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**THE POTENTIAL OF SMART TECHNOLOGIES IN THE DEVELOPMENT OF SUSTAINABLE BIOCLIMATIC HOUSING**

**1. Introduction.** Contemporary challenges of sustainable development—including global warming, increasing urban density, and limited natural resources—demand fundamentally new approaches to residential design. Sustainable housing must not only be energy-efficient but also capable of adapting to rapidly changing climatic and microclimatic conditions.

The city of Almatyexemplifies a complex microclimatic environment. Its foothill geography, significant elevation variations, high solar exposure, and seasonally active wind patterns create unique climate conditions that vary across neighborhoods. In such a context, traditional architectural approaches based solely on formal typologies or standard planning models are no longer sufficient. There is an urgent need for the integration of smart technologies—systems capable of collecting, analyzing, and interpreting environmental data in real-time and adjusting building parameters (heating, ventilation, shading, lighting) accordingly.

This study focuses on analyzing the potential of such a synthesis: combining passive architectural strategies—including building orientation, spatial configuration, density, and landscaping—with intelligent digital technologies that enable dynamic microclimatic management.

Three implemented residential complexes in Almaty were selected for analysis, each representing a distinct type of architectural organization:

**The Hills Residence** — a terraced development integrated into the slope of a hillside. Its stepped structure enhances solar access and natural ventilation, forming a cascading microclimate that is highly compatible with the application of smart façade and climate control systems.

**Arman Village** — a linear, low-rise development characterized by regular structure and façade rhythm. This typology is well-suited for modular integration of control systems, benefiting from predictable orientation and repetitive building forms.

**Alatau Village** — a perimeter-block configuration with enclosed green courtyards. The layout forms semi-autonomous microclimatic zones, making it ideal for the implementation of complex, smart environmental control scenarios.

The aim of this research is to evaluate the effectiveness and potential synergies between architectural design and smart technologies in shaping sustainable housing in Almaty, and to develop a methodological foundation for the next generation of climate-adaptive residential architecture.

**2. Materials and Methods**

This research is based on an interdisciplinary approach that integrates architectural analysis, climate modeling, smart system efficiency assessment, and geoinformation analytics. The methodology is aimed at identifying the interrelationship between architectural composition, microclimatic parameters, and the effectiveness of smart technologies in the context of the urban environment of Almaty.

**2.1. Selection of Case Study Projects**

Three residential complexes were selected, differing in morphology, development density, and level of technological integration:

**The Hills Residence** — a terraced structure located on a hillside;

**Arman Village** — a linear low-rise residential development;

**Alatau Village** — a perimeter-block system with enclosed internal courtyards.

**2.2. Morphological Analysis**

This analysis focused on identifying the spatial organization of the selected projects. The following parameters were examined: building height and massing, form and orientation, courtyard configuration, street-to-courtyard connections, landscape features, compositional axes, and density.

**2.3. Assessment of Smart System Potential**

An audit was conducted to evaluate existing and potential smart engineering solutions, including:

Automated façade systems (shading and natural ventilation control);

Microclimate sensors (CO₂, humidity, temperature);

Predictive control systems for heating, ventilation, and lighting;

Energy consumption management based on data from renewable energy sources (RES).

**3. Results**

**Morphological Analysis of Residential Complexes**

**1. The Hills Residence (Terraced Structure on a Hillside)**

**Building Height:**2–3 stories, arranged in a stepped manner along the slope; height varies according to the topography, ensuring visual and spatial adaptation to the landscape.

**Building Form and Orientation:**Compact, terraced volumes predominantly oriented to the south and southeast, maximizing solar exposure during the colder seasons.

**Courtyard Structure:**The spaces between terraces partially function as private courtyards, green roofs, or personal terrace zones.

**Street-to-Courtyard Connections:**Access is organized through a cascading network of roads and pedestrian paths, providing multi-level connectivity. Circulation follows the slope's natural contours.

**Landscaping:**Emphasis on ground cover vegetation, terraced gardens, green roofs, and retaining wall plantings. Local drought-resistant plants are used to aid moisture retention.

**Compositional Axes:**Axes follow the slope lines, guiding the layout of terraces. The vertical rhythm enhances the natural landscape articulation.

**Density:**Low development density, ensuring privacy, open spaces, and effective natural ventilation.

**2. Arman Village (Linear Low-Rise Development)**

**Building Height:**Uniform two-story structures. The consistent height contributes to a calm and ordered urban rhythm.

**Building Form and Orientation:**Elongated, rectangular blocks primarily oriented to the south and east, with a regular façade grid.

**Courtyard Structure:**No enclosed courtyards; instead, the complex features open spaces between buildings, serving as recreational zones and landscaped corridors.

**Street-to-Courtyard Connections:**A clear, linear street layout with minimal curves. Open connections between buildings enable through-ventilation and pedestrian permeability.

**Landscaping:**Localized tree planting along pedestrian routes, with lawns and shrubs. Moderate level of greenery.

**Compositional Axes:**The main axes run parallel to the building blocks and are emphasized by vegetation and rhythmic façade elements.

**Density:**Medium density. Adequate spacing between buildings maintains a balance between built and open areas.

**3. Alatau Village (Perimeter Block Configuration)**

**Building Height:**Ranging from 2 to 4 stories. Blocks of different heights are grouped to create visual diversity.

**Building Form and Orientation:**Rectangular volumes arranged along the block perimeters. Internal orientation varies, sometimes reducing optimal solar access.

**Courtyard Structure:**Enclosed or semi-open courtyards form private inner spaces protected from wind and urban noise.

**Street-to-Courtyard Connections:**The site includes both perimeter vehicular access and internal pedestrian routes. Some courtyards are semi-private or restricted.

**Landscaping:**Generously planted internal yards with trees, lawns, and small architectural features. Microclimatic landscaping is feasible and beneficial.

**Compositional Axes:**Determined by block geometry; internal axes emphasize central courtyard features and functional zoning.

**Density:**Moderately high, yet the combination of vertical development and enclosed green spaces creates a sense of enclosure and comfort (Figure 1).

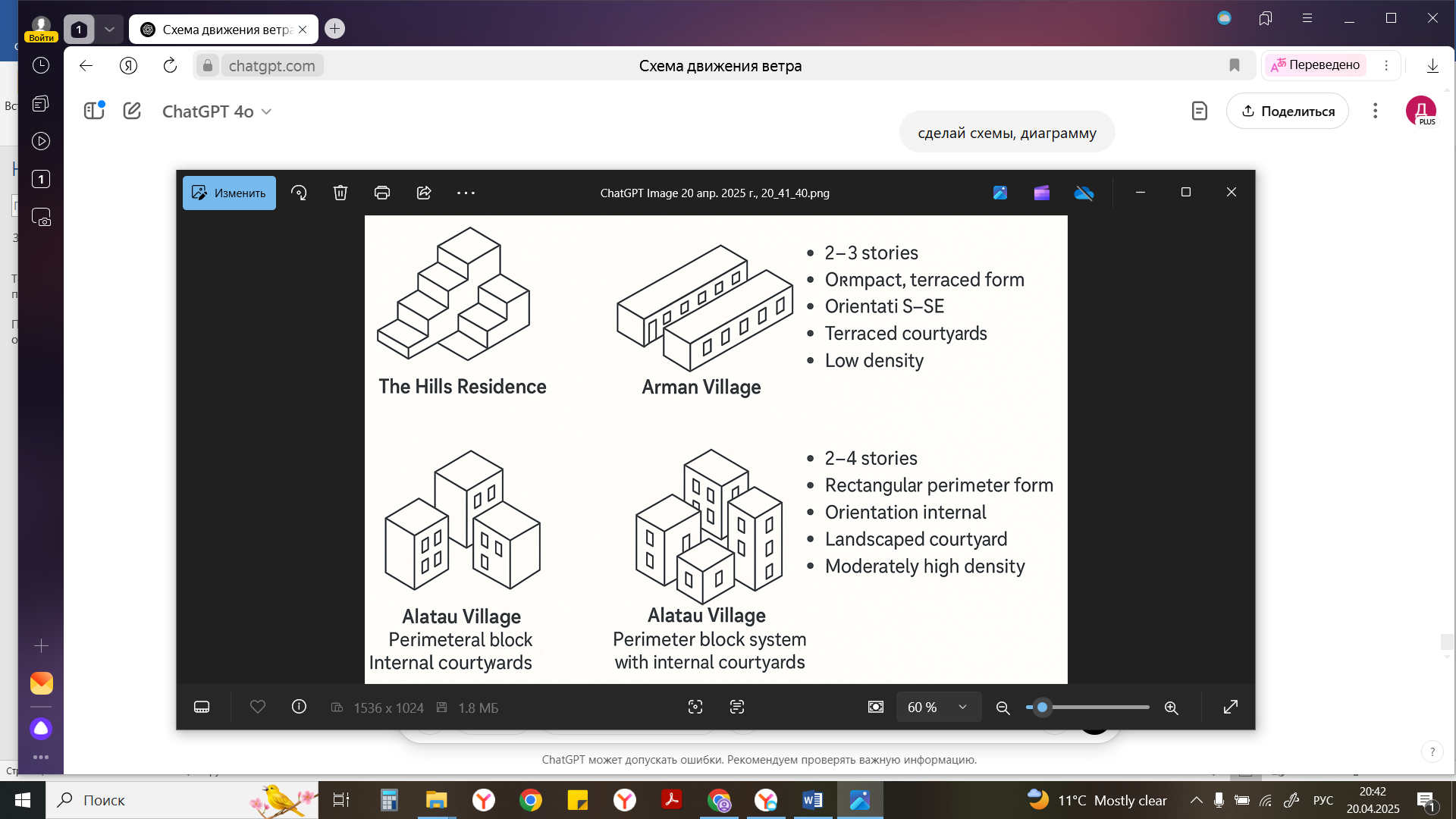


Figure 1.**Morphological Analysis of Residential Complexes**

**Table 1.Assessment of Smart System Potential**

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| --- | --- | --- | --- | --- | --- |
| **Project** | **SmartFacadeSystems** | **MicroclimateSensors** | **Predictive HVAC &LightingControl** | **Integrationwith RES** | **AdaptationPotential** |
| **TheHillsResidence** | Applicable for local shading/ventilation on terraces | Suitable for multilevel deployment across slope levels | High potential due to tiered spatial configuration | Rooftopsolarintegrationfeasible | **High** |
| **ArmanVillage** | Simple solutions along linear façades | Easy installation of sensor nodes | Facilitatescentralizedpredictivecontrol | RES can be efficiently applied with linear orientation | **Medium–High** |
| **AlatauVillage** | Effective around perimeter façades and courtyards | Zonal differentiation required (interior/exterior) | Strong potential for scenario-based zoning management | Combined system with internal energy storage feasible | **High** |

**4. Discussion**

The results of this study confirm the relevance of an interdisciplinary approach to sustainable housing design that combines architectural principles of bioclimatic design with intelligent engineering systems. Contemporary scientific literature (Emmanuel, 2005; Givoni, 1998; Shaviv, 2020; Chen et al., 2021) emphasizes the shift from static design solutions to dynamically adaptive systems capable of responding to fluctuations in temperature, solar radiation, humidity, and indoor air quality in real-time.

In the context of Almaty, a city characterized by microclimatic heterogeneity due to its foothill topography, strong seasonal variability, and continental climate, the integration of smart technologies is of particular importance. Architectural strategies—such as building orientation, the creation of buffer zones, and the use of terraced forms—provide the basis for bioclimatic responsiveness. However, it is only with the inclusion of smart systems—sensors, automated control mechanisms, data analytics, and predictive algorithms—that a building can adapt to changing conditions with maximum efficiency.

It is especially important to emphasize the **early-stage integration** of such systems into the design process. Isolated implementation of smart technologies without consideration of architectural composition significantly reduces their effectiveness. Therefore, **close collaboration between architects, engineers, climate specialists, and IT developers** is essential. The role of the architect is evolving: from a designer of space to a coordinator of the project’s climatic and technological strategy.

Thus, this discussion demonstrates that the sustainable and adaptive housing of the future results from the **systemic integration** of architectural form, microclimate analysis, and digital technologies—not merely a combination of individual energy-efficient components.

**5. Conclusion**

Contemporary approaches to sustainable housing design require not only a rethinking of architectural principles but also the active incorporation of smart systems capable of adapting buildings to rapidly changing environmental conditions. The results of this study show that the synergy between bioclimatic architectural techniques and digital technologies significantly enhances energy efficiency, climatic adaptability, and occupant comfort.

The analysis of three typological models of residential development in Almaty—terraced, linear, and perimeter block—revealed that each possesses unique potential for the integration of smart systems. The highest performance was observed in cases where climatic conditions were considered from the outset, and technological solutions were coherently embedded within the architectural concept. In this context, terraced developments on slopes, linear low-rise complexes with southern orientation, and perimeter block configurations with green internal courtyards demonstrate substantial potential for the implementation of comprehensive bioclimatic strategies.

The most critical conclusion of this study is the necessity of **early integration of smart technologies** into the architectural process. This requires interdisciplinary collaboration among architects, engineers, microclimate experts, urban planners, and IT developers. The architect of the future must possess not only design proficiency but also an understanding of energy exchange, climate adaptation, and the logic of algorithmic building control.

The proposed methodology and identified patterns can serve as a foundation for future academic and practical research in the field of sustainable housing. They also offer practical value for architects, developers, and urban policymakers in developing new building codes, standards, and typologies for climate-adaptive urban environments.

The synthesis of architectural methods and intelligent technologies opens new horizons in sustainable housing design. In the context of Almaty, this approach enables the creation of adaptive residential structures that combine energy efficiency, environmental responsiveness, and high levels of comfort. The findings of this study demonstrate the scalability of such solutions and their applicability within broader frameworks of sustainable urban planning. This paper lays the groundwork for future research and regulatory integration of smart bioclimatic approaches into architectural practice.

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