ISSN 3071-9658

European Journal of Interdisciplinary Issues

https://www.eujini.org.pl

Energy-Efficient Window Restoration: Innovative Approaches to Heat Conservation in Historic Buildings

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ARTICLE INFO

Research Article

Received:
25 August 2025
Revised:
12 October 2025
Accepted:
20 November 2025
Published online:
25 December 2025

DOI: 10.5281/zenodo.19040640

ABSTRACT

The restoration of historic buildings aims to preserve and maintain the durability of structures, improve their energy efficiency, and create a safe indoor climate. The purpose of this article is to analyze modern approaches and technologies for window restoration in the context of historic building restoration, which allow for reduced heat loss without compromising architectural authenticity. Based on the study of historical and modern experience in the preservation of architectural monuments, the study formulates key architectural and engineering solutions that ensure the preservation and durability of monuments of historically valuable architecture. The article discusses the topic of window replacement, which is relevant for reconstructed historic buildings. In particular, it is proposed to replace traditional wooden windows in the reconstruction of historic buildings with polyvinyl chloride (PVC) windows, subject to approval by the relevant authorities. PVC windows allow you to replicate a wide variety of window shapes and elements, and, if necessary, imitate the most delicate and complex patterns of window frames. At the same time, the tasks of architectural conformity to the original appearance of the building and ensuring modern energy efficiency requirements are solved. It has been proven that an additive approach to reconstruction opens up a range of new opportunities for the practical application of environmentally friendly and recycled materials, which not only minimizes the negative impact on the environment but also integrates the principles of sustainable development. The approaches proposed in the study will reduce heat loss without compromising architectural authenticity and will contribute to the transformation of modern construction concepts in the context of greater environmental friendliness and social responsibility. It is necessary to find solutions that allow preserving the architectural appearance of a historic building and facilitate its energy-efficient operation with minimal costs in each case.

KEYWORDS

restoration, energy efficiency, architectural authenticity, energy conservation, energy-efficient glass.

Introduction

Historic buildings are an integral part of the world's cultural heritage, while continuing to be used in the present day. The processes of their restoration and reconstruction are accompanied by numerous problematic issues that, to a certain extent, affect all elements of the architectural model.

In this context, the problem of restoring and replacing only one element of buildings—windows—requires special attention. Windows are one of the most distinctive elements of a building's architecture, which require maximum preservation of the architect's original design and the materials used in the reconstruction process. When replacing or restoring windows in buildings of historical and architectural value, it is necessary to focus on two main tasks: ensuring maximum authenticity and conformity to the original, as well as improving the energy efficiency of the building in accordance with modern standards without compromising the external appearance of the structure. Wood was the main material used to make windows when historically valuable buildings were constructed. It is often preferred when replacing windows today, as modern wooden windows allow the architect's original design to be fully recreated, preserving the atmosphere of antiquity and the maximum authenticity of the building's historical appearance. At the same time, modern industry has mastered the production of windows from other materials - polyvinyl chloride (PVC), metal, and combinations thereof. The most interesting in the context of reconstruction and replacement are PVC windows, which allow you to reproduce the most diverse shapes of windows and their elements, and, if necessary, imitate the most delicate and complex patterns of window frames. The main advantage of plastic windows, compared to wooden ones, is their relative cheapness, simplicity and speed of manufacture, and ease of use.

Unresolved issues include research into the effectiveness of new materials and technologies for window restoration, as well as analysis of the impact of restoration technologies on the carbon footprint of buildings.

Literature Review

Ivanović-Šekularac et al. (2016) and Šekularac et al. (2020) consider modern methods for determining energy efficiency, study modern energy-saving profile systems for window blocks, the problem of edge zones, as well as modern technical solutions for insulating window profiles. Kim (2025), Nair et al. (2022) research the thermophysical properties of double-glazed windows and plastic window profiles in their publications, noting that most of the heat loss occurs through the double-glazed windows and profiles.

Specific issues within the scope of the problem are discussed in articles by Brambilla et al. (2018), Femenella & Femenella (2025), and Tan et al. (2025). Researchers devote their scientific attention to various aspects of the restoration of historically valuable buildings, paying particular attention to windows. In addition, scientists note the need to combine the concept of preserving authenticity with modern requirements for energy efficiency and sustainable development of production processes. The issue of carbon footprint is also present in the industry developments of Wasielewski (2004) and Yuk et al. (2024). At the same time, several concepts for innovative approaches to heat conservation in historic buildings remain understudied. The topic of preserving the historical appearance of architectural monuments when replacing windows has been little studied, so this article is a review aimed at examining the current context of the issue.

Problem Statement

The aim of the study is to conduct an in-depth analysis of modern technologies for restoring wooden and aluminum windows, which allow reducing heat loss without losing architectural authenticity.

Methods and Materials

The theoretical and methodological basis of the work was formed taking into account the priority principles of implementing systemic research, based on a comprehensive approach. In order to reveal the issue as fully as possible, a number of theoretical research methods were used -

methods of abstract logical and comparative analysis, formalization, dialectical method, and some others.

Methods of abstract logical analysis and synthesis were used to identify the most significant aspects and basic concepts of the phenomenon under study. The dialectical method, comparison, and generalization were used to detail the system of definitions, identify basic categories and theoretical generalizations, and form a concept of the holistic restoration process.

Results and Discussion

Maximum preservation of the authenticity of historically valuable buildings is positioned as one of the key tasks in the process of their reconstruction. Particular attention should be paid to the issue of replacing or restoring windows, as modern solutions are quite varied and, in addition to the aesthetic aspect, allow for adjustments to energy efficiency. For example, it is worth noting the potential of new technologies using PVC windows, which restore the historical appearance of a building with a high degree of authenticity.

PVC profile windows can be given any shape: arched, square, triangular, multifaceted, and the plastic profile can be cut and welded at any angle, as well as bent. The color options for windows are diverse, ranging from imitation wood to any desired shade. The surface of the window can also be artificially “aged.” Today, there are many options for decorating plastic windows, which allow you to completely recreate the architectural features of past centuries and fit PVC structures into the overall appearance of the building’s facade without changing its original appearance (Ivanović-Šekularac et al., 2016).

Manufacturers produce a wide range of special parts for replacing windows in historic buildings. With their help, individual profile elements are used to create contours similar to the authentic ones. Individual small fragments are used to recreate a complete composition - a window that exactly replicates the prototype. Various decorative overlay elements are also available, such as rosettes, capitals, pilasters, and cornices.

If this is not enough, false latticework is used—special self-adhesive facing profiles that are glued to both sides of the glass unit, imitating, for example, a transom window. With their help, it is possible to copy a window of any level of complexity with all its elements. Thanks to this, the design of non-standard window structures, as a rule, does not cause any difficulties (Alhazzaa, 2023).

The task of ensuring the energy efficiency of a building is solved, for the most part, by the design of the windows and their correct installation in the openings. Most buildings that are positioned as historical monuments continue to be used for economic purposes. Solving the problem of their energy efficiency allows for a favorable temperature regime and the necessary humidity with optimal operating costs (Ivanović-Šekularac et al., 2016; Šekularac et al., 2020).

Although window openings occupy no more than 20% of the facade area, they account for most of the heat loss.

During renovation, it is also very important to correctly model or calculate the thermal fields of the joints between window blocks and wall openings, since the width of the profiles of modern window blocks is significantly smaller than that of old ones, and this greatly affects the thermal performance of internal slopes. Violations in this area are likely to lead to the destruction of slopes, as well as the appearance of mold (Gagliano et al., 2014).

There is a so-called “restoration window” technology that allows you to make replacements without air penetration from the street. This design consists of two blocks: the outer one imitates the prototype and blends in perfectly with the building’s facade, while consisting of a double-glazed unit with double sealing; at the same time, the inner block faithfully copies the historical appearance of the interior. Such multi-component windows are often used in houses with thick walls.

A key area for improving the functionality of window units is to enhance the thermal insulation of double-glazed windows. Improving the energy efficiency of window openings is one of the most important tasks in improving the energy efficiency of buildings, and the improvement of plastic windows allows solving the problem of heat loss in the room (Pearman-Gillman, 2012).

Energy conservation is one of the most important issues worldwide, so all major manufacturers of double-glazed windows have mastered the production of energy-saving glass. Energy-saving glass has the most important function of glass–high thermal insulation. Today, the most effective type of energy-saving technology in the field of double-glazed window production is energy-saving double-glazed windows–low-emission glass. The inner side of such a double-glazed window is coated with silver, which acts as a reflector, while the coating does not affect the transparency of the windows. The silver coating on the inside of the glass reflects long-wave radiation.

In winter, such glazing does not allow cold air to "escape," and in summer, due to the reflection of thermal energy, the room will not be hot. The glass unit is filled with an inert gas–argon–which not only protects the silver from oxidation when interacting with air, but also increases the level of noise insulation, since argon has a higher dynamic modulus of elasticity than air. Argon has almost half the heat capacity of air, which means that its thermal insulation is almost twice as high. Argon is a completely harmless gas that has no color, smell, or taste.

As a rule, the design of energy-saving windows consists of a single chamber, which in terms of its characteristics exceeds double-chamber conventional double-glazed windows, allowing for a reduction in the weight of the structure and, therefore, an increase in the service life of the fittings and the window as a whole. The functionality of the windows depends on the correct installation. The most important stages of installation are: measuring window openings; aligning window openings; installing plastic windows; fastening fittings, accessories, and window openings; sealing windows (Ye et al., 2013).

The distance between the glass panes and their thickness also reduce heat loss. It should also be noted that improving the thermal insulation of window units is of great importance during the operation of buildings. After all, the physical wear and tear of buildings and their engineering systems increases energy consumption, which is determined by conducting an energy audit. In this case, an effective measure to reduce heat loss is to replace window units with energy-saving ones with low emissions, or at least apply film heat-protective coatings to the glass. This is much cheaper than insulating, for example, facades.

Certain structural changes to double-glazed windows make it possible to solve a range of problems related to improving the functional efficiency of window units, contributing to improved sound insulation, reduced heat loss, partial compensation for air exchange deficiencies, sun protection; and increased safety (Wasielewski, 2004; Yuk et al., 2024). Additive technologies allow building elements to be created by applying material layer by layer, which is significantly different from traditional methods that require large amounts of resources and time, resulting in significant waste. The use of 3D printing can significantly reduce both construction time and costs, while reducing environmental risks.

It is worth noting that the additive approach to reconstruction and construction opens up a range of new opportunities for the practical application of environmentally friendly and recycled materials, which not only minimizes the negative impact on the environment but also integrates the principles of sustainable development. Today, global climate dynamics require the construction industry to be actively involved in the process of optimizing the state of the environment, so the introduction of additive technologies is seen as a necessary and important step towards achieving the goals of reducing the carbon footprint (Brambilla et al., 2018; Femenella & Femenella, 2025).

Buildings, including restored ones, must be as energy-efficient as possible to achieve the above-mentioned goal, which implies a reduction in energy consumption, and windows play a key role in this context. The main measures for achieving this goal are high-quality thermal insulation, sealing, the use of energy-efficient materials and technologies for window manufacturing, and the application of intelligent energy management systems.

Conclusions

The relatively short service life of windows compared to the entire building makes the issue of renovation and replacement very relevant. It is necessary to find solutions that preserve the architectural appearance of the historic building and facilitate its energy-efficient operation with minimal costs in each case.

With the approval of the responsible organizations, this issue can be resolved by using PVC windows. The task can be solved at a lower cost than installing wooden windows. The use of plastic windows allows for the successful solution of the task of ensuring the energy efficiency of buildings. The existing theoretical basis allows for the calculation of the thermal parameters of windows, as well as their installation components in openings. This issue should be considered on a case-by-case basis.

The approaches proposed in the study will reduce heat loss without compromising architectural authenticity and will contribute to the transformation of modern construction concepts in the context of greater environmental friendliness and social responsibility. In the future, it is necessary to continue developing them in order to ensure their integration into restoration work practices, which will enable real positive changes in the restoration of authentic architectural models.

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