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CLIMATE-RESPONSIVE ECOLOGICAL DESIGN: BIOCLIMATIC STRATEGIES FOR GREEN BUILDING

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A B S T R A C T

This article examines the bioclimatic design of high-rise buildings as an efficient approach to integrating local climatic parameters to enhance the energy efficiency and environmental sustainability of contemporary urban development. The study considers major climatic parameters (temperature, humidity, atmospheric pressure, wind speed) alongside minor factors (solar radiation, precipitation, pollution, cloud cover), all of which influence the formation of the built environment's microclimate. The research methodology is based on applying biological principles concerning the equivalence and non-equivalence of climatic factors, enabling the establishment of a hierarchy of parameters and optimising their consideration at the design stage. Particular attention is given to mathematical modelling of variations in temperature, atmospheric pressure, wind speed, and humidity with altitude, substantiated by empirical data and physical laws. The analysis of major and minor climatic parameter interactions illustrates how these processes influence building operational regimes and highlights the necessity of adaptive design solutions. The findings contribute to both theoretical advancements and practical applications in optimising bioclimatic architectural strategies for shaping sustainable and environmentally responsive urban developments.

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1. INTRODUCTION

In modern cities with high-density high-rise developments, the dominance of artificial environments harms ecology and contributes to increasing energy consumption. The challenges of contemporary urban spaces prompt architects and engineers to seek new approaches to reducing environmental burdens. One of the most promising directions for shaping cities based on ecological balance and sustainable nature-conscious solutions is the advancement of "green" or environmental building design (Ruefenacht et al., 2022; Sharifi, 2021). Bioclimatic design represents a specialised field within green architecture aimed at creating buildings that function as elements of natural ecosystems, adapting to the environment in response to local climatic factors (Krivenko et al., 2023; Manzano-Agugliaro et al., 2015). The theoretical foundation of bioclimatic design began in 1963 when Victor Olgyay introduced the term "bioclimatic" and developed a bioclimatic chart, linking

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climatic data to the design strategies necessary for creating thermally comfortable buildings (Olgyay, 1973). Subsequent studies (Aroztegui, 1980; Bo, 2013; Sealey, 1979) established the basis for integrating local climatic characteristics into architectural solutions and contributed to developing bioclimatic design tools and methodologies. Contemporary research (Marsh, 1997; McCartney & Matsika, 2004; Golasi et al., 2016) confirms the practical efficiency of bioclimatic diagrams, demonstrating their capacity to inform adaptive design strategies tailored to local climatic conditions.

Despite the increasing relevance of bioclimatic concepts in architecture, their practical implementation faces challenges, often due to the discrepancy between theory and practice. For instance, in the study (Touman & AL-Ajmi, 2005), the authors highlight that neglecting climate as a design factor remains one of the primary reasons for the inefficiency of architectural solutions about their natural environment.

In Ukraine, climatic zoning has been established based on long-term meteorological observations, enabling the formulation of architectural design principles based on regional climatic parameters, as outlined in "Architectural and Building Climatology" (Tymofyeyev et al., 2015). However, despite substantial advancements in this field, there remains a need for adaptation in response to the current challenges of bioclimatic building design.

The optimisation of climatic parameter modelling remains a critical research area to enhance the accuracy and usability of design processes (Caetano et al., 2023).

2. METHODOLOGY AND OPTIMISATION OF CLIMATIC PARAMETER CONSIDERATION

2.1 The Concept of Optimisation in Bioclimatic Modelling

The optimisation process in bioclimatic design involves identifying the most adaptive and practical approach for integrating multiple climatic parameters. Bioclimatic architectural solutions resemble the evolutionary adaptation of living organisms, which respond to various climatic factors over time, shaping their biological properties according to environmental conditions.

The number and nature of climatic parameters influencing local conditions and design objectives can vary, with parameters fluctuating continuously or discretely. Typically, the volume of data characterising dynamic changes in climatic systems is substantial. This study applies two well-established biological principles to optimise the handling of this complex and interdependent system of climatic factors:

- Equivalence of climatic factors for life.
- Non-equivalence of environmental factors.

The principle of equivalence of climatic factors states that no single factor can replace another. In natural ecosystems, these factors include heat, light, moisture, air, and nutrients. Similarly, specific climatic conditions are essential for human comfort in bioclimatic design. For instance, a well-lit environment is necessary for human health and well-being; a lack of natural light may lead to health disorders, even if other climatic parameters (such as temperature and humidity) are optimal. In this sense, light cannot replace heat, and heat cannot replace air humidity, underscoring the irreplaceability of individual climatic factors in architectural design.

The principle of non-equivalence of environmental factors aids in structuring the influence of climatic parameters on building performance. Climatic factors fall into two categories: major and minor, where minor factors modify the effects of the major ones. For example, cloud cover directly affects the quality and intensity of natural light. However, secondary factors become primary only when their intensity surpasses a critical threshold, which may be time- or location-dependent. A practical example is precipitation levels, which influence passive water conservation systems or stormwater drainage calculations.

Thus, the optimisation of bioclimatic architectural solutions relies on analysing dynamic climatic systems using biological principles of equivalence and non-equivalence of climatic factors. This approach enables the establishment of a hierarchy of climatic parameters, defining their impact on comfort and energy efficiency and considering their interactions during the design process.

2.2 Formalisation of Measurements in Building Climatology

Bioclimatic modelling involves the application of various climatic parameters, each measured using specific units (e.g., air temperature in °C, humidity in %, and atmospheric pressure in Pa). This diversity in measurement complicates the assessment of the cumulative impact of climatic factors in bioclimatic design. Principles of building climatology are applied to ensure that measured data can be systematically integrated into a unified bioclimatic framework.

Building climatology (Tymofyeyev et al., 2015) classifies weather types based on monthly average temperature, humidity, and wind speed values, categorising them as hot and dry, hot, warm, comfortable, cold, or severe. Experts determine the most appropriate building operational mode for each dominant weather type in a given region. These operational modes: isolated, enclosed, semi-open, and open — serve as guidelines for selecting architectural, structural, and engineering solutions during the design process. This classification establishes a structured relationship between climatic characteristics, weather types, and building operational

modes, facilitating optimising their interaction within bioclimatic design.

By applying the biological principles of equivalence and non-equivalence, researchers can determine the major climatic parameters that define the prevailing weather type: temperature, humidity, atmospheric pressure, and wind speed. Other parameters — such as solar radiation, precipitation, air pollution levels, and cloud cover — are considered minor in climatic analysis under various weather conditions. A comprehensive evaluation of the interactions between major and minor parameters forms the basis for assessing the influence of climatic factors on building operational modes.

The following section will explore these interactions in greater detail, focusing on bioclimatic modelling for high-rise buildings.

3. MODELLING CHANGES IN CLIMATIC PARAMETERS WITH BUILDING HEIGH

3.1. Influence of External Microclimate on High-Rise Developments

The design of high-rise buildings with consideration of climatic conditions is a critical aspect of sustainable architecture. As building height increases, the impact of natural climatic factors becomes more pronounced and uneven compared to low-rise structures.

For example, the study by Ellis and Torcellini (2005) analysing over 706 buildings found a correlation between energy consumption and building height, primarily due to increased exposure to external climatic conditions. Computational analyses conducted by Ellis and Torcellini (2005) on Freedom Tower (Lower Manhattan, New York, USA) indicate the following variations in climatic parameters at 1.5 m and 284 m heights:

- Air temperature decreases by 1.85°C (12.3%).
- Atmospheric pressure drops by 3,365 Pa (3.3%) where appropriate.
- Wind speed increases by 5.29 m/s (21.5%), impacting energy demands.

Thus, the key feature of high-rise bioclimatic design is the variation of climatic parameters with height. The objective of bioclimatic high-rise architecture is to develop adaptive design solutions that effectively respond to changes in the external microclimate.

3.2. Variation of Key Climatic Parameters with Height

The major climatic parameters — temperature, humidity, atmospheric pressure, and wind speed — are the foundation for defining weather conditions and building operational regimes. Their interaction determines the air environment's physical state, directly influencing building energy efficiency and occupant comfort.

The relationship between temperature and height is fundamental in building microclimate calculations. Empirical studies suggest a linear decline of approximately 1°C per 100 meters in moderate climates (Navarro-Serrano et al., 2020), expressed as:

$$t(h) = t_0 - \frac{h}{100}, \quad (1)$$

where t(h) – temperature (°C) at height h (m), t_0 – temperature (°C) at ground level. This approximation is based on statistical averages for temperate climatic zones. However, the linear model may not accurately reflect actual conditions in some instances, such as temperature inversion or variable atmospheric conditions. In complex scenarios, non-linear regression models considering vertical temperature profiles, temperature inversions, and precipitation distribution provide a more precise description of temperature variation patterns.

The variation of atmospheric pressure with height is determined using a basic approximation, indicating a pressure decrease of 1 GPa for every 8 metres:

$$p(h) = p_0 - \frac{h}{8}, \quad (2)$$

where p(h) – pressure (GPa) at height h (m), p_0 – pressure (GPa) at ground level. This approximation provides a rough estimate that is suitable for preliminary calculations. However, the barometric equation is applied for a more precise description of pressure distribution by height, incorporating exponential dependence on altitude, temperature variations, and air molecular mass. Different models are used for wind speed variation with height, including the Ekman spiral, logarithmic law, and power law (Lopez-Villalobos et al., 2022). These models enable the estimation of wind speed v (m/s) at height h (m), given a known wind speed v_0 at height h_0. For example, the power law for wind speed variation is given by:

$$v(h) = v_0 \left(\frac{h}{h_0}\right)^a, \quad (3)$$

where v(h) – wind speed (m/s) at height h (m), v_0 – wind speed (m/s) at reference height h_0 (m), a – coefficient characterising wind distribution unevenness depending on the terrain type (0.33 – for dense high-rise urban areas, 0.22 – for low-rise developments and forested areas, 0.14 – for open terrain).

The variation of air humidity with height is dependent on temperature changes. Warm air retains more moisture than cold air, meaning temperature decline with altitude leads to humidity reduction, condensation, and the formation of clouds and fog. Experimental studies show that humidity distribution is non-uniform, with layers of decreasing humidity alternating with layers of increasing humidity (Dai, 2006). In the atmosphere's lower 50–100

metres, turbulent water vapour flux remains relatively constant with height. The Clausius-Clapeyron equation demonstrates that a 1°C temperature change corresponds to a 7% change in atmospheric water vapour capacity (Trenberth, 2011).

Thus, when determining weather types and building operational modes, it is crucial to consider height-dependent variations in all key climatic parameters to select appropriate architectural and structural energy-efficient solutions for high-rise bioclimatic buildings (Krivenko et al., 2018).

3.3. Minor Climatic Parameters: Impact Analysis

We analyse the interaction between major and minor external climatic parameters when modelling their impact on a building with height, where minor parameters (solar radiation, precipitation, air pollution levels, cloud cover) modify the effects of major parameters (air temperature, wind speed, humidity, atmospheric pressure). For example:

- Solar Radiation: The intensity of solar radiation affects the surface temperature of structures. On warm days, the exposure of external building surfaces to solar radiation increases their temperature, which differs from the ambient air temperature. Due to the temperature difference, convective heat flow is directed upwards along the building surfaces, creating a so-called near-surface (boundary) layer of heated air. The variation in temperature between the building's external surface and the surrounding air depends on the solar radiation intensity and the solar absorption coefficient of the facade materials.
- Precipitation: Precipitation can influence the heat exchange between a building and its environment. Heavy rain or snow leads to uneven cooling, freezing, and ice formation on building surfaces, in addition to exerting mechanical stress on structural elements. An increase in wind speed with height affects the angle of raindrop impact (driving rain), which can result in excessive moisture absorption by vertical enclosing structures on the upper floors.
- Air Pollution: Air pollution can change the radiation balance, as dust and other particles affect the absorption and reflection of solar radiation. This, in turn, influences the building's microclimate, particularly temperature and indoor air quality.
- Cloud Cover: Cloud cover determines the intensity of direct solar radiation and light diffusion. A decrease in cloud cover under certain weather conditions may lead to a sudden increase in solar exposure, affecting the thermal regime of buildings. As the temperature drops with height, humidity condenses, leading to cloud formation.

The analysis shows that major parameters (temperature, humidity, pressure, wind speed) interact with minor parameters (solar radiation, precipitation, pollution, and cloud cover) in a multi-level system influencing the building's climatic conditions. This interaction must be considered when developing bioclimatic architectural concepts to ensure high comfort and energy efficiency.

4. CONCLUSION

The article highlights the importance of bioclimatic design in modern urban development, particularly in the context of increasing urban density and environmental degradation. The presented study contributes to the advancement of bioclimatic design, especially for high-rise buildings, by optimising the consideration of climatic parameters.

The authors propose an innovative approach to optimising bioclimatic design solutions by applying the biological principles of equivalence and non-equivalence of climatic factors. The study analyses a structured system of interrelations between climatic characteristics, weather types, and building operational regimes. The research also systematises and mathematically describes changes in key climatic parameters with building height and the impact of minor climatic parameters on major ones. Specific dependencies of climatic parameter variations with height have been identified, allowing for more precise high-rise building design.

It is important to note certain limitations of the study, namely, the difficulty of accurately predicting climatic parameters with height and the need for additional validation of mathematical models in various climatic conditions.

This research aims to develop the theoretical and methodological foundations of bioclimatic design and to facilitate the implementation of the proposed approaches in the architectural design of environmentally sustainable urban developments.

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