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COMPREHENSIVE ASSESSMENT OF THE DURABILITY OF WINDOWS MADE FROM DIFFERENT MATERIALS: WOOD, VINYL, ALUMINUM

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Abstract. *The characteristics of the frame materials significantly affect the properties of the window. The window itself plays a decisive role in determining the overall energy efficiency of a building. This article analyzes four different types of frames: aluminum, polyvinyl chloride (PVC), and wood, as well as composite, in particular, wood with aluminum coating, from the perspective of sustainable development. These types of frames were examined according to various parameters, such as: environmental impact, durability and service life, maintenance and repair features of window frames. It was found that wooden windows, as well as those with aluminum coating over wood, are environmentally friendly products due to their ecological characteristics, i.e., low embodied energy consumption, low environmental impact, better durability, and longer service life. Aluminum and PVC frames, on the other hand, have high embodied energy values and associated environmental impacts. In the current era of sustainable development, the window industry is emphasizing how to improve the energy efficiency and environmental friendliness of its products, and this must be taken into account by modern window manufacturers. It has been proven that an important factor in extending the life cycle of a building as a whole and window structures in particular is high-quality monitoring of their technical condition and timely identification of damage to determine the feasibility of repair. The results of the study represent the importance of effectively transforming approaches to the selection of materials for the manufacture of windows when replacing or reconstructing them as an important tool for modernizing the concept of energy efficiency, environmental friendliness, and sustainable development. The article lays the theoretical and methodological foundations for further empirical research and practical projects to find composite solutions that will allow the advantages of individual materials to be combined in the most beneficial way and avoid shortcomings in operation, extending the life cycle of window structures.*

Keywords: *window structures, durability, energy efficiency, wood, polyvinyl chloride (PVC), aluminum, environmental friendliness.*

Introduction

Currently, the construction market offers a wide selection of windows made from various materials: wood, aluminum, vinyl (polyvinyl chloride – PVC), as well as combined materials, which are differentiated into wood-aluminum and wood-vinyl. PVC window structures are currently positioned as the most common budget option, which are practically immune to external influences, are unpretentious, and have high resistance to ultraviolet solar radiation, which even high-quality varnish and paint coatings cannot achieve. Plastic does not require special care, is antistatic, resistant to fungal diseases, and inert to moisture. In addition, vinyl windows have good thermal insulation properties, do not deform, and are available in a wide range of colors.

Wood is positioned as the most traditional window material, combining the aesthetics of nature with practicality. Since wood is a renewable material, wooden windows can be considered environmentally friendly, and proper care as they wear out extends their service life. Aluminum windows are an alternative—a modern and durable option that is resistant to corrosion, unaffected by weather conditions, and serves as a basis for various design solutions. Finally, composite windows, made of different materials, have noise and energy reduction, durability, easy installation, and design flexibility features.

Each of the materials currently used in window construction has a number of advantages and disadvantages. At the same time, the current context of window manufacturing, along with durability, emphasizes the importance of energy efficiency and environmental friendliness, which requires further scientific analysis.

Literature Review

The theoretical and methodological basis in the field under study was formed by scientific research by D. Búryová [3], M. Jahangir, R. Aboutorabi [5], R. Landolfi, M. Nicolella [7], J. Park [9], and others. The publications by S. Carlisle, E. Friedlander [4], Z. Kowalczyk [6], M. Riahinezhad, and others [10] raise topical issues of the deterioration of window structures to varying degrees under the influence of the environment: PVC is sensitive to heat and ultraviolet radiation, and PVC is sensitive to moisture and humidity. [10] raise topical issues of the deterioration of window structures to varying degrees under the influence of the environment: PVC is sensitive to heat and ultraviolet radiation; wood, in the absence of regular treatment, is easily subject to destruction; aluminum, if not properly protected with coatings, is damaged by corrosion, especially in coastal and industrial areas.

At the same time, authors often position aluminum frames as the best choice due to their protective coatings. However, M. Bissoli-Dalvi [2], E. Sällström, L. Lidelöw [12], and J. Souviron [14] draw attention to the environmental context of the problem, as aluminum frames have the greatest impact on the environment due to the emission of hazardous pollutants and high energy consumption during aluminum production, while PVC releases large amounts of toxic pollutants throughout its life cycle. Authors

J. Salazar and T. Sowlati [11] conclude that wooden window frames have the least impact on the environment, which raises the question of the balance between durability and environmental friendliness of window materials.

The studies by M. Asif [1] and G. Pajchrowski [8], which compare different samples of materials for window structures, deserve special attention. Uncoated aluminum samples showed signs of corrosion in humid and high-temperature conditions, while painted and anodized samples remained intact. Small wooden samples showed deformation and cracking under the influence of moisture and temperature, but whole wooden window blocks and other samples that had been properly surface-treated did not show such defects, and UV testing resulted in slight discoloration of the wood. The PVC samples remained intact under wet conditions; however, PVC deteriorated significantly as a result of temperature and UV testing (in particular, the latter test resulted in severe discoloration). It should be noted that the aluminum-coated wood samples were not affected, as the aluminum itself remained rust-free thanks to its coating layers and effectively protected the wood underneath from adverse conditions.

Despite the significant achievements of scientists in the field of research on the selected issues, the question of finding the most optimal solutions for creating durable window structures, taking into account environmental factors, remains open. This requires additional scientific research.

The purpose of the article is to determine the most optimal combinations of materials and repair technologies to extend the life cycle of window systems.

Research Results

Against the backdrop of global trends in socio-economic development towards sustainability, environmental friendliness, and energy efficiency, the processes of establishing standards in the field of construction and restoration are currently gaining particular importance. One of the decisions adopted in this area is the European standard EN 13115:2020 "Windows. Classification of mechanical strength. Vertical loads, static torsion and forces acting", which was introduced by the European Committee for Standardization in August 2020 to replace EN 13115:2001. The

document focuses on the durability of carpentry and construction products as one of the key production indicators.

Improving the quality of products, ensuring the necessary strength, functional reliability, and durability of their operation under operating conditions are the main and defining tasks of the industry. However, in practice, there are cases when the strength of joints is compromised even in the initial period of operation after repair or reconstruction, as a result of which the normal operation of the joint (product) is either impeded or impossible.

Durability is, in fact, positioned as the property of a product to remain operational until it reaches a limit state, at which point further operation of the product must be discontinued due to an insurmountable violation of safety requirements, parameters exceeding the established limits, or a sharp decrease in operational efficiency [13]. This indicator is determined experimentally and regulated in the quality guarantee. Each manufacturer must know the guaranteed service life of the product and its short-term strength.

Despite the growing popularity of plastics and light alloys, wood remains the main material used in window manufacturing because of its excellent insulating properties and relatively low cost. Spruce, larch, and pine are most often used for window frames. With proper surface treatment, these species are highly resistant to any atmospheric changes. Spruce wood is used only for interior windows because it is not very strong.

The functional reliability and durability of wooden structural elements depend on the choice of material, design, and careful execution of all work by a specialist. Even the best design is useless if the wrong material is chosen or the installation is poorly executed. A product is considered functionally reliable if it performs its task flawlessly at all times. With regard to wooden windows, violations such as excessive gaps, improper fastening, and incorrect proportions of the structure are often observed, which reduces the service life of the product.

The number of defects in the wood used to make windows must be strictly limited. Atmospheric and climatic influences change the hygroscopic properties of wood: it swells and shrinks, warps and cracks. The swelling and shrinkage of wood materials

associated with changes in humidity can lead to undesirable deformation (warping) and cracking of parts. In this case, the dimensional stability of the product's design and the presence of a protective and decorative coating on the product are of great importance for the durability of the product [15].

The adhesive joints of the corner connections of window frame structures must be water-resistant. At the same time, the adhesive itself must not have a harmful effect on the surface of the wood. In addition, the rigidity of the structure and the strength of the corner connections play an important role.

The quality of wooden windows is subject to very high requirements, since the unsuitability of one bar of the box leads to the deformation of the entire window. In most cases, wood defects that can negatively affect the strength of the wood (e.g., cracks, large knots, blue rot) are not allowed, as well as those that can cause frame warping or affect the quality of the finish (infection with rot and other fungi, untreated resin pockets, resin pockets, etc.) [4]. The moisture content of the wood should be 12-15%. At the same time, the factor of moisture dynamics must be taken into account during the design of products: it is necessary to form the product with the prediction of inevitable changes in the size and shape of parts in the process of their possible moistening and shrinkage without destroying the integrity of the product and changing its shape.

In the context of increasing the durability of wooden window products, the following measures are considered promising: tightening the requirements for permissible deviations in wood moisture content in batches of dried sawn timber; developing methods and techniques for the selective selection of mating parts and assemblies by moisture groups; high-quality chemical treatment of wood; the use of steam stabilization technology; the use of glued materials that significantly exceed solid wood in terms of stability [7; 12].

Vinyl windows are more durable than wooden ones and, provided they are of high quality, correctly installed, and properly maintained, can last 20-40 years. Being resistant to atmospheric influences, PVC windows retain their geometry for a long time and have high thermal insulation properties, although over time they require adjustment

of fittings or replacement of seals. The durability of window structures is also confirmed by tests of profiles, double-glazed windows, and fittings [2; 8].

Windows are considered durable if their profiles withstand tests for discoloration, tensile strength, Charpy impact strength not exceeding 50% of the initial value, color change on the gray scale not lower than the third threshold, and dimensional change not exceeding 2.5% [14]. Aluminum windows occupy a rather advantageous position in terms of durability compared to their wooden or PVC counterparts. Their exceptional resistance to numerous external influences is determined by their extraordinary strength and lightness, resistance to deformation and corrosion, and the possibility of long-term functionality while maintaining an authentic appearance.

Obviously, to extend the service life of window structures made of different materials, it is necessary to timely restore window fittings and seals, which involves regular cleaning, lubrication with special oils, and adjustment of the sash pressure with a hexagon wrench. Fittings must be thoroughly cleaned of dirt and old grease residues, after which a special grease, silicone spray, or technical oil should be applied to the moving parts [10]. Seal maintenance includes cleaning and treating with petroleum jelly, glycerin, or silicone spray to maintain elasticity and prevent drying out. If the seal has lost its original shape, it must be replaced by removing it from the grooves.

After conducting a preliminary analysis, it is possible to determine the most optimal combinations of materials and repair technologies to extend the life cycle of window systems, since during their operation, damage, moisture penetration, and other external factors occur, which significantly reduce the performance characteristics of buildings. The impact of man-made factors manifests itself as a result of increased environmental aggressiveness, technological pollution, and mechanical action [11]. Polluted air, especially in combination with moisture, leads to premature wear, corrosion, and destruction of window structures.

Analyzing the ability of each material to counteract the destructive effects of the external environment, we can identify the main advantages and disadvantages of the main materials used in window production (Table 1).

Table 1 – Advantages and disadvantages of window manufacturing materials in terms of durability

Type of material	Advantages	Disadvantages
Wood	Affordability, environmental friendliness, naturalness, aesthetics, high thermal insulation properties, suitability for repair and reconstruction	Risks of drying out, appearance of cracks due to evaporation of resins from wood over time, loss of initial heat-saving properties and tightness, the need for regular renewal of the protective paint coating of frames, design limitations, fire hazard
Polyvinyl chloride	Functionality, long service life, affordable cost, customizable format, variety of fittings, high heat-saving and noise-insulating characteristics, design variability, additional options (insect protection, child locks, micro-ventilation, anti-burglary fittings, etc.), ease of maintenance, fire-resistant properties	Artificial origin of PVC, low environmental friendliness of recycling, excessive airtightness, difficulty of repair
Aluminum	Strength, lightness, high light transmission, possibility of creating large glass structures, reliability and high thermal conductivity, ease of operation, stylish and modern design	Complexity and high cost of technical solutions, repair, and restoration

Note: systematized by the author based on sources [3; 7; 10]

Summarizing the information presented above, it should be noted that the optimal choice of material for windows should be made based on the specifics of the place where they will be installed, since each of the materials is most functional and durable in its «own» place. For example, aluminum is best for cold glazing of a loggia, while PVC profile windows are perfect for an apartment. However, for the reconstruction and major repair of a historic building, you can use not only wooden windows, but also modern PVC solutions that can match the style as closely as possible.

An important factor in extending the life cycle of a building in general and window structures in particular is high-quality monitoring of their technical condition, which involves the complete and timely identification of major damage and defects to determine the feasibility of their elimination. Monitoring should be carried out in conjunction with a forecast of the potential development of damage due to the influence

of destructive factors of a technogenic and operational nature. Optimizing the service life of window structures combines modernization, reconstruction, and repair measures, the feasibility of which is determined by comparing the possibilities of reconstruction with the costs of replacement, taking into account the terms of further planned operation.

Conclusions

The need for durable window structures and the integration of environmentally sustainable practices in the construction sector is becoming increasingly relevant. There is an urgent need to explore strategies aimed at creating a thriving market for recycled window materials. The study analyzes the life cycle and assesses the durability of window renovation, focusing on aspects of environmental friendliness and energy efficiency, resistance to external influences and wear and tear.

The results highlight the significant environmental benefits associated with window renovation compared to the production of new windows. In particular, composite window solutions are seen as the best alternative, as they combine durability, aesthetics, authenticity, and environmental safety. The results of the study illustrate the potential of window renovation as a sustainable alternative in the construction sector and promote sustainable practices in the construction industry. The conclusions represent the importance of effectively transforming approaches to the choice of materials for window manufacturing when replacing or renovating windows as an important tool for modernizing the concept of energy efficiency, environmental friendliness, and sustainable development.

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