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Impact of Building Envelope Performance Improvements on Heat Loss Reduction: A Comparative Analysis

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Abstract – **The building envelope is a primary source of heat loss, underscoring the importance of technical strategies to improve its performance. This paper presents a comparative analysis of heat loss reduction in an existing building following the implementation of envelope-related improvements and evaluates the effectiveness of these strategies, providing insights into optimal solutions for improving building energy efficiency.**

Keywords – **Building Envelope Optimization, Heat Loss Reduction, Energy Efficiency Measures, Energy Conservation.**

I. Introduction

Indoor and outdoor thermal environments exchange heat through the building envelope which serves as a protective barrier against atmospheric conditions [1]. Its primary role is to create a comfortable and healthy indoor environment, influenced by hygrothermal properties, which depend on the structural design, material selection, and arrangement [2]. Heat loss through the envelope represents a significant share of the total energy consumption. Therefore, the aim is to reduce heat loss and increase energy efficiency [3].

An energy-efficient envelope design reduces building energy consumption and ensures optimal thermal comfort for occupants. The thermal performance of external walls is a fundamental factor in improving the energy efficiency of buildings [4]. A critical parameter in this regard is the heat transfer coefficient, which defines the thermal performance of the building envelope and serves as the basis for calculating the energy required for heating, ventilation, and air conditioning (*HVAC*) to maintain indoor thermal comfort [5].

Numerous studies have investigated strategies to minimize *HVAC* energy consumption through building envelope optimization. Increasing thermal resistance has been shown to reduce *HVAC* energy consumption by 20-80% [6]. Similarly, replacement of windows has resulted in 17-47% reduction in *HVAC* energy consumption [7].

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The main objective of this study is to evaluate the impact of envelope improvements on heat loss reduction in an existing building by conducting a comparative analysis examining the conditions prior to and subsequent to the implementation of envelope-related modifications.

The proposed improvements include replacement of external doors, replacement of windows, installation of thermal insulation on external walls and combinations of these measures. The study evaluates the effectiveness of these strategies in reducing heat loss using quantitative methods and offers insights into optimal approaches for enhancing the energy efficiency of buildings.

II. Methodology

The building under consideration is a standalone, single-unit structure located in an unprotected area in terms of wind exposure. It consists of a ground floor with a total internal floor area of 139 [m^2] and an internal volume of 436.82 [m^3]. Regarding the climatic conditions at the building's location, it is situated in a temperate region with a heating degree-day value of 2,635 [ºC-day] and a design outdoor winter temperature of -18 [ºC]. Except for the storage room, which has a design indoor winter temperature of 16 [ºC], the remaining five rooms in the building are maintained at a design indoor winter temperature of 20 [ºC].

There are two construction types for the exterior wall as an enclosing element of the building: an exterior wall made of solid brick without a decorative facing brick layer on the outer side of the building, and an exterior wall made of solid brick that includes a layer of facing brick on the outer side of the building. The walls are not thermally insulated. The exterior doors and windows have wooden frames with double glazing using standard glass and no protection against solar radiation.

Fig. 1 illustrates the percentage distribution of the various components within the building envelope.

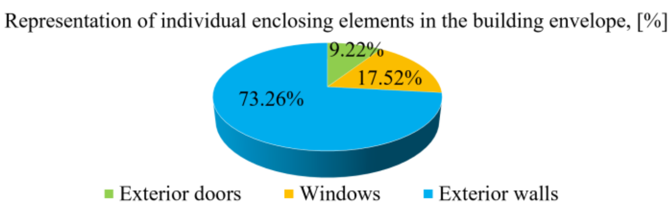

Fig. 1. Percentage distribution of individual enclosing elements in the building envelope

The overall heat transfer coefficients, the total and specific heating load of the building, the total and specific required energy, as well as the total and specific final and primary energy consumption, were calculated by conducting an energy audit of the building in accordance with the methodology for calculating these parameters, as specified in the Rulebook for energy auditing [8] and the Rulebook for energy characteristics of buildings [9].

According to the results obtained from the building's energy audit, it was concluded that the largest amount of heat is transferred through the windows and the exterior walls without a facing brick layer. The total calculated heat losses for the building amount to 32,747.303 [W]. The annual final energy consumption is 114,152 [kWh], while the primary energy consumption is 169,117 [kWh].

According to the findings from the energy audit performed on the building, suitable measures have been identified, as detailed in Table I. The anticipated implementation of these measures is expected to considerably decrease the building's heat losses, thereby reducing energy consumption and improving the building's energy class from its current classification of F.

TABLE I
PLAN FOR IMPLEMENTING THE PROPOSED MEASURES

Combination	Proposed measures	Description
	1	Replacement of external doors
	2	Replacement of windows
I	1+2	Replacement of external doors and windows
	3	Installation of thermal insulation on external walls
II	1+2+3	Measures for improving the building envelope

The process of replacing the current exterior doors involves the removal of the old wooden doors and their substitution with new PVC doors featuring triple glazing. These new doors are noted for their effective thermal and acoustic insulation, superior sealing capabilities that guard against moisture and drafts, remarkable stability, and extended durability.

The windows and glazed elements of the building envelope represent the most dynamic component in the exchange of energy between the building and its surroundings, primarily due to their high heat transfer coefficients compared to other elements, as well as the fact that windows are designed to facilitate natural ventilation within the building [10].

As part of the second measure, *PVC*-framed windows with triple glazing are installed in the building.

After installing the windows, just as with the installation of exterior doors, a final finishing process is carried out on the edges and the surrounding wall sections using airtight materials and sealing any gaps to minimize infiltration around the window frame edges as much as possible.

The principle of thermal insulation is based on the proper installation of high-energy-efficiency insulation materials, which reduce heat losses, resulting in lower energy costs. The thermal properties of the building envelope are essential for energy consumption; therefore, thermally insulated walls can reduce the building's overall energy consumption [11].

To achieve better building envelope performance and to prevent issues related to water vapor diffusion, insulation is applied to all exterior walls from the outside of the building.

The insulation of the building comprises an External Thermal Insulation Composite System (*ETICS*), a compact facade system with rock wool insulation boards with a thermal conductivity coefficient of 0.034 [W/mK] and thickness of 180 [mm]. This complies with thermal insulation regulations that require a minimum thickness exceeding 100-120 [mm] [10]. Fig. 2 depicts the components of the *ETICS* facade system.

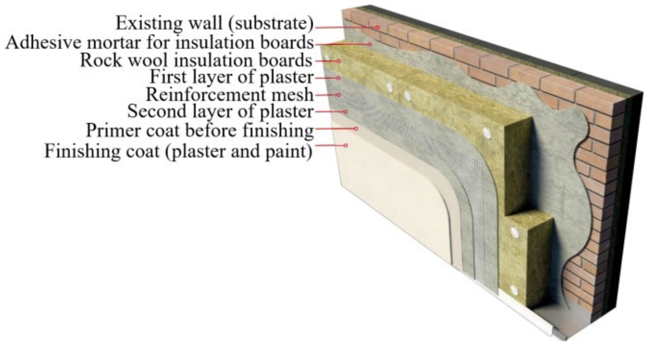

Fig. 2. Components of the *ETICS* facade system

III. RESULTS AND DISCUSSION

The analysis of the improvements attained after the execution of the proposed measures and solutions is carried out, including a comparative assessment of the individual measures and an evaluation of the building's condition prior to and following their implementation.

Fig. 3 illustrates the reduction in thermal losses achieved by implementing building envelope performance improvements.

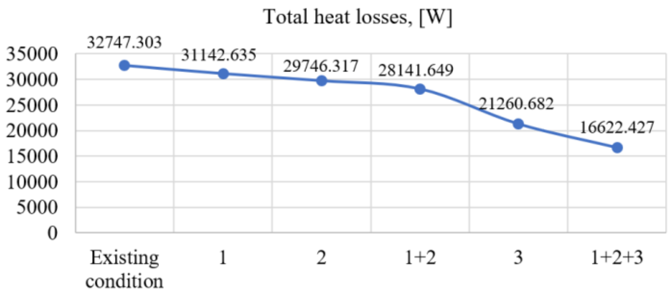

Fig. 3. Reduction of total heat losses through the implementation of measures to improve the building envelope

The replacement of exterior doors results in a 4.9% decrease in energy loss. Additionally, substituting the current windows with new *PVC* models equipped with triple-glazed insulating glass leads to a 9.16% reduction. When these two strategies are combined, the overall reduction reaches 14.06%. Furthermore, the installation of insulation contributes to a significant 35.08% decrease in the building's total thermal losses. By executing all proposed measures, an overall reduction of 49.24% is attained, translating to savings of 16,124.876 [W].

The observed results arise from the decreased heat transfer coefficients of the components that comprise the building envelope, as illustrated in Fig. 4. Specifically, the reductions are as follows:

- a 91.75% decrease for external walls;
- a 67.51% decrease for windows;
- a 71.96% decrease for external doors.

This analysis indicates that the most significant enhancement in the performance of the building envelope is attained through the installation of insulation on the external walls.

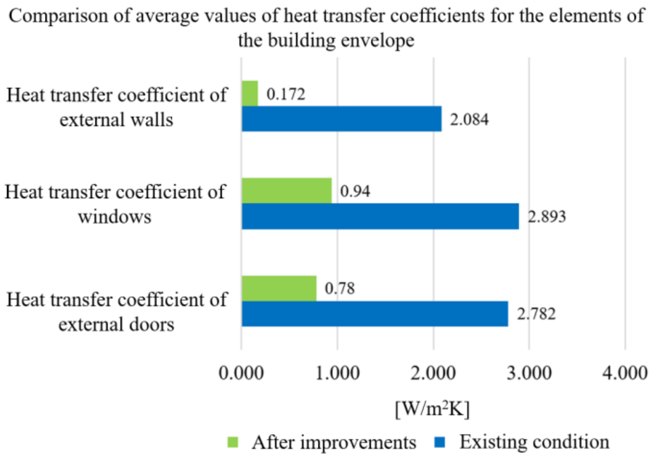

Fig. 4. Heat transfer coefficients of envelope elements before and after improvements, [W/m^{2}K]

If the data from Table II is also taken into account, where a comparison is made between the values for the total heating energy demand and the total required energy for the building (which, with the installation of insulation on the exterior walls of the building, amount to 31,636 [kWh/year] and 39,272 [kWh/year], respectively), it is confirmed that this solution is optimal when comparing only individual measures 1, 2, and 3.

TABLE II
DATA ON THE TOTAL HEATING ENERGY DEMAND AND TOTAL REQUIRED ENERGY FOR THE BUILDING

Considered condition	Total heating energy demand, [kWh/year]	Total required energy for the building, [kWh/year]
Existing condition	48,728	56,364
1	46,340	53,976
2	44,263	51,899
1+2	41,875	49,511
3	31,636	39,272
1+2+3	24,734	32,370

On the other hand, when all measures, including their combinations, are analyzed, the achieved savings are greater compared to the savings obtained through the individual implementation of the measures. For this purpose, in Fig. 5, the change in the consumption of final and primary energy for the building is presented, where a sharp decline is observed with the implementation of measure number 3, while the lowest value is reached when all three measures (1+2+3) are implemented. These reductions in the building's energy consumption simultaneously contribute to a decrease in the total annual costs for energy procurement and a reduction in the negative environmental impacts. The improvement of these performance indicators is a characteristic of an energy-efficient building, which is a direct consequence of the implementation of measures aimed at enhancing the properties of the building envelope, specifically reducing heat losses.

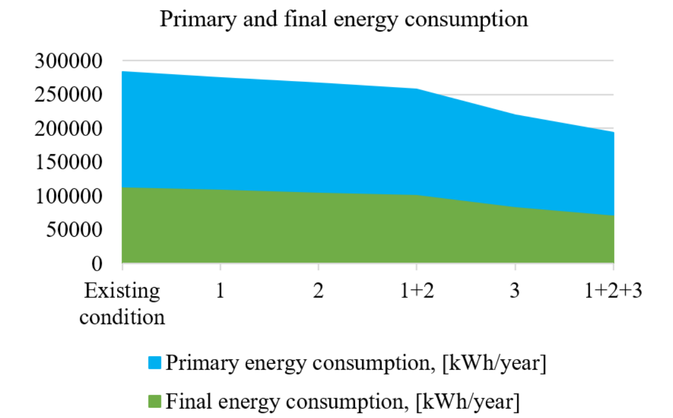

Fig. 5. Impact of building envelope enhancements on the reduction of final and primary energy consumption within the building

Fig. 6 illustrates the correlation among heat losses, the overall energy consumption of the building, and the relative measure of the total specific heating energy demand, which underpins the classification of the building's energy efficiency category.

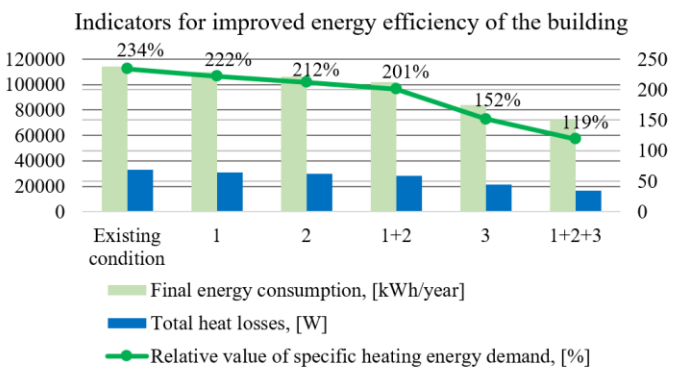

Fig. 6. Indicators for improved energy efficiency of the building

According to the obtained value for the total specific heating energy demand, which amounts to 177.944 [kWh/m^{2}year] as well as the relative value of the total specific heating energy demand of 119%, after the implementation of all measures, the building transitions from energy class F to energy class D. This indicates the effectiveness of these measures in improving the performance of both the building envelope and the overall structure. The reduced values of all these parameters, along with the improved energy class, serve as indicators of the building's enhanced energy efficiency.

To confirm that the simultaneous implementation of all measures for improving the performance of the building envelope contributes to optimal energy performance of the building, Fig. 7 presents the relationship between the reduction of heat losses, which is the primary objective of the proposed measures, and the achieved energy savings. A gradual decrease in heat losses is observed with the step-by-step implementation of the proposed measures, along with a sharp increase in the building's energy savings.

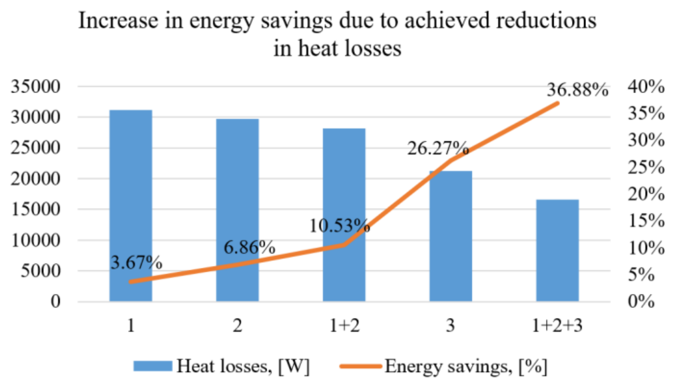

Fig. 7. Dependence between the reduction of heat losses and the increase in energy savings

Table III provides an overview of the energy savings realized through the independent application of each suggested measure, in addition to the savings resulting from the combination of these measures.

TABLE III
ACHIEVED ENERGY SAVINGS

Measure	Energy savings	
	[kWh/year]	[%]
1	4,189	3.67%
2	7,834	6.86%
1+2	12,023	10.53%
3	29,986	26.27%
1+2+3	42,095	36.88%

According to the results from Table III, if the individual measures (1, 2, 3) are considered, it can be observed that the greatest energy savings are achieved by installing insulation on the exterior walls. When considering the combinations of measures (I, II), the implementation of all measures results in the highest energy savings. With achieved reductions of approximately 37% and taking into account the improvement in the building's energy class, the selection and implementation of these measures are justified. However, since improvements to the building envelope performance involve extensive renovations, an economic analysis is necessary to consider key factors – required investment costs, payback period, and financial savings achieved through the implementation of each measure. In that case, a comparative analysis can be used to determine the optimal solution.

IV. CONCLUSION

This study highlights the potential of building envelope optimization measures in reducing heat losses and improving energy efficiency. The comparative analysis shows that the most effective individual measure is the installation of thermal insulation on the exterior walls, achieving a reduction in heat losses by 35.08% and a decrease in annual energy consumption by 26.27%. Optimal performance is achieved through the combined implementation of all measures, resulting in a total heat loss reduction of 49.24%. The results indicate the significant contribution of these measures to energy savings and the sustainability of buildings. Future studies may focus on advanced thermal insulation materials, insulation systems using waste materials, phase change materials, integration of photovoltaic systems into the building envelope (Building Integrated Photovoltaics – *BIPV*) etc. Additionally, a comprehensive techno-economic analysis would provide a better assessment of the cost-effectiveness of the proposed measures.

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