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Influence of Technological and Regional Factors on Protective and Aesthetic Functions of Facade Glazing in Multi-Story Office Buildings

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Abstract The study aimed to determine the influence of technological, social, economic, and regulatory factors on protective and aesthetic functions in building facade glazing design. Based on the research (the main methods of collecting information were document analysis and an expert survey), the authors determined the facade indicators that perform aesthetic and protective functions, including the function of thermal protection and energy generation and the function of providing sunlight to illuminate the interior of the building and protect it against excessive overheating. Technologies and measures to facilitate their implementation were identified. The prerequisite for the study was the importance of glass in the appearance and space of a modern city. The authors identified the key indicators of glazed facades, including thermal protection, solar lighting, and innovative technologies, such as thermal mirrors and filling the gap with gas. The results confirmed the effectiveness of modern glazing technologies for sustainable architecture in an extreme continental climate and demonstrated the importance of traditions, trends, and economic factors. The results can be used in building fa çade design to achieve the principles of sustainable development.

Keywords Sustainable Architecture, Urban Environment, Climate, Economic Factors, Facade

1. Introduction

Construction and architecture are the largest economic sectors for infrastructure development and raw material distribution. According to the McKinsey consulting company, construction is the largest industry in the world, accounting for about 13% of global GDP [1]. The volume of the global construction industry market was estimated at 11.56 trillion dollars/year in March 2022 and was projected to reach 17.25 trillion dollars by 2029, with an average annual growth rate of 7.3% [2].

Modern construction is largely guided by the principles of sustainable architecture [3]. Within the framework of these principles, several characteristics of buildings that meet the requirements of sustainable architecture are proposed [4,5], including optimal energy use (minimizing energy loss) and harmonization with the environment (combination with elements of the surrounding architectural space) [6,7].

Our research aims to study an important architectural element of a building – the façade. Facades significantly affect energy saving due to heat transfer between the indoor and outdoor environment [8]. The facade as the front part of the building is more than all other architectural elements designed to harmonize buildings with the surrounding architectural ensemble and the environment [9]. The facade performs two main functions: aesthetic and protective [10,11].

The material for the facade is an important characteristic on which the aesthetic and protective functions will depend [12,13]. Modern architectural concepts focus on facade glazing (an important and characteristic form of sustainable architecture). This is explained by the low thermal conductivity values, achieved with technological solutions. The search for solutions for the optimal use of facade glazing is carried out constantly. For example, the annual Challenging Glass Conference [14] and the Facade Tectonics Congress [15] regularly discuss using glass for facade solutions. Researchers and practitioners are actively searching for effective and technologically advanced ways to use glass in facades.

The search for optimal methods depends on several factors described in scientific research.

First, the climate. The need for energy efficiency drives choosing glazing, especially in extreme climates. In hot regions, glazing systems minimize the influx of solar heat, while in colder regions, they prevent heat loss and optimize natural lighting. The features of the glazed building facades may vary. The choice of a facade solution depends on the climatic zone [16]. The relevance of our research implies considering the trends in the design of glazed facades for areas with an extreme continental climate [17].

Second, history and traditions. Historical and cultural preferences play a role in the choice of glazing materials. In some regions, using glass facades is explained by traditional architectural forms adjusted for modern needs [18].

Third, technological advances and innovations, such as thermochromic and electrochromic glass, allow using adaptive facade systems that respond to environmental changes, increasing the operational characteristics of the building [19].

Fourth, economic factors. The cost of materials and installation significantly affects glazing solutions. Highly efficient glazing systems that increase energy efficiency are often used in regions where long-term savings justify higher initial construction costs [20,21].

Fifth, national building codes and regulations. National regulations affect the design of facades to ensure safety, energy efficiency, and sustainability, which vary in different regions due to environmental conditions, scientific and technological development, and national standards.

2. Literature Review

Facade design uses the possibilities inherent in the structure of glass itself. The production technology of a double-glazed window allows for supplementing its initial structure with thin layers capable of changing its physical properties. They can limit solar radiation access into the room or scatter direct light radiation. Low-emission coatings also reduce the transfer of radiated heat from the glass surface by blocking the influx of infrared radiation. This significantly improves the thermal insulation coefficient of the double-glazed window.

Using glass in facade design leads to qualitatively new opportunities in protective and aesthetic functions.

The protective function of glass in facade design is as follows. First, it provides the building with high thermal insulation due to sealed windows, dimensions, and orientation of glazing [22-24]. Second, glass provides the room with sunlight, protecting it from excessive overheating, and allows for ventilating the rooms [25].

The aesthetic function of glass is as follows. First, the glazed facade is designed to ensure harmonious visual contact with the surrounding external space due to transparent parts of certain divisions, sizes, proportions, angles, colors, and types of glazing [27]. Second, ensuring the scattering of light in daylight and visual contact with the environment is an important factor in the mental comfort inside the building [26-28].

The scientific literature analysis allowed us to identify various types of facade glazing providing low thermal conductivity and additional measures that reduce heat transfer.

The main technological solution relevant to the protective function of glass is the thermal mirror. It usually consists of outer transparent glass and an inner coated glass with low far-infrared emissivity (finite impulse response (FIR) is a type of digital filter), with the coated surface facing the inner gap. Due to this technology, the exchange of thermal radiation between the two glasses is stopped, and the heat transfer coefficient is reduced by about 40%.

Good thermal and light conductivity indicators can be achieved due to the quantity or location of the glass in the frame and with the help of special technologies. When upgrading a building, the parameters of the existing glazing can be improved by using a low-emission transparent film placed on the inner or outer surface. Such a solution, which protects the room from unnecessary ultraviolet rays and helps to preserve heat inside the building, is economically feasible and is actively used in facade design.

Another technology that makes it possible to effectively use facade glazing in construction is filling the space between the frame panes with a mixture of air and a noble gas, such as argon or krypton, with a thermal conductivity lower than that of air. Gases with low thermal conductivity parameters significantly improve the insulation. After we identified the main structural and technological features of facade glazing that allow it to perform protective and aesthetic functions, it is worth outlining the climate conditions in which those features must be used in Russia and Kazakhstan. Russian architectural regulatory codes are increasingly being influenced by climate considerations, reflecting a need to adapt to both environmental changes and international standards. The integration of climate factors into architectural regulations is evident in several areas, including corrosion protection, indoor air quality, and urban planning. These adaptations are crucial for ensuring the longevity and sustainability of structures in varying climatic conditions.

The current urban planning codes, such as SP 131.13330.2020 “Construction Climatology”, are insufficiently equipped with climate data due to the closure of many weather stations since the 1990s [29]. Extreme weather events, including heavy rainfall and droughts, are becoming more frequent, posing challenges to urban infrastructure and water management ("Providing urban climate analyses to support climate sensitive urban planning and climate change adaptation", 2023). Urban climate governance in cities like Moscow and St. Petersburg is crucial for addressing climate change through social and technological transitions [30].

Urban areas in Kazakhstan, like many globally, are affected by the urban heat island effect, which exacerbates local climate conditions. Urban planning strategies are being developed to mitigate these effects by incorporating green spaces and sustainable building practices ("Climate Integration in Sustainable Urban Planning", 2022).

The issue arises of how climate, technological achievements, history, traditions, economic factors, and national building codes and rules combine when designing facades. Considering that construction is influenced by regional features, we selected Russia and Kazakhstan for our study.

The study aimed to determine the influence of technological, social, economic, and regulatory factors on protective and aesthetic functions in facade glazing design.

3. Methods and Materials

We conducted the study from January to March 2024.

We applied qualitative analysis methods. In the first stage, we selected scientific articles and monographs from Scopus, Web of Science, Google Scholar, and eLibrary containing the keywords "facades", "glazed facades", "sustainable architecture", "glazing technologies", "innovative glazing". The source base was limited by the requirement of free access to the materials.

In the second stage, we analyzed existing architectural projects that passed national certification, confirming their construction under the principles of sustainable development. We selected class A+ office buildings in large cities in Russia (Figures 1, 2) and Kazakhstan (Figures 3, 4), which used modern projects with glass as the main facade material.

Figure 1. Business Park "Khimki Business Park" (Moscow)

Figure 2. Business Center "Orbion" (Moscow)

Figure 3. Business Center "Lotos" (Almaty)

Figure 4. Business Center "Nurly Tau" (Almaty)

In the third stage, we collected information about the reliability of facade decisions which we have found in the research papers via e-mail interviewing 37 experts in architectural design. The criteria for expert selection were publications on the topic in journals from Scopus, Web of Science, eLibrary, and Google Scholar affiliated with Russia or Kazakhstan. A questionnaire with 5 questions was sent to the experts to evaluate the selected documents.

The purpose of the questionnaire was to gather insights into key factors influencing the aesthetic and functional characteristics of modern building facades:

1. Which facade indicators perform an aesthetic function?
2. What are the main issues of sustainable architecture in thermal protection and energy generation?
3. What types of facade glazing have low thermal conductivity?
4. What additional measures are used to reduce heat transfer?
5. What types of blinds should be used to reduce heat transfer?

This questionnaire was designed to collect expert opinions on current trends and challenges in facade design, as well as to identify the most effective approaches and technologies in the field of sustainable architecture.

The experts assessed them based on the Harrington scale. The Harrington scale assesses the quality of objects or phenomena and converts quantitative indicators into qualitative ones. The scale uses a range from 0 to 1, where each area corresponds to qualitative ratings "very bad", "bad", "satisfactory", "good", and "very good". Two questions had an open form, and the experts could indicate suggestions for increasing/decreasing the number of important sources and comment on their answers. As a result, 34 experts sent responses and rated the reliability of the sources by 0.74 points, which is a high indicator. The experts proposed six more works on the topic.

We processed the results using descriptive statistics methods in Excel. The data were visualized on graphs.

4. Results

The ranking of indicators characterizing the aesthetic function of facades is presented in Table 1 and Figure 5.

The study showed that the ways of using glass in building facades are characteristic of the extreme continental climate in the studied regions. Technological advances are actively used in structural elements that affect the aesthetic function performed by an architectural structure.

4.1. Protective Function

When analyzing the protective functions of the glazed facade, we observed greater variety. We identified the main functions (Figure 6).

The main indicators of the facade performing a protective function turned out to be thermal protection of the building and energy generation, as well as providing sunlight to illuminate the interior of the building and protection against excessive overheating. The extreme continental climate is characterized by hot summers and cold winters, which may explain the high rank of such opposite characteristics.

Table 1. Indicators of a glazed facade performing an aesthetic function

No.	Facade indicators that perform an aesthetic function	Rank	Weight
1	shape, scale, and external design	1	0.36
2	optical balance and harmonious arrangement of facade elements	2	0.26
3	choice of parts conditioned by sustainable technologies	3	0.18
4	color affecting the desired absorption or reflection of sunlight	4	0.13
5	rational helioplasty and night lighting	5	0.07

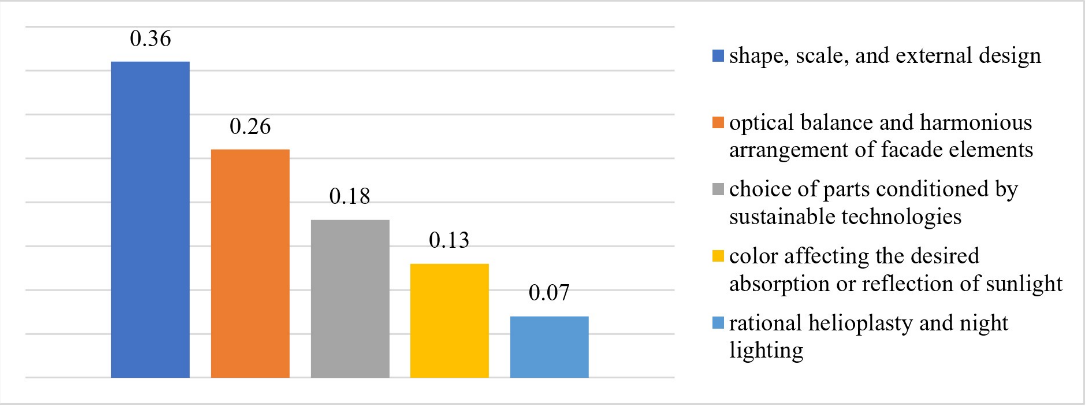

Figure 5. Weight distribution

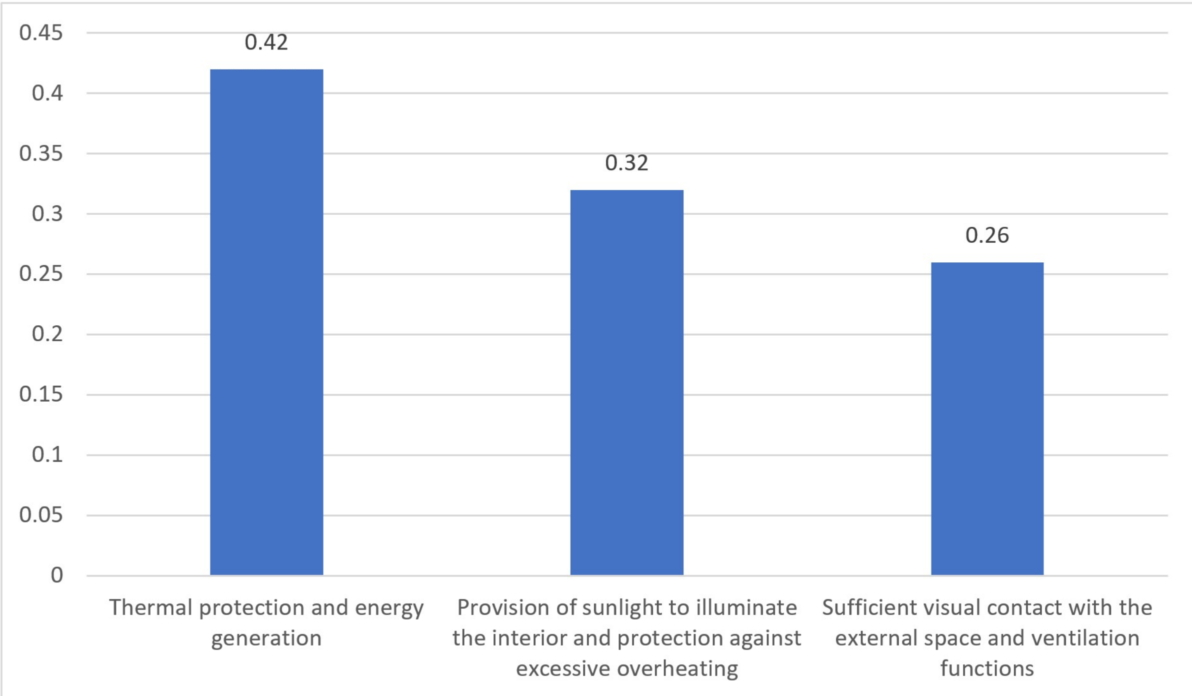

Figure 6. Main functions

Table 2. The main issues of sustainable architecture in thermal protection and energy generation

No.	Main issues	Rank	Weight
1	control of heat loss and inflow on transparent surfaces using frames and glazing	1	0.31
2	improved thermal insulation due to facade cladding (matte or transparent; the first option was more often used in the objects selected for the study since it is easier to design and control)	2	0.24
3	control of the heat flow on transparent surfaces using smart glass and shading devices	3	0.19
4	reduction of air infiltration through cladding (window and door frames, cracks in walls, connections between cladding elements)	4	0.14
5	control of ventilation openings and reduction of heat loss (in case of mechanical ventilation, heat recovery from the air coming out of the building)	5	0.12

4.1.1. Protective Function

The energy efficiency of a building is influenced by the quality and type of building systems (Table 2).

The most important factor in thermal protection and energy generation is the control of heat loss and influx on transparent surfaces using frames and glazing (Table 3).

The widespread use of double or triple glazing is an important factor in the climates of Russia and Kazakhstan. When designing glazing, it is important to consider that a double-glazed window with energy-saving coated glass has better thermal characteristics than a triple-glazed window made of an external reflective glass panel and two internal transparent glass panels.

We analyzed the thermal insulation of the external fence (Table 4, Figure 7).

The most influential of the points presented in the study is an additional reduction in heat transfer by about 20%, which is possible to achieve by filling the gap with a mixture of air and a noble gas, such as argon or krypton, with a thermal conductivity lower than that of air. Gases with low thermal conductivity parameters significantly improve the glazing insulation.

4.1.2. Providing Sunlight to Illuminate the Interior of the and Protecting against Excessive Overheating

The energy efficiency of a building is influenced by the quality and type of building systems.

The results of the evaluation of different types of glass in the facade design are presented in Table 5.

Table 3. Types of facade glazing with low thermal conductivity

No.	Main issues	Rank	Weight
1	control of heat loss and inflow on transparent surfaces using frames and glazing	1	0.33
2	improved thermal insulation due to facade cladding (matte or transparent; the first option was more often used in the objects selected for the study since it is easier to design and control)	2	0.26
3	control of the heat flow on transparent surfaces using smart glass and shading devices	3	0.18
4	reduction of air infiltration through cladding (window and door frames, cracks in walls, connections between cladding elements)	4	0.13
5	control of ventilation openings and reduction of heat loss (in case of mechanical ventilation, heat recovery from the air coming out of the building)	5	0.10

Table 4. Additional measures to reduce heat transfer

No.	Additional measures to reduce heat transfer	Rank	Weight
1	Filling the gap of the double-glazed window with a gas mixture	1	0.36
2	Low-emission transparent film	2	0.27
3	Orientation of the glazed facade	3	0.21
4	Material for the facade glazing frames	4	0.16

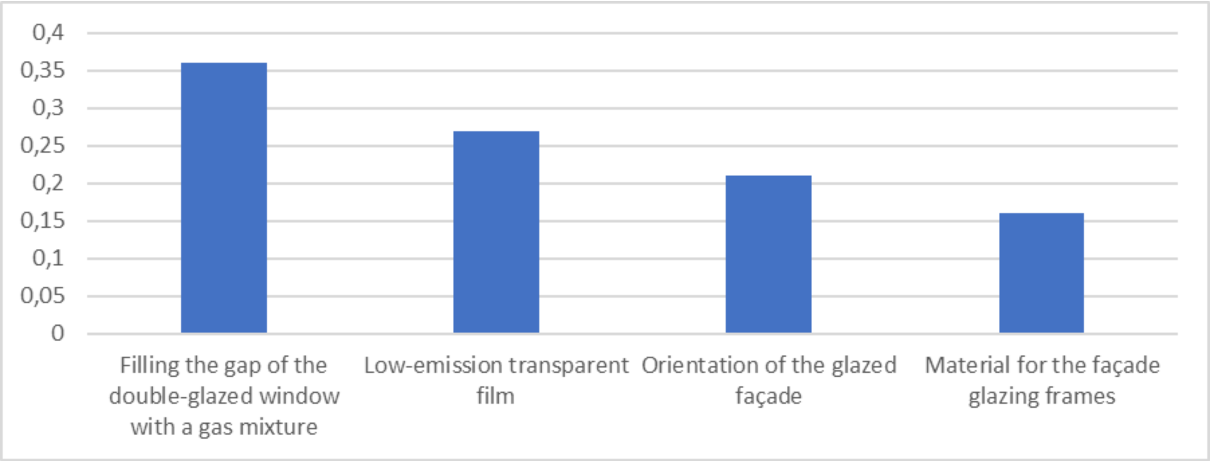

Figure 7. Additional measures to reduce heat transfer

Table 5. Comparative analysis of the types of switchable glass (indicators vary depending on glass thickness)

No.	Types of switchable glass	Heat transfer coefficient, $W/(m^2K)$	Dimming coefficient	Visible light transmittance coefficient (%)	Sound insulation, dB
1	photochromic glass	0.25-0.35	0.4-0.55	35-55%	38-46
2	thermochromic glass	0.45-0.55	0.35-0.45	25-45%	48-54
3	electrochromic glass	0.30-0.40	0.4-0.55	45-55%	32-42

Note:

The heat transfer coefficient is the thermal power transferred to the building or beyond it to the surface of the partition due to the temperature difference on both sides. Low values are important for reducing heat losses in winter.

The dimming coefficient is the ratio of the one-time solar energy transmitted inside the building with a given glazing to the total energy transmission coefficient of colorless float glass with a thickness of 3 mm. The lower the dimming coefficient, the less solar energy is transferred inside.

The visible transmittance coefficient is the fraction of individual sunlight transmitted inside the building. High values increase daylight access.

Our research showed that photochromic coating is the most effective solution in terms of protective function in an extreme continental climate. Table 6 (and Figure 8) shows the highest efficiency in terms of heat transfer coefficient.

Table 6. Different types of blinds to reduce heat transfer

No.	Types of shading devices	Rank	Weight
1	blinds with automatic control	1	0.30
2	blinds with manual control	2	0.25
3	roller shutters	3	0.18
4	stationary devices (solar partitions, blinds)	4	0.14

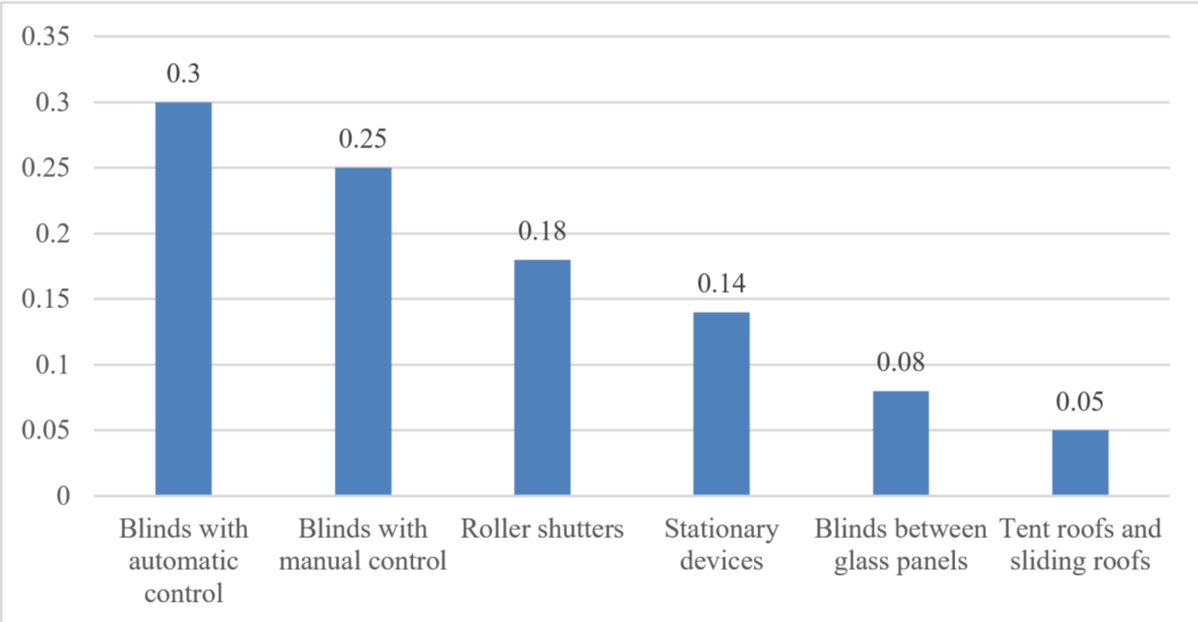

Figure 8. Types of shading devices

To provide effective protection from the sun in an architectural structure, various technological solutions are used.

Our analysis showed that the preferred types of shading devices are blinds with automatic and manual control. This is explained by the economic opportunities and the subjective preferences of investors and project managers.

5. Discussion

The analysis of projects and architectural structures that passed national certification and complied with the principles of sustainable development showed that the glass facade is a common element for aesthetic and technical or functional reasons.

The results showed that for glazing technology, the key criteria are climate and national standards. In different climatic zones, various technologies minimize heat loss in cold regions or protect against overheating in hot regions. The requirements for materials and installation methods vary significantly depending on the standards regulating energy efficiency, safety, and durability.

In Russia, SNiP (Building Codes and Regulations) and GOST (State Standard) contain strict requirements for thermal insulation, materials, and construction methods that minimize heat loss. In a cold climate, it is important to reduce heating costs; therefore, such standards dictate using technologies that ensure high energy efficiency [31].

Kazakhstan also has the SNiP regulations largely based on Russian experience. Special attention is paid to thermal protection since most of the country is in an extreme continental climate zone with cold winters. The standards include requirements for thermal insulation of walls, windows, and door structures and ventilation systems to ensure comfortable living conditions and reduce energy consumption [32,33].

Thus, the ranking of thermal protection in Tables 2, 3, and 4 largely agrees with the policy of the countries with which the experts were affiliated.

Most experts' responses focused on the priority of innovative solutions to increase the thermal conductivity of glazing, paying attention to filling the space between the glasses with noble gas, photochromic glass, and portable devices for dimming the room. However, our analysis of the designed and built facilities showed that the existing practice of facade glazing design in terms of protective and aesthetic functions differs from the expert opinions since subjective factors affect the construction of office buildings (history, investors' preferences, architectural traditions, and economic opportunities).

Although energy-saving glass provides significant long-term benefits, the investment costs for such projects can be high. The choice of a solution depends on the goals and constraints of the project, including budget, environmental goals, and structural features of the building. Two factors influence economic feasibility.

The first factor is the costs at the stage of project financing. For example, a study on the Moscow office real estate market showed an increased demand for new office facilities, but the supply did not grow. The researchers explain that this discrepancy is explained by the problems caused by banks' reluctance to provide loans at the project development stage due to the long construction time [34].

The second factor is efficient design and low operating costs. Some energy-saving glass technologies, such as simple multilayer coatings, provide a balance between cost and performance. These technologies provide basic energy savings while reducing initial costs and maintenance requirements [35].

In addition to the protective function of office glazing, it is necessary to discuss the aesthetic side of architectural projects. Most experts stressed the importance of shape, scale, and exterior design of buildings. The question arises about which forms and exterior designs investors and developers choose. We concluded that climate has less influence on decision-making than on protective function. When making a decision, the role of national traditions and the influence of trends increase [36]. Most people prefer the architectural elements determined by culture, which attracts their attention to the architectural object more and does not disrupt the established ecosystem surrounding the building [37].

The modern architecture of Kazakhstan, especially in Astana, is significantly influenced by nomadic traditions, reflected in public space and urban design. Symbols, such as shanyrak (the dome-like part of the yurt) referencing the nomad yurt, and circular motifs symbolizing perfection and natural cycles emphasize the cultural heritage of the Kazakh people. This architectural approach aims to form a national identity and popularize a multi-ethnic narrative, balancing the historical significance of Kazakh culture with the modern needs of a diverse population in the newly created capital [38].

As for Russian cities, Kazan's architecture reflects a synthesis of national and regional traditions. The office buildings in Kazan use ornamental systems and materials that refer to historical styles, such as the Bulgarian-Tatar traditions, and harmonize with modernism and post-modernism. This combination creates a distinctive regional and national architectural identity [39].

6. Conclusions

In sustainable architecture, the mutual integration of aesthetics and technology is important. The design of the glazed facade, its shape, and materials using new technologies are determined by the climate, national standards, and economic opportunities. History, traditions, and trends are considered in the design to a lesser extent and depend on regional characteristics and the location of buildings. In modern architecture, the facade defines the exterior of the building. In buildings of sustainable architecture, technological glass coatings are used in the facade design. Glass provides thermal protection and minimizes the risks of possible overheating. The harmoniously designed facade creates the aesthetic value of the building and affects energy production, internal comfort, and well-being.

The following limitations could affect our results: only selected objects were examined; we turned to a limited number of experts to verify the results; our study was based on qualitative research methods.

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