# Optimizing Insulation Thickness for Energy and Cost Efficiency in Residential Buildings: A Case Study

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*Abstract*— **The growing demand for sustainable living solutions has intensified the need for energy-efficient designs in residential buildings. This paper examines the impact of specific measures of energy efficiency in single-family homes by analyzing the trade-offs between energy performance and cost. A recently constructed house in Croatia, representative of the current real estate market, is used as a case study. The study focuses on the role of insulation thickness in exterior walls and roof, evaluating its effects on reducing heat loss and minimizing heating and cooling demand. In addition, an economic analysis is conducted to identify cost-effective energy efficiency improvements. The findings, with payback periods ranging from 2 to over 100 years, underscore the importance of balancing energy savings with financial feasibility, providing valuable insights to homeowners, contractors, and policymakers involved in sustainable residential construction.**

## I. Introduction

Advancements in building simulation software tools have significantly improved the ability to conduct comprehensive energy assessments even before construction begins. These tools are essential, as they enable early identification and resolution of potential energy inefficiencies through a holistic approach, fostering collaboration between architects and engineers. This integrated decision-making process helps prevent costly renovations or modifications later in the building lifecycle. In 2022, the number of newly completed buildings in Croatia increased significantly by 26.1% compared to the year before [1]. Considering that the building sector is one of the highest energy consumers in Europe [2], this highlights the growing importance of optimizing designs for energy performance. The high energy consumption resulting from inefficient design has economic and environmental repercussions throughout the lifecycle of a building.

Building simulation tools allow the analysis and optimization of various energy parameters, significantly reducing the overall energy footprint of a building. Typically, the first line of defense to reduce energy consumption in buildings is to improve the thermal envelope of the building, primarily through investments in insulation. Numerous simulation studies have examined the influence of such upgrades on building thermal performance. One such study demonstrates that the incorporation of appropriate thermal insulation and glazing can produce energy savings ranging from 20% to 55%, underscoring the critical role these factors play in improving the energy efficiency of the building [3], [4]. In [5], the total energy consumption of the residential building considered was reduced by 47.2% by optimizing the thermal insulation of the walls and roof. The use of new aerogel-based superinsulation materials is thoroughly analyzed in [6]. Although information on energy consumption provides valuable insight into the performance of the building with respect to specific parameters, it is equally crucial to consider cost. Therefore, an economic analysis of potential savings should be performed to determine the optimal values of construction materials.

This paper demonstrates how building simulation tools can be used to optimize the energy performance of buildings in a specific location. A recently built house in Croatia, representative of the current real estate market, was selected for this study. The house is located in the Central Croatia region, which experiences hot summers and cold winters, conditions that create a significant temperature difference between seasons. These temperature fluctuations have a major impact on energy consumption, as buildings require heating in the winter and cooling in the summer. Therefore, it is crucial to choose appropriate materials that help maintain a comfortable indoor temperature throughout the year. To evaluate the energy performance of the house, a detailed simulation model was developed using the Integrated Design and Analysis of Integrated Climate and Energy (IDA-ICE) simulation environment [7]. The research focuses on thermal insulation, assessing the impact of different insulation thicknesses on overall building energy performance through yearly simulations based on regional climate conditions.

The goals of the paper are as follows: *i*) to assess the energy behavior of a typical single-family home in continental climate conditions, *ii*) to evaluate the effect of thermal insulation upgrades, and *iii*) to conduct an economic analysis to identify cost-optimal solutions for insulation improvements in residential buildings. The paper is organized as follows. Section II describes the case study building. Section III details the building simulation model and the simulation parameters used to evaluate its thermal performance. Section IV presents the energy efficiency analysis for various insulation thicknesses of the exterior walls and roof, followed by the economic analysis. Section V concludes the paper.

## II. Case study building description

A single-family low-energy house is considered. It is located in the continental region of Croatia, with a total area of 138.18 $m^2$ and a floor plan as shown in Fig. 1.

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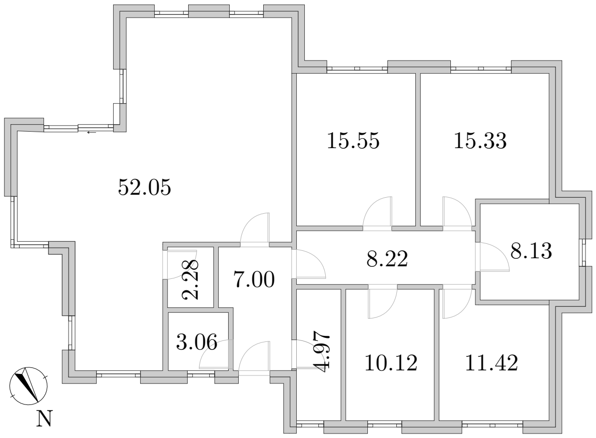



Fig. 1: Floor layout of the considered case study building [8].

The construction details of the building elements are provided in Table I.

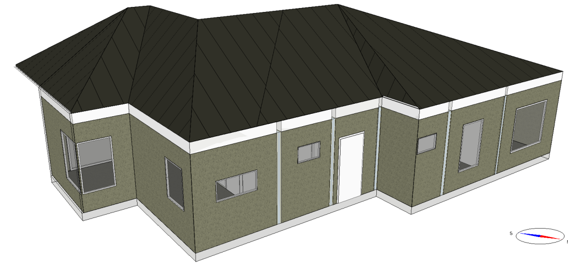
TABLE I: Construction details of the considered case study building.

| | |
|---|---|
| Number of floors | 1 |
| Total floor area | 138.18 $\mathrm{m}^2$ |
| Total ceiling area $A_\mathrm{r}$ | 155.9 $\mathrm{m}^2$ |
| Total exterior wall area $A_\mathrm{w}$ | 141.40 $\mathrm{m}^2$ |
| Exterior wall construction layers | Silicone-silicate plaster with adhesive 0.010 m<br>Rigid facade stone wool 0.16 m<br>Gypsum fiberboard + adhesive 0.0128 m<br>Mineral wool 0.16 m<br>Gypsum fiberboard 0.0125 m<br>Gypsum plasterboard 0.0125 m |
| Roof construction layers | Tile 0.011 m<br>Mineral wool 0.03 mm<br>Gypsum plasterboard 0.0125 mm |
| Glazing specification | 3 pane glazing, clear, 4-14-4-14-4<br>Argon<br>$U_\mathrm{g} = 0.6$ W/m$^2$K |

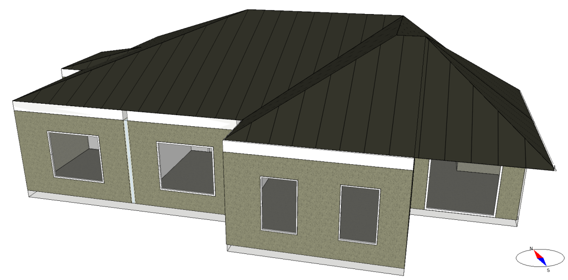
The heat transfer coefficient of the exterior wall is $U_\mathrm{w} = 0.11$ W/(m$^2$K), and that of the roof is $U_\mathrm{r} = 0.31$ W/(m$^2$K). The internal walls are composed of double gypsum boards on both sides, with 0.10 m of mineral wool insulation on the inside. The facade of the building's front is oriented towards the north, with a slight deviation of 30° from the true east-west axis.

## III. Building simulation model

To investigate the effect of different design parameters on energy consumption, the single-family home simulation model considered in the case study was implemented using the professional building simulation software IDA-ICE. Its flexibility allows users to optimize the building design and evaluate multiple scenarios for improved energy efficiency and comfort. The simulation model of the case study building, created in IDA-ICE, is shown in Figure 2.



(a) North facade.



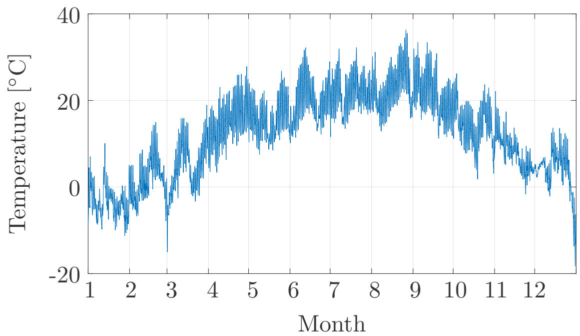
(b) South facade.

Fig. 2: 3D view of the IDA-ICE building simulation model.

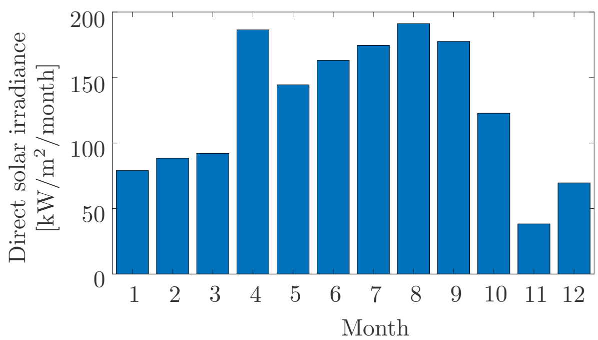
To focus solely on the impact of different building materials on energy consumption, this study assumes that the heating and cooling systems in the house are ideal, with equipment losses omitted. Heating and cooling are available in all rooms except the attic, which is not intended for living. The maximum capacities of ideal heating and cooling units are set at values sufficient to meet the demand under all conditions. The comfort setpoints are in accordance with the ISO 7730 standard [9] for systems with heating and cooling available year round, with a minimum temperature of 20°C and a maximum of 26°C in all rooms. The infiltration value is set to the default value of 0.5 Air Changes per Hour (ACH).

### A. Climate data

The climate is modeled using Typical Meteorological Year (TMY) data, based on weather observations from 2005 to 2023 [10]. TMY data consist of hourly meteorological values for each hour of the year, specific to a given geographical location. The data were selected from hourly measurements taken over a longer period, with monthly data chosen from the year considered most "typical" for each month. For example, January might be from 2007, February from 2012, and so on. The climate data file contains measurements of air temperature, relative humidity, wind speed, diffuse horizontal radiation, and direct normal solar radiation. Figure 3a shows a graph of the temperature throughout the TMY year, while Fig. 3b shows cumulative monthly sums of direct (beam) solar irradiance on a plane normal to the sun's rays throughout the year. The maximum temperature of 36.30°C, was recorded on August 13, while the minimum of -18.30°C occurred on December 9. The peak direct solar irradiance, reaching 1.16 kW/m$^2$, was observed on December 10.




(a) Temperature graph.




(b) Cumulative monthly sums of direct normal solar irradiance.

Fig. 3: TMY meteo data for the considered location.

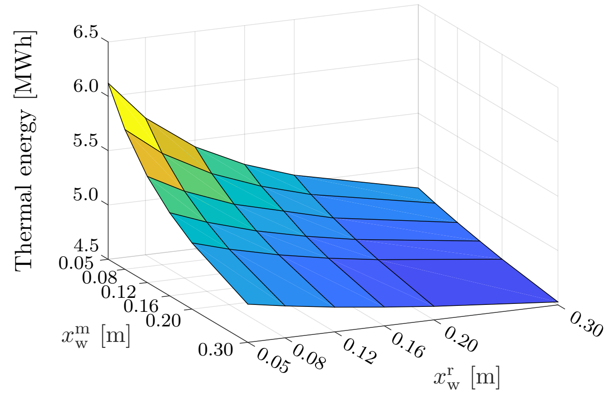
## IV. Energy-efficiency measures

To achieve a balance between construction costs and energy performance, the following insulation thickness parameters are optimized:

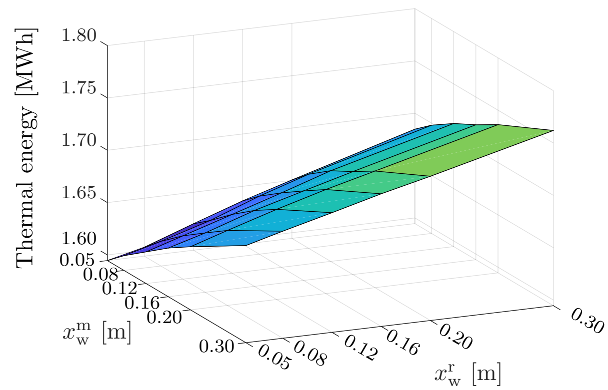
- $x_\mathrm{r}^\mathrm{m}$ - mineral wool insulation thickness in the roof,
- $x_\mathrm{w}^\mathrm{r}$ - rock wool insulation thickness on the outer surface of the exterior wall,
- $x_\mathrm{w}^\mathrm{m}$ - mineral wool insulation thickness on the internal surface of the exterior wall.

The subscripts ’w’ and ’r’ represent wall and roof insulation, respectively, while the superscripts ’m’ and ’r’ refer to mineral wool and rock wool, respectively. Six different insulation thicknesses of $x \in \begin{bmatrix} 0.05 & 0.08 & 0.12 & 0.16 & 0.20 & 0.30 \end{bmatrix}$ m were selected based on commercially available insulation materials thicknesses used in the construction of the house [8]. To gain insight into the relationship between insulation thickness and total energy consumption for heating and cooling, the energy consumption of the building was simulated for a TMY in all possible combinations of insulation thicknesses (a total of $6^3$ = 216 simulation scenarios).

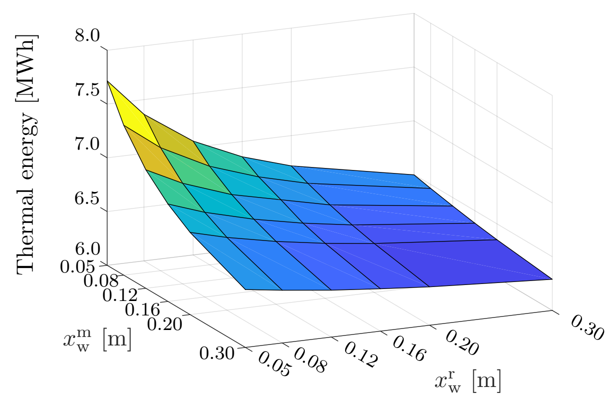
Figure 4 illustrates the relationship between annual thermal energy consumption and the insulation thicknesses of the inner and outer surfaces of the exterior wall, assuming a constant roof insulation thickness of $x_\mathrm{r}^\mathrm{m} = 0.3$ m, as in the case study building. The results indicate that total and heating energy consumption decrease with increasing insulation thickness. However, as shown in Fig. 4b, it is evident that with increasing insulation thickness, the demand for cooling energy also increases. Increased insulation in the building envelope reduces heat loss, but if the building is




(a) Heating thermal energy consumption.




(b) Cooling thermal energy consumption.




(c) Total thermal energy consumption (heating + cooling).

Fig. 4: The relationship between annual thermal energy consumption and the insulation thicknesses of the inner and outer surfaces of the exterior walls, with the roof insulation thickness set to $x_\mathrm{r}^\mathrm{m} = 0.3$ m.

highly insulated, it becomes more difficult for it to shed heat during the day, especially when external temperatures are high. In such cases, the building can retain more heat throughout the day, requiring more cooling energy to maintain a comfortable indoor temperature. Insulation increases a building's thermal inertia, meaning that the building becomes more resistant to temperature changes. This effect can be beneficial during the winter, but may have adverse effects during higher outdoor temperatures. As external temperatures rise, the building's thermal mass may absorb heat, and due to the high insulation, the heat can be "trapped" inside for longer periods. Therefore, while insulation is beneficial for reducing heating energy consumption, careful attention must be paid to balance insulation with other factors, such as passive cooling. Since the cooling demand (Fig. 4b) is much lower than the heating demand (Fig. 4a), its effect has minimal impact on the total energy consumption shown in Fig. 4c.

The energy savings range $S_\mathrm{e}$ quantifies the relative reduction in the total annual energy consumption between the minimum and maximum exterior wall insulation scenarios, for a specific roof insulation thickness. The minimum insulation scenario consists of 0.1 m of total insulation (0.05 m on both the inner and outer surfaces), while the maximum scenario consists of 0.6 m of total insulation (0.3 m on each surface). For the configuration shown in Fig. 4c, with $x_\mathrm{r}^\mathrm{m} = 0.30$ m, the calculated energy savings range is $S_\mathrm{e} = 18.48\%$. The full range of energy savings for various roof insulation thicknesses is presented in Tab. II.

TABLE II: The energy savings range $S_\mathrm{e}$ for different roof insulation thicknesses based on thinnest and thickest exterior wall insulation.

| $x_\mathrm{r}^\mathrm{m}$ | 0.05 | 0.08 | 0.12 | 0.16 | 0.20 | 0.30 |
|---|---|---|---|---|---|---|
| $S_\mathrm{e}$ [%] | 12.92 | 14.69 | 16.10 | 17.02 | 17.62 | 18.48 |

The relationship between total annual thermal energy consumption and roof insulation thickness, with the exterior wall insulation thicknesses set to those of the case-study building, $x_\mathrm{w}^\mathrm{m} = 0.16$ m and $x_\mathrm{w}^\mathrm{r} = 0.16$ m, is shown in Fig. 5.

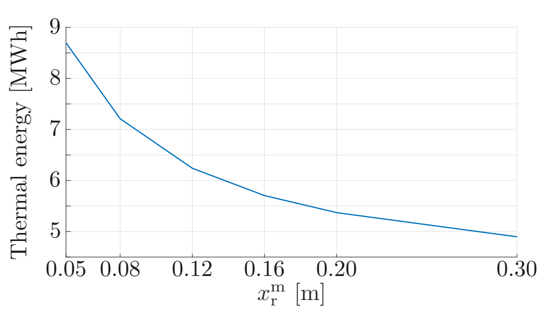



Fig. 5: The relation between total annual thermal energy consumption and roof insulation thickness with exterior wall inner and outer surface insulation thicknesses equal as in the case study building.

Thermal energy consumption decreases as the thickness of the roof insulation increases, with a slight sign of saturation, showing a 9.67% improvement between insulation thicknesses of 0.2 and 0.3 m. The total thermal energy consumption of the considered case study building, for the insulation thicknesses defined in the project (see Tab. I), is 7.23 MWh per year, or 52.36 kWh/m$^2$/year, which is within the expected range of energy consumption for low-energy houses.

Although the simulated results might suggest that the optimal choice is to use the highest possible insulation thickness for both the walls and the roof, economic factors must also be taken into account. The costs associated with increasing insulation thickness, both in terms of material and installation, should be weighed against the potential energy savings. The economic optimum is determined by considering the costs of the insulation materials. The optimal configuration aims to balance the trade-off between energy savings and installation costs, resulting in a solution that offers the best value for money.

The price of different insulation thicknesses for both mineral wool and rock wool is assumed to increase linearly with the thickness of the insulation:

$$\begin{aligned} c^\mathrm{r} &= 115.50 \cdot x^\mathrm{r} \quad [\mathrm{EUR/m^2}], \\ c^\mathrm{m} &= 27.51 \cdot x^\mathrm{m} \quad [\mathrm{EUR/m^2}], \end{aligned} \tag{1}$$

where the linear function coefficients are derived based on the insulation prices, excluding taxes, from retail stores in Croatia [11]. The rock wool used is of the "Frontrock Max Plus" type, while the mineral wool is of the "Domo G3, Isover" type.

The number of years required for the cumulative energy cost savings of the $i^\mathrm{th}$ building design to equal the additional initial investment, referred to as the payback period $\mathrm{PP}_i$, calculated without accounting for inflation or interest rates, is defined as follows:

$$\mathrm{PP}_i = \frac{C_{\mathrm{inv},i} - C_{\mathrm{inv},0}}{C_{\mathrm{ae},0} - C_{\mathrm{ae},i}}, \tag{2}$$

where $C_{\mathrm{inv},i}$ is the investment cost of insulation materials, and $C_{\mathrm{ae},i}$ is the annual energy cost for the $i^\mathrm{th}$ simulation scenario. The baseline scenario is denoted by $i = 0$. For simplicity it is assumed installation cost are equal for all insulation thicknesses so investment cost $C_{\mathrm{inv},i}$ is defined as:

$$C_{\mathrm{inv},i} = (c_\mathrm{w}^\mathrm{r} + c_\mathrm{w}^\mathrm{m}) \cdot A_\mathrm{w} + c_\mathrm{r}^\mathrm{m} \cdot A_\mathrm{r}. \tag{3}$$

The parameters $A_\mathrm{w}$ and $A_\mathrm{r}$ represent the total areas of the exterior wall and roof, in m$^2$, respectively. The annual energy cost $C_{\mathrm{ae},i}$ is calculated as:

$$C_{\mathrm{ae},i} = \frac{E_{\mathrm{ae},i}}{\mathrm{COP}} \cdot c_\mathrm{e}, \tag{4}$$

where $E_{\mathrm{ae},i}$ represents the total annual thermal energy used for heating and cooling in the $i^\mathrm{th}$ simulation scenario, COP is the coefficient of performance used to convert the thermal energy into the electrical energy required to generate it, and $c_\mathrm{e}$ [EUR/kwh] is the energy price. This study assumes that energy is generated using an air-to-water heat

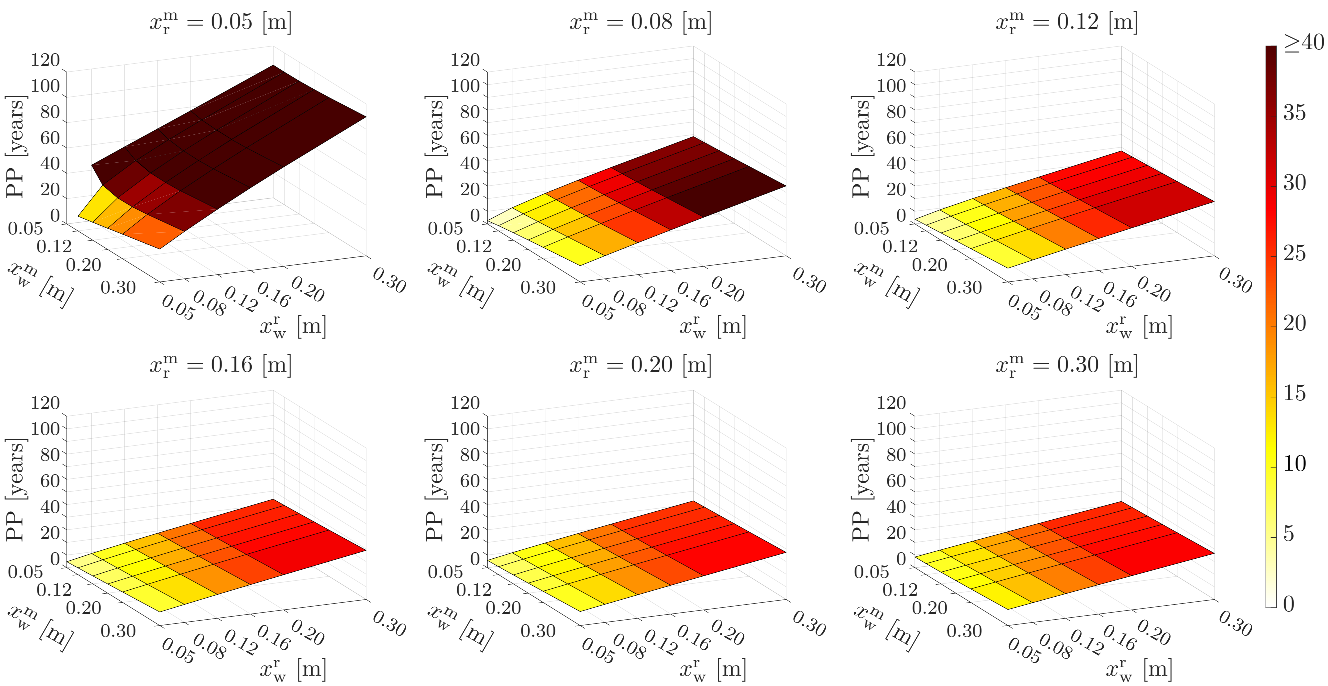



Fig. 6: Payback period for different insulation thicknesses.

pump, with a seasonally averaged constant COP value of 3.8 [12]. The energy price $c_e$ is considered constant and equal to averaged energy price for households in Croatia, i.e. $c_e$ = 0.1167 EUR/kWh excluding taxes and levies [13].

As the baseline scenario ($i = 0$) the situation with minimal insulation was selected, where all insulation thicknesses are set to a value of 0.05 m, i.e. $x_w^r = x_w^m = x_r^m = 0.05$ m. This scenario represents the configuration with the lowest possible insulation thicknesses for the exterior walls and roof, providing a reference point for evaluating the effectiveness of energy efficiency upgrades. PP for different insulation thicknesses is shown in Fig. 6. It should be noted that, in some cases, the PP exceeds 100 years, which is not economically viable. According to EN 13162 [14], the reference service life of thermal insulation of mineral wool is typically 50 years, although a longer service life can be considered for specific building elements. For the specific insulation thicknesses applied in the case study building, the PP is 21 years relative to the baseline with minimum thermal insulation. Generally, for most energy-efficient and renewable energy measures, an acceptable PP typically ranges from 5 to 15 years. However, as demonstrated in the case study, the PP can vary depending on the size of the investment, the expected energy savings, and the local energy prices. Table III shows the results with $9 \leq \text{PP}_i \leq 10$, and the expected annual energy savings calculated as a percentage relative to the baseline energy cost:

$$S_{\text{ae},i} = 100 \cdot \frac{C_{\text{ae},0} - C_{\text{ae},i}}{C_{\text{ae},0}}. \quad (5)$$

To investigate the relationship between PP, annual energy savings, and relative investment increase, the investment

TABLE III: Thermal insulation investments with $9 \leq \text{PP} \leq 10$.

| $i$ | $x_w^r$ [m] | $x_w^m$ [m] | $x_r^m$ [m] | $C_{\text{inv},i}$ [EUR] | $C_{\text{ae},i}$ [EUR] | $S_{\text{ae},i}$ [%] | $\text{PP}_i$ [year] |
|---|---|---|---|---|---|---|---|
| 1 | 0.08 | 0.05 | 0.20 | 2390.64 | 241.86 | 33.53 | 9.37 |
| 2 | 0.08 | 0.08 | 0.12 | 2166.70 | 263.87 | 27.48 | 9.20 |
| 3 | 0.08 | 0.08 | 0.16 | 2338.26 | 246.22 | 32.33 | 9.27 |
| 4 | 0.08 | 0.08 | 0.20 | 2509.81 | 235.02 | 35.41 | 9.80 |
| 5 | 0.05 | 0.12 | 0.30 | 2597.24 | 218.11 | 40.06 | 9.26 |
| 6 | 0.05 | 0.16 | 0.30 | 2756.14 | 212.08 | 41.71 | 9.94 |
| 7 | 0.05 | 0.20 | 0.08 | 1971.50 | 283.82 | 22.00 | 9.05 |

increase relative to the baseline scenario is calculated as:

$$C_{\text{inv},\%,i} = 100 \cdot \frac{C_{\text{inv},i} - C_{\text{inv},0}}{C_{\text{inv},0}}. \quad (6)$$

The relation obtained is graphically presented in Fig. 7, with the points obtained marked by black dots and an interpolated piecewise linear surface fitted to best represent the results [15].

The results indicate that even with annual energy savings of 40% or more, the PP exceeds 20 years when suboptimal insulation thicknesses are selected. Furthermore, it is evident that for annual energy savings greater than 25%, the relationship between PP, relative investment increase, and annual energy savings is almost linear. Motivated by this, the portion of the PP characteristics corresponding to annual energy savings greater than 25% is interpolated using

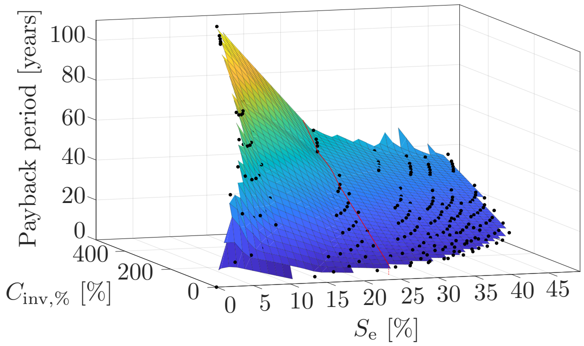



Fig. 7: Payback period with respect to annual energy savings and relative investment increase.

a bilinear function, in the form:

$$\text{PP}_i = p_0 + p_1 \cdot S_{\text{ae},i} + p_2 \cdot C_{\text{inv},\%,i} + p_3 \cdot S_{\text{ae},i} \cdot C_{\text{inv},\%,i}, \quad (7)$$

and unknown coefficients $\begin{bmatrix} p_0 & p_1 & p_2 & p_3 \end{bmatrix}$ identified using MATLAB Curve Fitting Toolbox [15] and listed in Tab. IV.

TABLE IV: Identified coefficients of bilinear $\text{PP}_i$ function.

| Coefficients | $p_0$ | $p_1$ | $p_2$ | $p_3$ |
|---|---|---|---|---|
| values | 1.09 | 0.1939 | -0.04365 | -0.002606 |

The resulting R-squared value of 0.995 indicates a good fit, which means 99. 50% of the variance in the PP is explained by the model. The identified function with the calculated points is shown in Fig. 8 with the obtained points marked by black dots and an interpolated bilinear function [15].

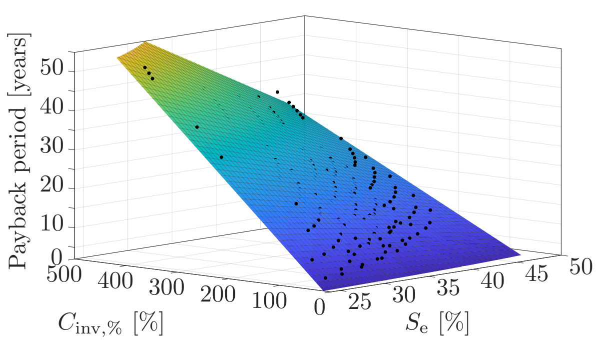



Fig. 8: Interpolated bilinear PP function for annual energy savings greater than 25%, with respect to annual energy savings and relative investment increase.

## V. Conclusion

The study demonstrates that insulation thickness plays a crucial role in optimizing energy performance for low-energy houses in continental climates. Although increasing insulation thickness reduces total energy consumption, it also increases demand for cooling, highlighting the need for a balanced approach that addresses both heating and cooling requirements. The economic analysis reveals that the payback period for energy-efficient insulation upgrades varies significantly, ranging from 2 to more than 100 years, even with substantial energy savings exceeding 20%. This variation is influenced by key factors, including the type of heating and cooling system, the building climate, and the costs of thermal insulation materials and energy, all of which are decisive in determining the optimal thickness of thermal insulation. The use of advanced building simulation tools for existing and planned buildings can reduce operational costs and optimize construction expenses by enabling more precise predictions of energy use. The findings emphasize the importance of considering both energy savings and economic feasibility when selecting optimal insulation solutions for residential buildings. The identified bilinear function allows for an effective balance between energy savings and financial feasibility, providing valuable information for homeowners, contractors, and policy makers to make informed decisions.

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