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Study regarding adaptive envelopes based on origami

Studiu privind fațadele adaptabile inspirate de origami

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Abstract. *This paper explores the integration of adaptive façade systems in curtain wall buildings as a means to enhance energy efficiency, thermal performance, and visual comfort. Starting from the geometric versatility of the hexagon and drawing inspiration from origami folding principles, the study proposes a kinetic external shading system capable of responding dynamically to variations in solar radiation. The design is inspired by principles of biomimicry and aims to contribute both aesthetically and functionally to the building envelope.*

Key words: sustainable design, adaptive envelope, hexagon tessellation, ventilated façades, wellbeing.

Rezumat. *Această lucrare analizează integrarea sistemelor de fațade adaptabile în clădirile cu pereti cortină, având ca obiectiv îmbunătățirea eficienței energetice, a performanței termice și a confortului vizual. Având ca punct de plecare versatilitatea geometrică a hexagonului și fiind inspirat de principiile de pliere din origami, studiul propune un sistem de umbrire exterioară cu mecanism cinetic, capabil să reacționeze în mod dinamic la schimbările radiației solare. Designul este ghidat de principii de biomimetism și urmărește să contribuie atât estetic, cât și funcțional la anvelopa clădirii.*

Cuvinte cheie: design sustenabil, anvelopă adaptabilă, teselare hexagonală, fațade ventilate, stare de bine.

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1. Introduction

In the context of growing global efforts to reduce energy demand and mitigate greenhouse gas emissions, the construction industry emerges as a key contributor, responsible for nearly 40% of worldwide energy consumption. Nonetheless, such reduction strategies must ensure that occupant comfort and overall well-being are not affected.

The building envelope plays a fundamental role in separating the interior environment of a structure from external conditions. It typically comprises structural construction elements and operable components such as doors and windows. A comprehensive definition [1] describes the building envelope as the physical barrier that separates the heated volume of the building from: the outdoor air; the ground (in the case of floors in direct contact with the soil, whether located above or below the finished ground level, as well as walls in contact with the soil); adjacent unheated or minimally heated spaces within the building, such as storage areas, technical basements, cellars, attics, enclosed balconies, and loggias, which are thermally insulated from the heated volume; internal spaces with different functions (e.g., commercial spaces at the ground floor of residential buildings, office areas); and neighboring buildings, provided that they are separated by expansion joints. In the current context, where minimizing energy consumption is a major priority, the performance and quality of the building envelope are of critical importance.

The building envelope serves multiple functions, including:

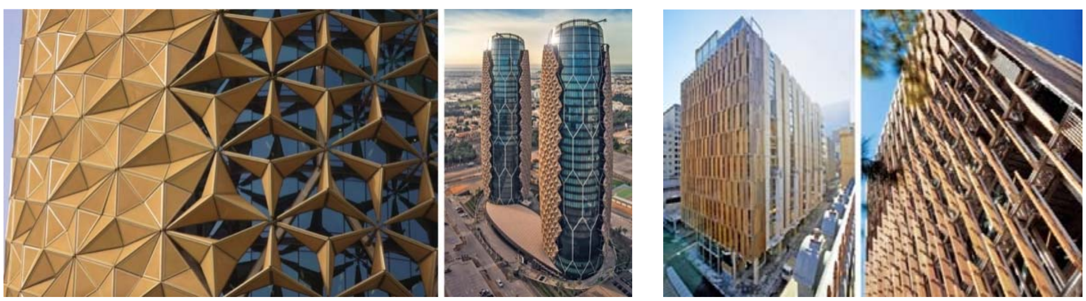
- thermal insulation of the building,
- regulation of indoor air humidity,
- protection against wind and weather conditions,
- acoustic insulation,
- fire protection,
- admission of natural light,
- and, not least, contributing to the architectural identity of the building through aesthetically designed solutions.

Traditionally, building envelopes were regarded as static components, albeit incorporating operable elements. Maintaining indoor comfort required constant attention and manual intervention from occupants. However, in the late 20th century, and increasingly in the early 21st century, a new approach to façades emerged: the concept of the adaptive façade, also referred to as responsive or dynamic façade [2].

This concept refers to the ability of building envelopes to change their form and functions in response to external environmental changes, such as seasonal variations or the time of day. This adaptability can be achieved through the integration of layers or spaces equipped with systems that regulate airflows, enable ventilation, provide shading, or modulate natural lighting. These functions are typically managed by automated control systems that respond to external conditions and indoor microclimate requirements. In addition, photovoltaic systems for energy generation can be incorporated either within or on the surface of the envelope. A related approach is the use of kinetic façades, which use mechanical systems to dynamically change their configuration in response to environmental conditions.

Another emerging concept in architecture, also observed in other fields, is the use of nature as a source of inspiration, a principle known as biomimicking or bioinspiration. In building design, analogies have been drawn between the function of the building envelope and the behavior of biological skin in humans and animals. Such observations have led to the development of innovative technical solutions and the discovery of new materials.

The design of adaptive façades, fully aligned with current energy efficiency and sustainability policies, requires the collaboration of multidisciplinary design teams composed of architects and engineers from various fields. This integrated approach is essential to address the complex challenges such systems present. Even though the concept of adaptive façades has been known for some time, its practical implementation is relatively recent, with several notable projects exemplifying its application, such as the Al Bahr Towers in Abu Dhabi (2012–) - Fig. 1.a, and the Council House CH2 in Melbourne (2004–2006) - Fig. 1.b [3].



a) b)

Fig.1. Adaptive envelope - exemples

2. Proposed solution

A comprehensive evaluation of a building's performance, considering all previously discussed aspects, requires large, multidisciplinary design teams and complex multi-criteria analyses. This is due to the fact that certain design measures may enhance specific performance parameters while potentially having a less favorable impact on others.

This paper aims to propose a shading system suitable for a building having glass wall façade, intended to enhance the performance of the building envelope from several perspectives:

- aesthetic enhancement, through the addition of a secondary layer applied over the curtain wall, which also contributes to improved energy performance;
- a study focused on improving thermal performance;
- analysis of airflow behavior within the newly created structure;
- ensuring visual comfort for building occupants.

2.1 Defining the Design of Adaptive Façade. Geometric exploration

As climate concerns have intensified in recent years, the field of responsive façades has gained increasing attention, as it enables buildings to adapt their exterior envelopes to fluctuations in outdoor temperature and variations in solar radiation intensity [4].

As a source of inspiration for the development of the proposed shading system the authors explored the folding techniques found in origami art, which allow for the creation of a wide variety of geometric forms. The primary objective was to design a planar structure composed of modules interconnected with adjacent units to form a continuous network. Based on this interconnected grid and utilizing Rhino 7 software, the hexagon was selected as the fundamental geometric shape.

The hexagon can be harmoniously subdivided due to its symmetrical structure. It is the only regular polygon whose side length is equal to its radius. Among the three well-known regular tessellations, triangular, square, and hexagon, the hexagonal grid yields the minimum perimeter for a given unit area. As a result, the hexagonal pattern also emerges naturally in structures shaped by physical forces, as exemplified by the honeycomb. The equal distribution of in-plane stresses, the tendency toward structural stability, and material efficiency all contribute to the formation of equally sized circular cells that are arranged in the most compact and isotropic configuration. Whether formed by internal growth or external compression, these conditions inherently lead to a hexagonal network.

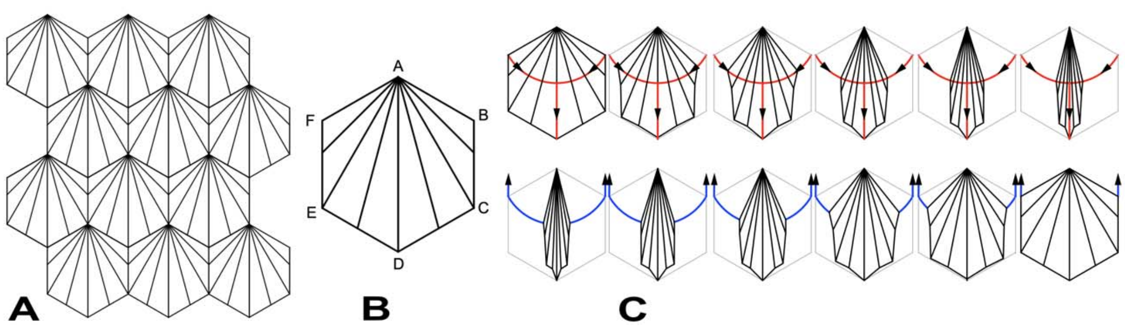


Fig.2. a. Hexagonal tessellation; b. Hexagonal symmetry; c. Opening/closing system of the shading system

Starting from the hexagonal shape and its interconnection with adjacent areas in a grid, tessellation was selected as the geometric strategy. In simple terms, surface tessellation refers to covering a surface with one or more polygonal shapes without overlaps or gaps. While numerous examples of tessellations on curved surfaces are known [5], this study focuses on a more straightforward case, tessellating a flat surface, specifically the planar façades of a building, as illustrated in Fig. 2.a.

In descriptive geometry, the tiling of a plane using regular polygons of equal side length and type is classified as regular or homogeneous tessellation. The admissible polygons include equilateral triangles, squares, regular hexagons, as well as semi-regular polygons. There are eight known types of semi-regular tessellations with a single vertex type and fourteen types involving multiple vertex types. Such tessellations are only possible using regular polygons whose internal angles are exact divisors of 360 degrees.

Based on this principle, by applying symmetry to a regular hexagon ABCDEF along the diagonal AD and dividing the sides BC, CD, DE, and EF into two equal segments (Fig. 2.b), a mechanism can be implemented that allows for dynamic opening and closing, as shown in Fig. 2.c. In the following section, the geometric configurations of the proposed shading system and the folding motion of the façade based on origami principles are analyzed.

2.2 Dynamic characteristics of sun shading device

Architectural design involves, among other aspects, the study of how natural light enters in the space and how the surrounding environment is perceived factors that can be significantly enhanced through the proposed façade system [6]. The entire system becomes an integral part of the building envelope, influencing the overall architectural expression. A key design consideration lies in selecting actuation mechanisms that are both efficient and visually appealing. Consequently, parameters such as the number of actuating points, required displacements, and actuation forces must be carefully evaluated during the design phase to ensure the long-term sustainability of the system. The façade is designed to respond to specific levels of solar radiation. Functioning like an origami structure, it seamlessly integrates into the building envelope, with its primary role being the regulation of indoor light intensity. The geometric properties and symmetry of the hexagon enable its large-scale repetition across a planar surface. The actuation axis for the shading module's closing mechanism corresponds to the diagonal AD of the hexagon ABCDEF, as illustrated in Fig. 2. By pulling tension cables located at the lower edge of the façade along the direction of diagonal AD, indicated by red arrows in Fig. 2.c, the shading system rotates the vertices F and B around the fixed-point A, initiating the closing motion to allow sunlight to enter the interior space. Conversely, to activate the opening mechanism, represented by blue arrows in Fig. 2.c, tension cables located at the upper edge of the façade, aligned with edges EF and BC, are engaged. This movement causes vertices F and B to rotate around point A in the opposite direction, thereby deploying the shading elements and fully protecting the façade from direct solar radiation.

Through folding, the module creates new angles that reflect incoming solar radiation away from the façade. Fig. 3.a presents a top view of the shading device, illustrating a gradient transition from 100% opacity to 60%, and further to 30% opacity. The same assembly is shown in perspective view in Fig. 3.b.

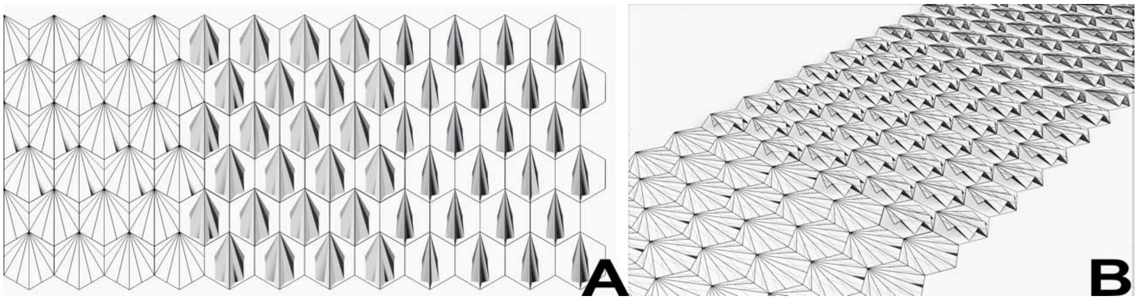


Fig.3. a. Plan view of the shading system with different opening; b. Perspective of the shading system with different opening.

During operation, the system generates animated patterns across the building façade, which are perceptible both from the exterior and the interior, as illustrated in Fig. 3 and Fig. 4.

The visual appearance of these movements can vary across the entire façade, creating a customized scenographic effect for the building's occupants. Due to the independent operation of individual modules, natural light can enter interior spaces without altering the overall geometry of the façade. Offering a high degree of flexibility and a wide range of configurations, the kinetic shading device can adapt effectively to varying solar intensities. The resulting hexagonal units form openings of different sizes, producing inventive dynamic compositions and generating a three-dimensional textured surface along the vertical axes of the façade. The responsive and vibrant envelope becomes dynamic through the formal attributes of its surface, modulating its appearance in accordance with light intensity, as demonstrated in Fig. 4.a (exterior view) and Fig. 4.b (interior view).

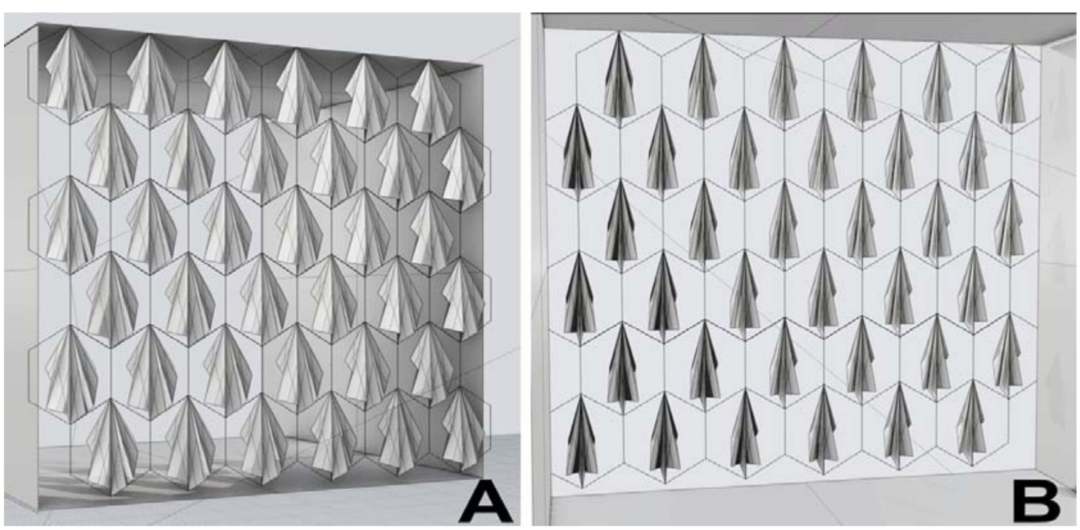


Fig.4 a.View of the shading system from the outside; b. View of the shading system from inside

As illustrated, the system can be fully closed (100%) to create complete shading and prevent direct sunlight from entering the interior when solar rays strike the façade perpendicularly. As previously described, the shading system can be opened by applying force at the lower part of the façade along the vertical diagonal of the hexagon, while closing is achieved by applying force at the upper part of the façade along the vertical edges of the hexagon. The proposed shading design alters the façade's geometry through a kinetic structure that passively responds to variations in light intensity [7]. Future research, in collaboration with colleagues from the Faculties of Mechanical and Electrical Engineering, will enable a more in-depth investigation of the shading system's performance.

1.1. Energy efficiency and well-being

The concept of well-being encompasses the fulfillment of multiple criteria, which can be evaluated through both objective and subjective indicators. From an objective standpoint, well-being is closely linked to quantifiable physical parameters related to indoor environmental quality, including thermal comfort, visual comfort, acoustic performance, and indoor air quality. These factors can be measured using established engineering and environmental metrics. However, well-being also depends on subjective, psychological components, such as perceived comfort, emotional response to space, and a sense of control over the environment, which cannot be directly measured. Instead, these aspects require statistical evaluation, typically conducted through structured surveys and interviews with a significant number of building occupants [8].

1.2. Thermal comfort elements

In terms of the building envelope's contribution to achieving thermal comfort, several key parameters must be met, with recommended values provided by experts in the field [1, 11]:

- Indoor air temperature (t_i) and its spatial and temporal distribution within the occupied zone: These values should generally fall within the range of 19 - 23°C.
- Mean radiant temperature ($\overline{\theta}_{mr}$) and the solid angle under which an occupant perceives surrounding surfaces with varying temperatures: The difference between indoor air temperature and the mean temperature of enclosing surfaces should be minimal (not exceeding 3°C). Additionally, surface temperatures of enclosure elements must be no lower than 16°C.
- Air velocity within the occupied space, particularly in rooms with mechanical ventilation or air conditioning: The recommended range is 0.15 - 0.2 m/s to avoid drafts while ensuring proper air circulation.
- Indoor relative humidity (φ_i): Recommended values fall within the range of 35 - 70%, ensuring both comfort and indoor air quality.

Thermal transfer can be characterized using several physical parameters [1], among which the most relevant is:

- Thermal resistance (measured in m^2K/W)**:** → describes a material's ability to resist heat flow and is critical in assessing the insulating performance of building components. For a multilayer construction element composed of homogeneous materials, the total thermal resistance is calculated as the sum of the convective resistances of the adjacent fluid layers (typically air) and the conductive resistances of the solid layers. The overall thermal resistance can be expressed by the following equation:

$$R = R_{si} + \sum R_s + \sum R_a + R_{se} \quad (1)$$

or explicitly,

$$R = 1/\alpha_i + \sum d/\lambda + \sum R_a + 1/\alpha_e \quad (2)$$

where,
R_{si}, R_{se} represents superficial thermal resistances, calculated according to the direction and sense of the thermal flow (they are given in norms);
R_s represents the resistance of a homogeneous layer of a construction element;
Ra resistance of unventilated air layers;
$a_{i,e}$ - coefficient of superficial surface heat transfer to the inside, respectively to the outside [W/m^2K];
d - finished thickness of the wall [m];
l - the thermal conductivity of the material [W/mK].

- Heat transfer coefficient (or transmittance) [W/m^2K], frequently used both in thermotechnics calculations of construction and also in the catalogues of some companies that produce or sell construction materials, represents the reverse of the thermal resistance and is determined with the relationship:

$$U = 1/R \quad (3)$$

It reflects the heat transfer capacity, so the lower the U value is, the lower the transmission losses are.

According to current Romanian standards, conventional building envelopes for residential structures must meet a minimum thermal resistance of R_{min} = 1.8 m^2K/W and a maximum thermal transmittance of U_{max} = 0.6 W/m^2K, as specified by MDRAPFE Order 2641 from 2017. Unfortunately, in the case of lightweight façade systems typically used for administrative and commercial buildings, the thermal performance often falls below these required thresholds. As a result, efforts are being made to identify alternative design solutions and advanced materials to enhance the energy performance of such façades.

In order to evaluate the effect of the shading system during the cold season, a comparative simulation was performed. The analysis focused on a building with aluminum frame envelope and triple-glazed glass. Ubakus software [9], a U-value calculator that evaluates wall components for insulation, moisture protection, and thermal performance, was used to calculate the Heat Transfer Coefficient of the wall, both with and without the shading system.

In the case of the wall without the shading system, a value of R=1.43 m^2K/W was obtained. In the case of the same glass wall with the application of the shading system, the thermal resistance increased to R=1.523 m_2K/W, indicating a 6% improvement.

While the proposed solution has a limited impact on heating performance during the cold season, it significantly reduces cooling needs in the warm season, thus improving the building's overall energy efficiency.

Table 1

Analysis of the obtained results

Layers (from inside to outside)	Without shading		With shading	
	Thickness [mm]	R [m²K/W]	Thickness [mm]	R [m²K/W]
Thermal contact resistance		0.130	-	0.130
Insulation glass, tripple glazed	36	1.263	36	1.263
Thermal contact resistance		0.040	-	0.130
Ventilated level	-		200	
Shading	-		2	
Whole component	36	1.433	238	1.523

2.3.2. Aspects Related to Air Quality. Airflow Along the Façade

To ensure an adequate level of indoor air quality, it is essential to provide controlled air exchange with the outdoor environment. This process compensates for oxygen consumption and facilitates the removal of excess pollutants, including metabolic byproducts, combustion residues, tobacco smoke, volatile organic compounds (VOCs), microorganisms, radioactive substances, settleable particulate matter, and other harmful agents generated by technological processes occurring within buildings.

This air exchange can occur either with or without the use of external energy. Air movement may result from the building's inherent physical properties or be assisted by mechanical systems. Accordingly, the following ventilation scenarios can be identified [10]:

- Natural ventilation
  - unorganized (passive infiltration and exfiltration)
  - organized (intentional airflow paths, such as operable windows or vents)
- Mechanical ventilation
  - basic (forced air supply or exhaust)
  - integrated with:
    - heating/cooling systems
    - humidification/dehumidification systems

- Mixed-mode ventilation
  - mechanical air supply combined with natural exhaust
  - natural air supply combined with mechanical exhaust
- Air conditioning
  - for thermal comfort
  - for technological or process-specific requirements

Technical literature provides methods for calculating air flow rates based on seasonal conditions (summer or winter) and depending on the selected ventilation or air conditioning system. In addition to air flow rate calculations derived from pollutant balance assessments, an approximate method is often used during the early design phases, as well as for validating classical calculation methods. Two key indicators are commonly defined in this context:

➢ Specific air flow rate:

$$L_s = \frac{L}{N} \quad [\text{m}^3/\text{h, object}] \qquad (4)$$

➢ Air exchange rate:

$$n = \frac{L}{V} \quad [\text{h}^{-1}] \qquad (5)$$

where:
L = air flow rate [m³/h]
N = number of occupants, equipment, or sanitary fixtures
V = room volume [m³]

These indicators have recommended values established by technical standards, depending on the intended use of the indoor spaces, and are employed for preliminary estimations of air flow rates. It is important to note that for rooms without significant emissions of harmful substances, the air flow rate can be determined based solely on these indicators, without the need for detailed pollutant balance calculations. While both indicators are used depending on the application, the air exchange rate is more commonly referenced in practice. In the specific case of the analyzed building, which accommodates office activities, current regulations recommend an air exchange rate of $n = 3 - 6$ [h^{-1}].

When implementing external shading devices, it is essential to consider the airflow dynamics along the façade. The ventilated cavity between the shading system and the façade promotes natural convection, enabling continuous air circulation that dissipates heat effectively – Fig. 5.

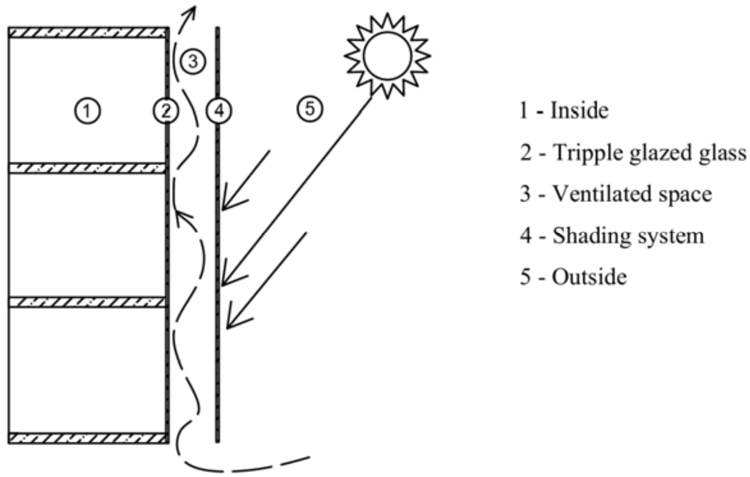


Fig. 5. Air circulation on the facade

2.3.3. Visual Comfort Elements. The Importance of Applying Shading Devices.

The building envelope also plays a crucial role in ensuring access to natural daylight. Glass façades have become a defining feature of contemporary architecture due to their ability to provide consistent natural illumination. However, to optimize energy efficiency, it is essential to strike a careful balance between the amount of daylight admitted into the interior and its thermal impact on the indoor environment.

An important point of view in achieving this balance is adjusting illumination levels according to the function of the space and the nature of activities performed within. In office environments, for instance, current standards recommend an illuminance level of 300–500 lux, with a maximum permissible value of 750 lux, in order to support both visual comfort and occupant productivity.

Visual comfort is a fundamental aspect in the design of office spaces, having a significant impact on user productivity and well-being [12]. It extends beyond mere illumination levels and encompasses a range of qualitative parameters that must be met to ensure an optimal visual environment, as specified in the SR EN 12464 standard, some of which are summarized below.

For instance, the lighting uniformity level should exceed 0.6 to ensure an even distribution of light, thereby avoiding discomfort caused by overly bright or insufficiently lit areas. Additionally, the unified glare rating (UGR) must be equal to or less than 19, in order to minimize visual disturbances caused by glare and reflections, which can negatively affect concentration.

Another important parameter is the Color Rendering Index (CRI), which ranges from 0 to 100. In office environments, the CRI should exceed 80 to ensure accurate color representation and maintain a natural visual atmosphere. In addition, the Correlated Color Temperature (CCT) is also critical. For office spaces, a recommended CCT value is 4000 K, on a scale typically ranging from 2700 K to 6500 K, corresponding to a neutral white light that supports concentration and reduces visual fatigue.

Incorporating these parameters into the design of lighting systems, whether natural or artificial, plays a key role in ensuring that workspaces are both comfortable and high-performing. By aligning with ergonomic standards and sustainability goals, this design strategy emphasizes the value of integrated solutions and thoughtful planning in enhancing the functionality and quality of office environments.

3. Conclusions

Natural daylight helps reduce the reliance on artificial lighting. However, when solar radiation is too intense, it can lead to increased indoor temperatures and greater energy demand for cooling. Therefore, adaptable shading systems enable the reduction of unwanted heat gains while still maintaining high-quality natural illumination.

Building façades can no longer be regarded only as barriers between interior and exterior spaces. They are evolving into intelligent interfaces between humans and the environment, playing a crucial role in energy performance, occupant comfort, and architectural expression. Their design must be approached as a complex engineering challenge, multidisciplinary in nature and guided by the principles and demands of sustainability.

References

[1] Mârza, C., Abrudan, A., Elemente de termotehnica construcțiilor, Ed. UT Press, Cluj-Napoca, 2012.
[2] Sandak, A., Sandak, J., Marcin, B., Kutnar, A., State of the Art in Building Façades, https://www.researchgate.net/publication/331516581, 2019.
[3] Alotaibi, F., The Role of Kinetic Envelopes to Improve Energy Performance in Buildings, Journal of Architectural Engineering Technology, 2015.
[4] Mârza, C., Graur, A.M., Corsiuc, G., Adaptive Shading Envelope – a Challenge for Architects and Engineers, 10th Jubilee International Conference on Geometry and Graphics -Mongeometrija 2025, 5-6 june, Belgrade, Serbia.
[5] Fioravanti, A., Cursi, S., Elahmar, S., Gargaro, S., Loffreda, G., Novembri, G., Trento, A., Square tessellation patterns on curved surfaces: In search of a parametric design method, ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference - Volume 2, Sapienza University of Rome, Rome, Italy, 20-22 September 2017, pp. 371-378, doi https://doi.org/10.52842/conf.ecaade.2017.2.371.
[6] Graur, A.M., Design of adaptive solar shading system based on the Cuboctahedron, Revista Română de Inginerie Civilă, vol. 13, no.2, pp.182-191.
[7] Graur, A.M., Mârza, C., Corsiuc, G., Adaptive shading envelope inspired by the geometry of nature, Journal of Industrial Design and Engineering Graphics, vol. 19 no. 1, 2024, pp. 203-206.
[8] Boon Lay Ong, Beyond environmental comfort, Ed. by Routledge Taylor and francis Group, London and New York, 2013.
[9] https://www.ubakus.de/u-wert-rechner.
[10] Mârza, C., Corsiuc, G. ,Despre relaţia confort ambiental-calitate a aerului-permeabilitate la aer a construcţiilor. Revista Română de Inginerie Civilă, 2017, vol. 8, no.3, pp. 167-172.
[11] C107-2005 Normativ privind calculul termotehnic al elementelor de construcţie ale clădirilor.
[12] Albu, H., Beu, D., Rus, T., Moldovan, R., Domnita, F., Vilcekova, S., Life cycle assessment of LED luminaire and impact on lighting installation –A case study, Alexandria Engineering Journal, Vol. 80, 2023, pp. 282-293, https://doi.org/10.1016/j.aej.2023.08.068.