is to be received at some future date

The PWF value depends on the interest rate ($i$), the inflation rate ($f$) and the duration of the insulation material (N). and it can be estimated using the following formula:

$$PWF = \frac{(1+r)^N - 1}{r \cdot (1+r)^N} \tag{1}$$

$$r = \frac{i-f}{1+f} \tag{2}$$

with:

$i$: interest rate [%]

$f$: inflation rate [%]
N: insulation material lifetime [years].
Therefore, the total cost of the intervention ($C_t$ ) in €/m$^2$ is given by the following formula:

$$C_t = C_h + C_c + C_{ins} \tag{3}$$

In particular, $C_{ins}$ represents the cost of the insulating material and is calculated according to the unit cost of the material ($C_m$) expressed in €/m3 and its thickness ($x$) in meters:

$$C_{ins} = C_m \cdot x \tag{4}$$

Instead, $C_h$ and $C_c$ represent respectively the heating cost and the cooling cost in €/m$^2$ and have been calculated with the following formulas:

$$C_h = \frac{86400 \cdot HDD \cdot C_f \cdot PWF}{\left(R_{tw} + {}^{x}/_{\lambda}\right) \cdot H_u \cdot \eta_h} \tag{5}$$

Where:
$C_h$total heating cost following the intervention [€/m$^2$].
86400: conversion factor (1day = 86400s)
$HDD$: heating degree-days [°C-days].
$C_f$: cost of natural gas [€/kg].
$PWF$: Present Worth Factor
$R_{tw}$: total thermal resistance of the wall in the absence of the intervention [(m$^2$K)/W].
$x$: insulation thickness [m]
λ: thermal conductivity of the insulation [W/(m-K)].
$\frac{x}{\lambda}$: thermal resistance of the wall following the intervention [(m$^2$K)/W].
$H_u$: lower heating values of natural gas [J/kg].
$\eta_h$: efficiency of the heating systems

$$C_c = \frac{86400 \cdot CDD \cdot PWF \cdot C_e \cdot 2.778 \cdot 10^{-7}}{\left(R_{tw} + {}^{x}/_{\lambda}\right) \cdot COP} \tag{6}$$

With:
$C_c$: total cooling cost following the intervention [€/m$^2$].
86400: conversion factor (1day = 86400s)
$CDD$: cooling degree-days [°C-days].
$C_e$: cost of electricity [€/kWh].
$PWF$: Present Worth Factor
$R_{tw}$: total thermal resistance of the wall in the absence of the intervention [(m$^2$K)/W].
$x$ :insulation thickness [m]
λ: thermal conductivity of the insulation [W/(m-K)].
$\frac{x}{\lambda}$: thermal resistance of the wall following the intervention [(m$^2$K)/W].
$COP$: performance of cooling system
$2.778 \cdot 10^{-7}$: conversion factor (1Joule = $2.778 \cdot 10^{-7}$kWh]

Finally, the total cost by explicating $C_h$, $C_c$ and $C_{ins}$ is given by the following formula

$$C_t = \frac{86400 \cdot PWF}{\left(R_{tw} + {}^{x}/_{\lambda}\right)} \cdot \left(\frac{HDD \cdot C_f}{H_u \cdot \eta_h} + \frac{CDD \cdot C_e \cdot 2.778 \cdot 10^{-7}}{COP}\right) + C_m \cdot x \tag{7}$$

To calculate the thickness of the insulating material $x$ to minimize the total costs is necessary. Specifically, $x_{opt}$ is obtained by setting at zero the derivative of the $C_t$ function with respect to the thickness of the insulating material x:

$$\frac{\partial C_t}{\partial x} = 0 \tag{8}$$

$$\frac{\partial}{\partial x}\left(\frac{86400 \cdot PWF}{\left(R_{tw} + {}^{x}/_{\lambda}\right)} \cdot \left(\frac{HDD \cdot C_f}{H_u \cdot \eta_h} + \frac{CDD \cdot C_e \cdot 2.778 \cdot 10^{-7}}{COP}\right) + C_m \cdot x\right) = 0 \tag{9}$$

From equation 7 we derive the function capable of calculating the optimal thickness of the insulating material $x_{opt}$:

$$x_{opt} = \left[\frac{PWF \cdot 86400 \cdot \lambda}{C_m} \cdot \left(\frac{CDD \cdot C_e \cdot 2.778 \cdot 10^{-7}}{COP} + \frac{HDD \cdot C_f}{H_u \cdot \eta_h}\right)\right]^{1/2} - \lambda \cdot R_{tw} \tag{10}$$

**Multiple case studies**

This paper analyzes the economically optimal thickness of 10 insulating materials used to perform retrofit interventions of 5 masonry structures present in Italy. In detail, the economically optimal thickness of 10 insulating materials applied to 5 masonry structures defined by standard [18].

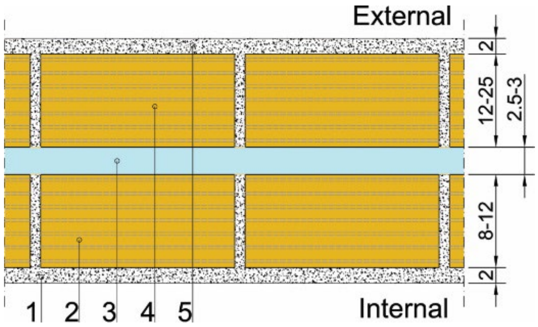
The following sections illustrate the characteristics of the different case studies for which the methodology described in Section 2.0 has been applied. In particular, section "Wall configuration" defines the characteristics of the masonry structures subject to the retrofit intervention. Section "Insulation materials" presents the insulating materials used in the retrofit intervention and, finally, "Imput data" section summarizes the parameters used to carry out the methodology.

**Wall configurations.** This section discusses the characteristics of the masonry structures undergoing retrofit. As said, the masonry structures examined were extrapolated from norm [18]. Specifically, the types of structures analyzed are as follows:

- MLP01 - Solid brick masonry;
- MCV01 - Hollow core masonry in perforated brick;
- MCO01 - Brick and stone masonry;
- MCO02 - Sack masonry with weakly bonded filler
- MCO03 - Masonry made of perforated concrete blocks.

The characteristics and properties of the wall structures MCV01, MLP01, MCO01, MCO02, and MCO03 are shown in Figures 1, 2, 3, 4 and 5, respectively.

The selection of masonry structures was carried out considering the structures most geographically spread in the Italian territory on the basis of the information transposed by the standard [18].

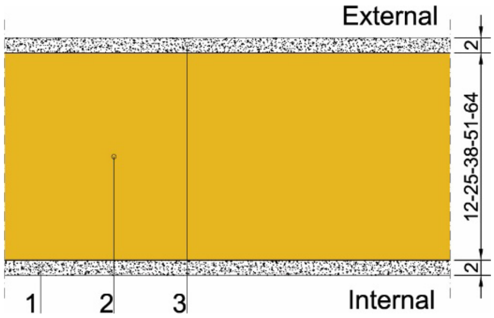



| *Description (thicknesses in cm)* | *Transmittance [W/(m² K)]* |
|---|---|
| Type 1: 2 - 8 - 2.5/30 - 25 - 2 | 0.67 |
| Type2: 2 - 12 - 2.5/30 -25 - 2 | 0.62 |
| Type 3: 2 - 8 - 2.5/30 - 12 - 2 | 1.10 |
| Type 4: 2 - 12 - 2.5/30 - 12 - 2 | 0.98 |

| *Layer* | **Thickness [cm]** | **Conductivity -[W/m K]** | **Resistance [$m^2K/W$]** |
|---|---|---|---|
| ***1*** *Interior plaster* | 2 | 0.700 | - |
| ***2*** *Hollow bricks* | 8 | - | 0.200 [a)] |
| | 12 | | 0.310 [a)] |
| ***3*** *Air gap* | 2.5/30 | - | 0.180 [b)] |
| ***4*** *Hollow bricks* | 12 | - | 0.310 [a)] |
| | 25 | | 0.890 [a)] |
| ***5*** *External plaster* | 2 | 0.900 | - |

*a) Thermal resistance obtained according to the UNI 10355 standard*
*b) Thermal resistance obtained according to the UNI EN ISO 6946 standard*

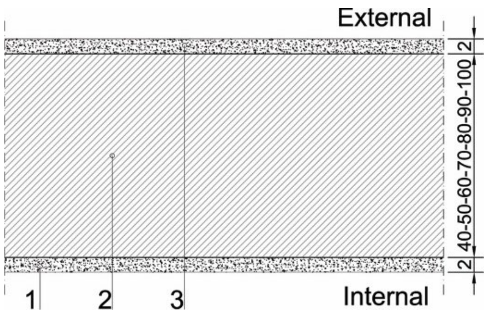
Figure 1- Properties and characteristics of MCV01




| *Description (thicknesses in cm)* | *Transmittance [W/(m² K)]* |
|---|---|
| Type 1: 2 - 12 - 2 | 2.58 |
| Type2: 2 - 25 - 2 | 1.76 |
| Type 3: 2 - 38 - 2 | 1.34 |
| Type 4: 2 - 51 - 2 | 1.08 |
| Type 5: 2 - 64 - 2 | 0.90 |

| *Layer* | **Thickness [cm]** | **Conductivity - [W/m K]** | **Resistance - [$m^2K/W$]** |
|---|---|---|---|
| ***1*** *Interior plaster* | 2 | 0.700 | - |
| ***2*** *Solid Bricks* | 12-64 | 0.720 | - |
| ***3*** *External plaster* | 2 | 0.900 | - |

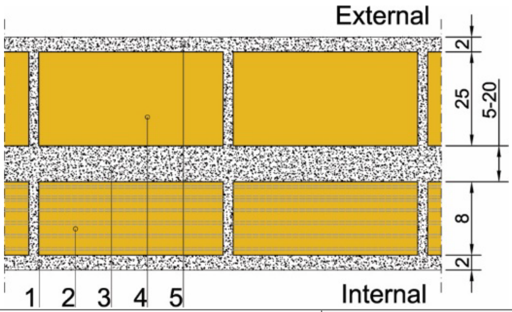
Figure 2- Properties and characteristics of MLP01




| *Description (thicknesses in cm)* | *Transmittance [W/(m² K)]* |
|---|---|
| Type 1: 2 - 40 - 2 | 1.50 |
| Type2: 2 - 50 - 2 | 1.29 |
| Type 3: 2 - 60 - 2 | 1.18 |
| Type 4: 2 - 70 - 2 | 1.00 |
| Type 5: 2 - 80 - 2 | 0.90 |
| Type 6: 2 - 90 - 2 | 0.82 |
| Type 7: 2 - 100 - 2 | 0.75 |

| *Layer* | **Thickness [cm]** | **Conductivity - [W/m K]** | **Resistance - [$m^2K/W$]** |
|---|---|---|---|
| ***1*** *Interior plaster* | 2 | 0.700 | - |
| ***2*** *Bricks and stones* | 40-100 | 0.900 | - |
| ***3*** *External plaster* | 2 | 0.900 | - |

Figure 3 - Properties and characteristics of MCO01

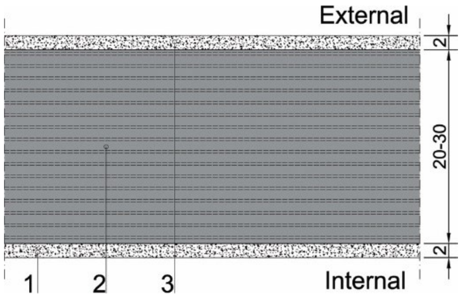



| *Description (thicknesses in cm)* | *Transmittance [W/(m² K)]* |
|---|---|
| Type 1: 2 - 8 - 5 - 25 - 2 | 0.67 |
| Type2: 2 - 8 - 10 - 25 - 2 | 0.62 |
| Type 3: 2 - 8 - 15 - 25 - 2 | 1.10 |
| Type 4: 2 - 8 - 20 - 25 - 2 | 0.98 |

| *Layer* | **Thickness [cm]** | **Conductivity - [W/m K]** | **Resistance - [m²K/W]** |
|---|---|---|---|
| ***1*** *Interior plaster* | 2 | 0.700 | - |
| ***2*** *Hollow bricks* | 8 | - | 0.200 [a)] |
| ***3*** *Weakly bonded filling* | 5-20 | 0.700 | - |
| ***4*** *Solid Bricks* | 25 | 0.720 | - |
| ***5*** *External plaster* | 2 | 0.900 | - |

*a) Thermal resistance obtained according to the UNI 10355 standard*

Figure 4- Properties and characteristics of MCO02




| *Description (thicknesses in cm)* | *Transmittance [W/(m² K)]* |
|---|---|
| Type 1: 2 - 20 - 2 | 1.61 |
| Type2: 2 - 30 - 2 | 1.22 |

| *Layer* | **Thickness [cm]** | **Conductivity - [W/m K]** | **Resistance - [m²K/W]** |
|---|---|---|---|
| ***1*** *Interior plaster* | 2 | 0.700 | - |
| ***2*** *Concrete blocks* | 20-30 | 0.500 | - |
| ***3*** *External plaster* | 2 | 0.900 | - |

Figure 5- Properties and characteristics of MCO03

**Insulation materials.** In order to insulate the masonry types described in the previous paragraph, 10 insulating materials have been examined, which differ in origin, thermal conductivity and cost. In particular, wood fiber (WF), hemp fiber (HF), linen fiber (LF) and Cork (CK) are of vegetable origin. Sheep wool (SW) is of animal origin while rock wool (RW) and fiber glass (FG) are of mineral origin. Finally, expanded polystyrene (EPS), extruded polystyrene (XPS), expanded polyurethane (PUR) are of fossil origin. Among the analyzed materials, PUR has the lowest value of thermal conductivity while CK has the highest value. The thermal conductivity values were extrapolated from standards [19] or, if not available, from data taken from product data sheets.
In addition, each insulation has a specific unit cost ($C_m$) expressed in €/m$^3$ obtained from literature [11]. Among the chosen materials, RW is the cheapest material while LF has the highest cost.

Table 1 summarizes the characteristics of the insulation materials chosen for the study, in particular the origin, the value of λ and $C_m$.

Table 1 - Characteristics of insulation materials

| *Insulation* | *Origin* | *λ [W/(m-K)].* | $C_m$ *[€/m³]* |
|---|---|---|---|
| *WF* | Plant | 0.040 | 194.63 |
| *HF* | Plant | 0.038 | 145.38 |
| *LF* | Plant | 0.040 | 236.38 |
| *CK* | Plant | 0.045 | 200.88 |
| *SW* | Animal | 0.038 | 177.00 |
| *RW* | Mineral | 0.033 | 93.50 |
| *FG* | Mineral | 0.034 | 115.75 |
| *EPS* | Fossil | 0.032 | 158.13 |
| *XPS* | Fossil | 0.036 | 138.13 |
| *PUR* | Fossil | 0.026 | 159.88 |

**Input data.** The parameters used to calculate the economically optimal thickness of the different insulating materials used for retrofit interventions of masonry structures are summarized in the following Table 2.

Table 2 - Input data [11,20].

| Variable | Value |
|---|---|
| $C_f$ | 0.96 €/kg |
| $H_u$ | 47141000 J/kg |
| $\eta_h$ | 0.93 |
| $C_e$ | 0.2006 €/kWh |
| $COP$ | 3.722 |
| CDD | 305.83 °C-days |
| HDD | 1813.91°C-days |
| $i$ | 2.8% |
| $f$ | 1.18% |
| N | 20 years |

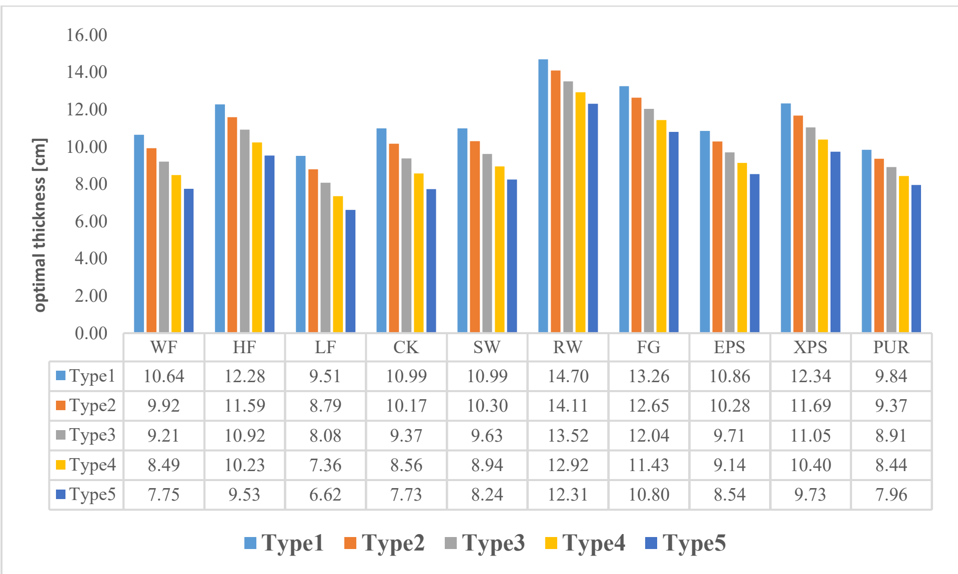
## Results and Discussion

This paragraph illustrates the optimal value of the thickness of the 10 insulating materials to be applied to 5 typical masonry structures present in Italy.

The optimal value of the insulating material allows to minimize both the energy cost for the cooling and heating system and the cost of the insulating material. In fact, the greater the thickness of the insulation to be applied to the wall structure, the better the thermal performance of the building. On the other hand, increasing the thickness of the insulation also increases the cost of the panel itself. In detail, the cost of the insulation increases as its thickness increases, while heating and cooling costs are inversely proportional to the thickness of the insulation. For this reason, it is essential to derive an insulation thickness for which both the energy costs and the one of the insulation are minimal.

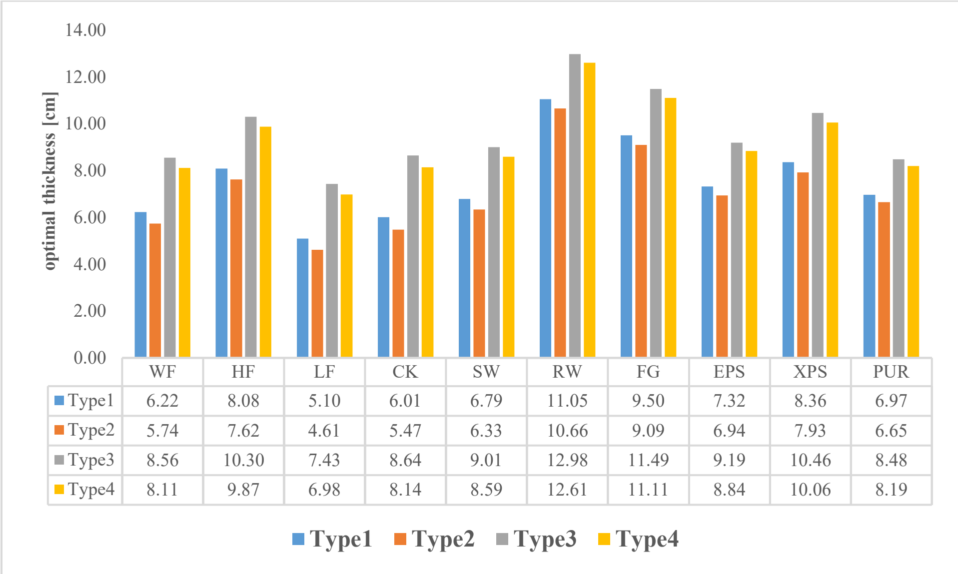
The study conducted leads to identify the values of the economically optimal thickness for the insulating materials under study. In particular Figures 6-10 report respectively the values of the economically optimal thickness of the wall structures MLP01, MCV01, MCO01, MCO02 and MCO03.

As can be seen from Figures 6-10, the value of the optimal thickness of the insulation varies according to the different material used and the different wall structures. The use of LF material allows to balance the investment cost and the operating costs due to heating and cooling, with a smaller thickness than other materials. In contrast, the RW material requires a greater thickness than the use of the other materials. However, this does not affect the choice of insulation materials since multiple factors must be considered such as the type of building in which they will be applied, their environmental impact, their properties.



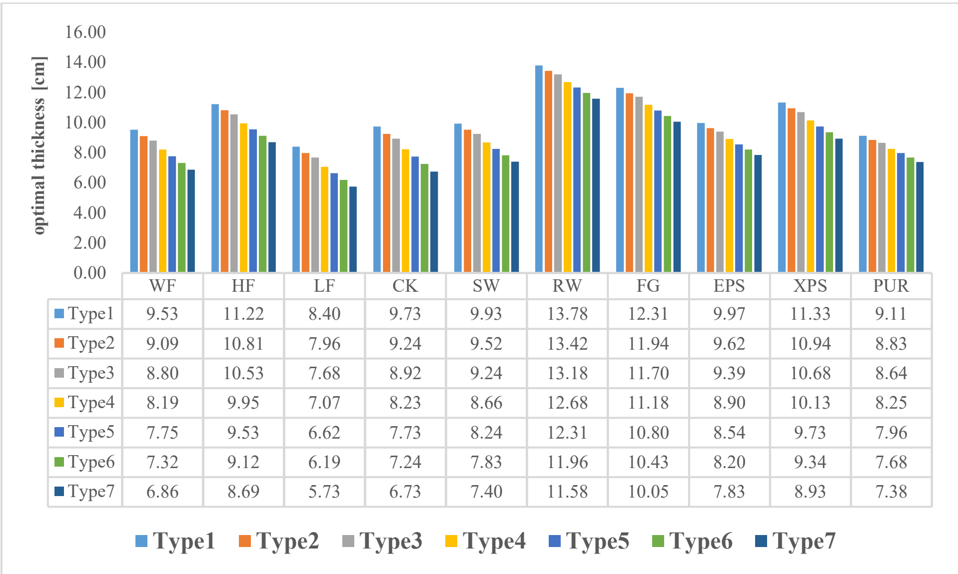

| | WF | HF | LF | CK | SW | RW | FG | EPS | XPS | PUR |
|---|---|---|---|---|---|---|---|---|---|---|
| Type1 | 10.64 | 12.28 | 9.51 | 10.99 | 10.99 | 14.70 | 13.26 | 10.86 | 12.34 | 9.84 |
| Type2 | 9.92 | 11.59 | 8.79 | 10.17 | 10.30 | 14.11 | 12.65 | 10.28 | 11.69 | 9.37 |
| Type3 | 9.21 | 10.92 | 8.08 | 9.37 | 9.63 | 13.52 | 12.04 | 9.71 | 11.05 | 8.91 |
| Type4 | 8.49 | 10.23 | 7.36 | 8.56 | 8.94 | 12.92 | 11.43 | 9.14 | 10.40 | 8.44 |
| Type5 | 7.75 | 9.53 | 6.62 | 7.73 | 8.24 | 12.31 | 10.80 | 8.54 | 9.73 | 7.96 |

Figure 6- Economically optimal thickness $x_{opt}$ in centimeters for MLP01



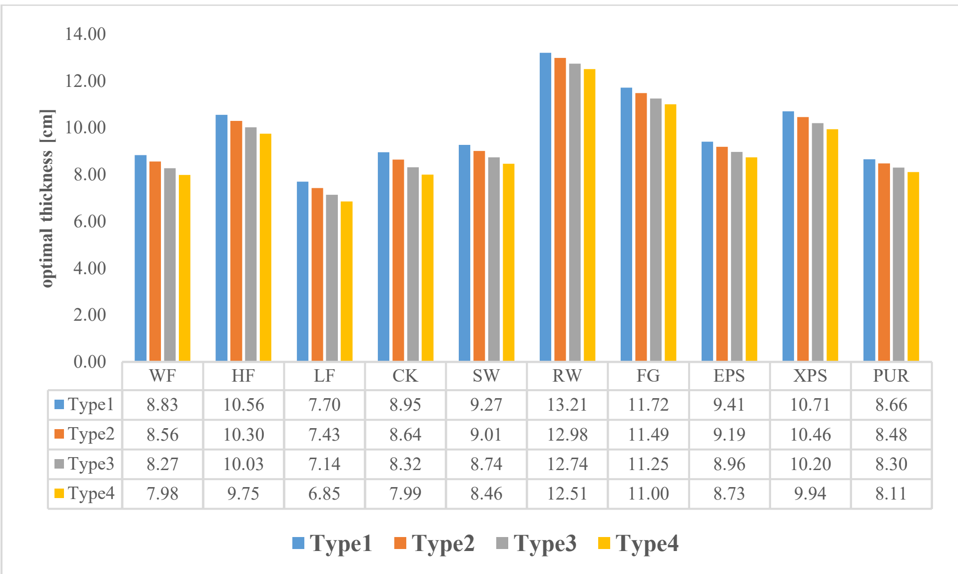

| | WF | HF | LF | CK | SW | RW | FG | EPS | XPS | PUR |
|---|---|---|---|---|---|---|---|---|---|---|
| Type1 | 6.22 | 8.08 | 5.10 | 6.01 | 6.79 | 11.05 | 9.50 | 7.32 | 8.36 | 6.97 |
| Type2 | 5.74 | 7.62 | 4.61 | 5.47 | 6.33 | 10.66 | 9.09 | 6.94 | 7.93 | 6.65 |
| Type3 | 8.56 | 10.30 | 7.43 | 8.64 | 9.01 | 12.98 | 11.49 | 9.19 | 10.46 | 8.48 |
| Type4 | 8.11 | 9.87 | 6.98 | 8.14 | 8.59 | 12.61 | 11.11 | 8.84 | 10.06 | 8.19 |

Figure 7- Economically optimal thickness $x_{opt}$ in centimeters for MCV01




| | WF | HF | LF | CK | SW | RW | FG | EPS | XPS | PUR |
|---|---|---|---|---|---|---|---|---|---|---|
| Type1 | 9.53 | 11.22 | 8.40 | 9.73 | 9.93 | 13.78 | 12.31 | 9.97 | 11.33 | 9.11 |
| Type2 | 9.09 | 10.81 | 7.96 | 9.24 | 9.52 | 13.42 | 11.94 | 9.62 | 10.94 | 8.83 |
| Type3 | 8.80 | 10.53 | 7.68 | 8.92 | 9.24 | 13.18 | 11.70 | 9.39 | 10.68 | 8.64 |
| Type4 | 8.19 | 9.95 | 7.07 | 8.23 | 8.66 | 12.68 | 11.18 | 8.90 | 10.13 | 8.25 |
| Type5 | 7.75 | 9.53 | 6.62 | 7.73 | 8.24 | 12.31 | 10.80 | 8.54 | 9.73 | 7.96 |
| Type6 | 7.32 | 9.12 | 6.19 | 7.24 | 7.83 | 11.96 | 10.43 | 8.20 | 9.34 | 7.68 |
| Type7 | 6.86 | 8.69 | 5.73 | 6.73 | 7.40 | 11.58 | 10.05 | 7.83 | 8.93 | 7.38 |

Figure 8- Economically optimal thickness $x_{opt}$ in centimeters for MCO01




| | WF | HF | LF | CK | SW | RW | FG | EPS | XPS | PUR |
|---|---|---|---|---|---|---|---|---|---|---|
| Type1 | 8.83 | 10.56 | 7.70 | 8.95 | 9.27 | 13.21 | 11.72 | 9.41 | 10.71 | 8.66 |
| Type2 | 8.56 | 10.30 | 7.43 | 8.64 | 9.01 | 12.98 | 11.49 | 9.19 | 10.46 | 8.48 |
| Type3 | 8.27 | 10.03 | 7.14 | 8.32 | 8.74 | 12.74 | 11.25 | 8.96 | 10.20 | 8.30 |
| Type4 | 7.98 | 9.75 | 6.85 | 7.99 | 8.46 | 12.51 | 11.00 | 8.73 | 9.94 | 8.11 |

Figure 9- Economically optimal thickness $x_{opt}$ in centimeters for MCO02

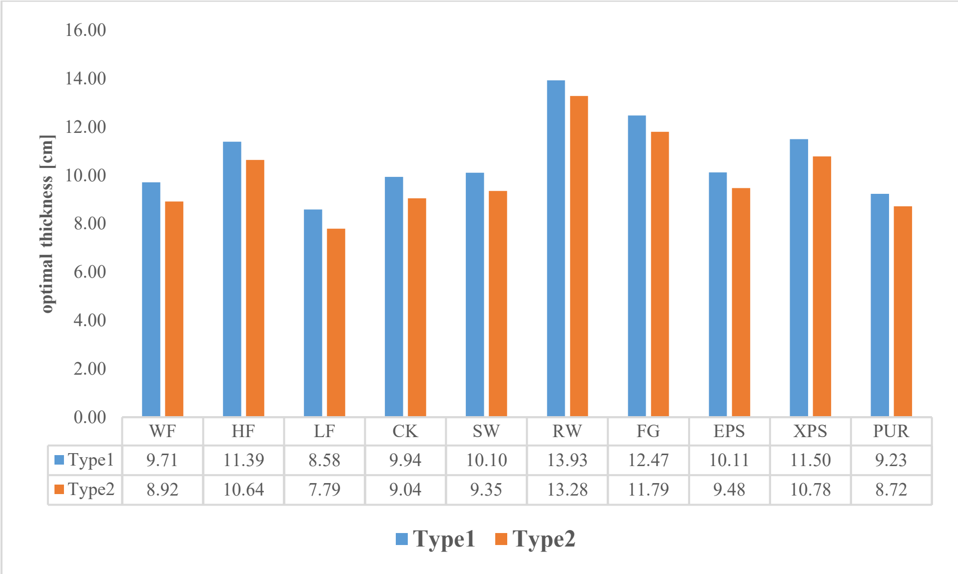



Figure 10- Economically optimal thickness $x_{opt}$ in centimeters for MCO03

However, during the last few years, efforts were made to substitute conventional insulators which had high environmental impact, with materials that are environmentally friendly and guarantee the same thermal performance [21].On the other hand, the value of the optimal thickness is useful to minimize the total costs and must be calculated for each material and for each wall structure subject to retrofit intervention. In fact, the analyzed structures present a specific value of optimal thickness. This means that, in order to undertake retrofit interventions by insulating external walls, it is essential to determine, for each wall structure and for each insulating material used, the value of the thickness of the insulation that allows to minimize the total costs. Many researchers are focused on this field of research. For example, in according to Idchabani et al. [22], it is preferable to choose expanded polystyrene, polyurethane and cork for the thermal insulation of walls in Morocco. Instead Yu et al. [23] have studied different solutions of optimum insulation thicknesses depending on different cities in China and in Cameroon, insulation materials and roof surface colours. A review has also been carried out optimum thickness of the thermal insulation material in a building envelope [24].

The construction sector has a significant impact on the environment, as it is responsible for polluting emissions, significant consumption of energy, water and extraction of raw materials. It is therefore necessary to practice circular practices, but also to promote the use of renewable energy and energy efficiency measures [25,26]. In addition, it is desirable to reduce heat transfer through the building envelope while also providing better thermal comfort [27] and building insulation plays a key role in achieving energy savings. This study provides technical and methodological skills that need to be developed within a broader vision and confirms analyses proposed in other sectors, where it has been highlighted that circular practices must concern effective optimization of resources with minimization of waste [28,29] and the analysis must concern all spheres of sustainability [30,31].

## Conclusions

The building sector is called to a process of innovation trying to follow models of sustainability, which aims to be not only one of the qualifying points of the Next Generation EU but a source of competitive advantage. The insulation of buildings supports energy savings, but its effectiveness is linked to the correct amount of insulating material. Circular models highlight the need to provide a comprehensive response to the problem without leading to a deterioration of ecosystems. The study conducted in this work identifies the economically optimal thickness values for the insulating materials under analysis. Indeed, building insulation helps reduce heat transfer through the envelope and thus improves energy savings, but it also increases the cost of installing insulation. The idea of the new business model is aimed at identifying the best long-term energy performance of the building with low operating costs. Several case studies are proposed because they highlight how the optimal thickness that minimizes the total costs, depends mainly on the material used as well as the different wall structures. In this direction it will be necessary in the future to explore the great potential associated with eco-friendly materials, their economic impact and the role of sustainable certification.

**Appendix**

*The following symbols are used in this paper:*

| | |
|---|---|
| $C_c$ | Total cooling cost following the intervention [€/m2]. |
| $C_e$ | Cost of electricity [€/kWh] |
| $C_f$ | Cost of natural gas [€/kg] |
| $C_h$ | Total heating cost following the intervention [€/m2]. |
| $C_{ins}$ | Cost of insulation [€/m2] |
| $C_m$ | Cost of insulating material [€/m3]. |
| $C_t$ | Total cost following the intervention [€/m2] |
| $CDD$ | Cooling degree-days [°C-days] |
| CK | Cork |
| $COP$ | Performance of cooling system |
| EPS | Expanded polystyrene |
| $f$ | Inflation rate [%]. |
| FG | Fiber glass |
| $H_u$ | Lower heating values of natural gas [J/kg]. |
| $HDD$ | Heating degree-days [°C-days] |
| HF | Hemp fiber |
| $i$ | Interest rate [%] |
| LCCA | Life Cycle Cost Analysis |
| LF | Linen fiber |
| N | Lifetime [years] |
| PUR | Expanded polyurethane |
| PWF | Present Worth Factor |
| $R_{tw}$ | Total thermal resistance of the wall in the absence of the intervention [($^{m2K}$)/W]. |
| RW | Rock wool |
| SW | Sheep wool |
| WF | Wood fiber |
| $x$ | Insulation thickness [m] |
| $x_{opt}$ | Optimum insulation thickness [m] |
| $x/\lambda$ | Thermal resistance of the wall following the intervention [($^{m2K}$)/W]. |
| XPS | Extruded polystyrene |
| $\eta_h$ | Efficiency of the heating systems |
| λ | Thermal conductivity of the insulation [W/(m-K)]. |

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