Digital Transformation of Rural Settlement Systems in Azerbaijan

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Abstract. This article presents a comprehensive analysis of the paradigmatic transition in the planning, design and management of urban and rural settlements in the Republic of Azerbaijan. The study was conducted in the context of the implementation of the "Great Return" state program in the liberated territories and "Azerbaijan 2030: National Priorities for Socio-Economic Development". The work synthesizes the historical urbanization theories of "group settlement systems" described in detail in archival urban planning documents with modern achievements of Industry 4.0 - Building Information Modeling (BIM), Geographic Information Systems (GIS), Digital Twins and Cyber-Physical Systems (CPS). Special attention is paid to the analysis of the "Smart Village" pilot project in the Agali village of Zangilan region as a benchmark for post-conflict reconstruction. The article argues that the successful digital transformation of the Azerbaijani village requires not only the application of smart technologies, but also a deep integration of generative design with local (vernacular) architectural traditions. The research aims to develop a strategic roadmap for creating sustainable, culturally rooted, and economically viable rural communities. This approach can reverse the historical trend of "rural-urban" migration and ensure balanced territorial development.

Keywords: smart villages, smart cities, IT integrated architecture, Aghali village, Azerbaijan architecture

1 Introduction

In the age of global digital transformation, architectural and urban planning practices are undergoing profound changes. One of the key challenges in developing economies, including Azerbaijan, is the decline of rural settlements and the "rural-urban" imbalance against the backdrop of accelerating urbanization.[1] Rural communities, traditionally

based on an agrarian economy, are today in the process of being rebuilt with the help of information technology (IT), advanced digital services, and modern architectural approaches.

Historical settlement systems in Azerbaijan are not only a collection of residential areas, but also morphological structures that carry the socio-cultural code of the regions. However, during the period of industrialization and modernization, the mass influx towards the Baku and Absheron agglomerations led to demographic depletion in the regions and the marginalization of traditional rural infrastructure.[2] To prevent this process and restore the potential of villages, the Azerbaijani government has put forward the "Smart City" and "Smart Village" strategies within the framework of the "Great Return" state program, as well as in accordance with the document "Azerbaijan 2030: National Priorities for Socio-Economic Development".[3]

This study hypothesizes the role of the synthesis of IT and architecture in the revitalization of rural settlement systems in Azerbaijan. According to the hypothesis, improving the quality of life in villages and ensuring demographic sustainability is possible not only through the construction of physical buildings, but also through the complex management of space using Digital Twin, Internet of Things (IoT), and parametric architectural methods. The article compares global "Smart Village" trends with the specific geographical and cultural realities of Azerbaijan and evaluates the contributions of this approach to future urban planning science.

2 Problem Statement

The current situation of rural settlements in Azerbaijan consists of several fundamental problems of a consistent nature:

Disruption of socio-spatial morphology and asymmetric urbanization. Research by S. Naghiyev and I. Bayramov (2025) shows that the level of urbanization in Azerbaijan, which has reached 54.5%, is the result of continuous migration from rural to urban areas. The migration of young people and the working-age population to large cities for education and work purposes results in demographic aging and a decrease in the level of reproduction in villages.[2] The gap between economic and demographic urbanization indicators undermines the traditional archetypes of rural communities (production-domestic core).[1]

Rural-urban service gap (Digital Divide). The weakness of technological infrastructure (high-speed internet, automated utilities) and modern healthcare and education services in rural areas creates sharp inequalities in living standards.[5]

Cultural and architectural degradation. The spread of universal and standardized construction practices to villages threatens to lose local vernacular architectural traditions in regions with distinct climate and cultural zones, such as Sheki-Zagatala, Lankaran-Astara, and Absheron. Passive design strategies that ensure the adaptation of space to climate are being forgotten.[7]

The need for complete reconstruction in post-conflict areas. As a result of 30 years of occupation, thousands of settlements in the Karabakh and East Zangezur regions have been completely destroyed. Traditional restoration methods are not applicable in

these areas; there is a need for sustainable and innovative (Smart) solutions, based on the "tabula rasa" (scratchboard) principle.[9]

The research question is: How can information technologies and advanced architectural techniques be synthesized to ensure the economic independence of the village, preserve its traditional identity, and prevent migration flows?

3 The Main Part

This study is based on the "IT-integrated architecture" model, which proposes a conceptual framework for the digital transformation of rural settlement systems in Azerbaijan. The research methodology synthesizes traditional "socio-spatial morphology" theories with Industry 4.0 technologies. The main methodological approaches are as follows:

3.1 Spatial Planning with BIM and GIS Integration.

The proposed methodology is based on the scientific analysis of spatial data and is implemented at two main levels:

GIS Macro-Analytics. Geographic Information Systems (GIS) data are used for planning large areas during the restoration of Karabakh and the modernization of existing villages. These analyses allow to determine the topography, water resources, agricultural potential of the land and mine-hazardous zones. Also, based on this spatial analytics, the concept of "15-minute city/village" is applied.

BIM (Building Information Modeling) Micro-Analytics. BIM systems are applied for 3D modeling of engineering and architectural parameters of buildings.

3.2 Digital Twins.

As an extension of BIM, Digital Twin technology creates a virtual copy of both a single building and an entire village (for example, Agali). This tool is used to predict environmental problems, optimally manage resources (water, energy), and involve the population in participatory planning.

3.3 Parametric and Generative Design.

In order to preserve national-cultural identity, the modern concept of "Vernacular Digital Architecture" is applied with Generative Design and algorithmic approaches. This involves the integration of vernacular architectural traditions (e.g., Sheki grid and girikh ornaments) into modern buildings through parametric coding (e.g., through Grasshopper/Rhino).

Climate adaptation. The orientation of houses is optimized with aerodynamic simulations that provide appropriate internal courtyard systems, facade voids, and cross-

ventilation for the windy and sunny climates of Absheron and the humid climates of Lankaran.

Digital Fabrication. Grid ornaments are transformed into kinetic facades of buildings through Digital Fabrication and CNC cutting methods, which regulate the internal thermal comfort of buildings.

3.4 Cyber-Physical Systems (CPS) and Social Layer Application.

The sociological impact of the methodology is provided through Cyber-Physical Systems (CPS) and Community Hubs. CPS proactively manages the rural living environment by connecting physical buildings with a virtual database. Community Hubs, on the other hand, act as a Social Layer that prevents migration by facilitating young people's access to coworking, e-commerce, and remote work opportunities.

In modern urban planning, the morphological development of villages is no longer considered as isolated agrarian centers, but within the framework of "Group settlement systems". Analysis of archival and modern research1 shows that the resilience of villages depends on how they are integrated into larger agglomerations.

As noted by the Deputy Chairman of the State Committee for Urban Planning and Architecture, architect Ilgar Isbatov, Azerbaijan is a country distinguished by its historical urban planning and architectural traditions, and these traditions are being developed in the modern era through new institutional mechanisms and global platforms such as WUF13. According to historical dialectics, the village house should remain a "single production-household core". That is, digitalization should not eliminate traditional homestead farming, but rather strengthen it with the principles of "Smart Agriculture". This plays the role of a major buffer preventing migration.[1]

Table 1. Regional characteristics of architectural typology.

Region	Climate characteristics	Traditional architectural response	Modern interpretation (Smart/Parametric)
Lankaran-Astara	Humid subtropical climate, abundant rainfall.	Sparse planning for cross ventilation. Orientation of streets along the latitude circle. Increasing the slope of roofs and water flows.	Aerodynamic modeling (CFD) of neighborhoods to maximize wind corridors. Pergola buildings with drainage systems integrated into the BIM model of the landscape.
Absheron	Semi-desert, strong northerly winds	Compact internal courtyards, blank north walls. Block	Parametric optimization of insolation. High-density cluster construction

	(Khazri), hot summer.	construction for wind protection.	with automated shading systems. Use of materials with high thermal mass.
Mughan Plain	Warm arid climate.	Exclusion of "mirror" arrangement of houses (window to window). Orientation of streets in the direction of the meridian.	Integration of rainwater collection systems into roofs. "Cool Roofs" and vertical greening to reduce the heat island effect.
Sheki-Zaqatala	Mild climate, rich craft traditions.	Use of river stone, brick, lattice stained glass. Large balconies.	Generative design of facades based on lattice patterns. Use of local materials as filler for 3D printing or modular blocks.

3.5 "Smart Village" Paradigm: The Aghali Example.

The practical application of digital transformation of rural settlements in Azerbaijan is demonstrated in the village of Aghaly (Fig.1) in the Zangilan region (the "Smart Village" project). This project is built on 5 main pillars: smart infrastructure, smart governance, smart energy, smart education/healthcare, and smart agriculture.[11]
In Agali, buildings and streets are equipped with Internet of Things (IoT) sensors. Water, energy and road infrastructure are integrated into a "Smart Cloud Platform".[12] In agriculture, soil and vegetation are monitored using UAVs (drones) and multispectral cameras, and precision agriculture is applied, which dramatically reduces water and fertilizer consumption.[13]

All buildings in the project area are designed in accordance with the "zero emission" goal. Special thermoblocks were used for thermal insulation. The village's energy needs are met from alternative sources - Archimedes-type hydroturbines built on the Hakari River, solar panels (325 kW) and geothermal heat pumps.[15]

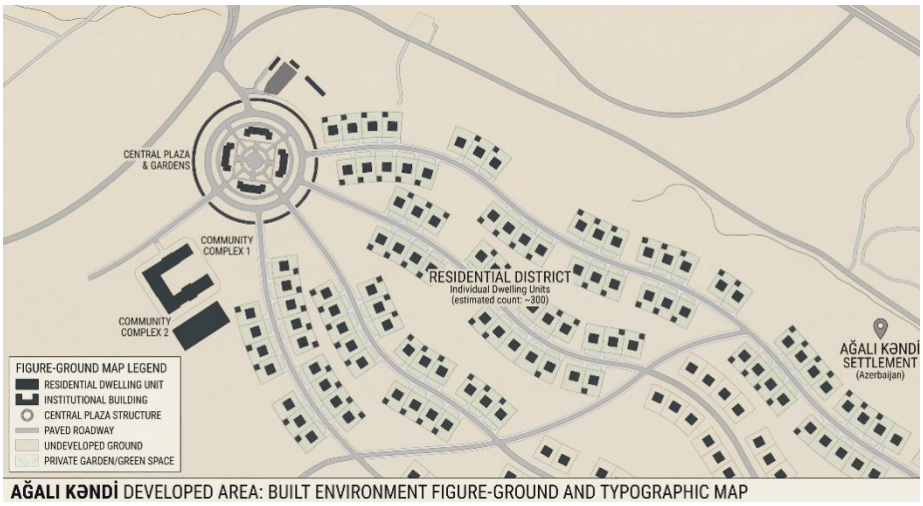

Fig. 1. Aghali Village. Built Environment figure-ground and typographic map

To increase the digital literacy of the community and facilitate access to public services, ASAN service kiosks and e-health (telemedicine) capabilities have been integrated into the village.[12] This connects rural residents to the global network, regardless of distance, and stimulates the activity of Community Hubs.

Spatial Planning with BIM and GIS Integration. The basis of digital transformation is the scientific analysis of spatial data. The "Improvised Methodology" proposed in the article is based on the integration of Geographic Information Systems (GIS) at the macro level and Building Information Modeling (BIM) at the micro level.[12]
During the reconstruction of Karabakh, as well as the modernization of existing villages, GIS data is being used to identify topography, water resources, agricultural potential of the land, and even mine-hazardous zones.[12] The implementation of the "15-minute city/village" concept is based on this spatial analytics.[14]

3.6 The Impact of Digital Transformation on Environmental and Sustainable Development

The digital transformation of rural settlement systems does not only serve demographic and economic purposes; it also forms the basis for environmental sustainability in Azerbaijan in order to achieve the Sustainable Development Goals (SDGs). The principles of "smart energy" and "green architecture", which are one of the main pillars of the Smart Village concept, are of critical importance in projects implemented in post-conflict areas (such as Agali). Technological tools not only reduce the energy demand of buildings through passive design strategies, but also fundamentally change the energy supply. Thanks to Internet of Things (IoT) sensors and Digital Twin platforms, the thermal efficiency, water consumption and electricity consumption of buildings are monitored in real time. This data is used, for example, to optimize cross-ventilation for the humid climate of Lankaran or to adjust facade gaps in the windy conditions of Absheron

(Parametric Design). The Agali example shows that by implementing alternative energy sources such as hydro turbines, solar panels and geothermal heat pumps on the Hakari River, rural settlements can become completely self-sufficient in terms of energy, "Net-Zero Energy" communities. This leads not only to economic savings, but also to a sharp reduction in carbon emissions, which is in line with Azerbaijan's Paris Agreement commitments.

Against the backdrop of urbanization, the revival of the rural economy is possible at the same time by reducing its ecological footprint. Precision Agriculture systems play a critical role, especially in areas that have been liberated from occupation, are at risk of landmines and need to restore soil quality. GIS macro-analytics allows for the precise identification of agriculturally suitable areas, water resources and micro-climatic zones. Monitoring of vegetation and soil health with multispectral cameras carried out by UAVs (drones) reduces irrigation and fertilizer consumption to the minimum needed. This is invaluable in terms of managing water resources (vital for Azerbaijan's arid climate) and limiting the use of chemicals. Thus, agriculture is transforming into a digital ecological farming model while preserving the tradition of "production-consumption core".

3.7 Community Hubs and the Shaping of the New Rural Economy

The lack of economic opportunities and weak social infrastructure, which are the main reasons for rural-urban migration, can be addressed through the concept of "Community Hubs" proposed through IT-integrated architecture. Acting as a functional continuation of the traditional village center in the digital age, these hubs are not just physical buildings, but also social and economic ecosystems managed by Cyber-Physical Systems (CPS).

Community Hubs, equipped with high-speed internet infrastructure, enable rural youth and the working population to find competitive jobs in the global market. These centers act as co-working spaces for remote workers, digital literacy courses, and startup incubation zones. This approach eliminates the need for young people to move to Baku or other large cities to find jobs, thus directly increasing demographic sustainability in villages.

The global marketing of agricultural and handicraft products through e-commerce platforms is a key element for the diversification of rural economies. Community Hubs assume a central function for the digital marketing, packaging and logistics management of these products. The integration of Cyber-Physical Systems ensures transparency and efficiency of the entire chain from production to sale, which increases trust in rural products.

As a result, this approach turns villages not just settlements, but also centers of the "Smart Spatial Economy". Strengthening social capital and community spirit through technological investments is seen as a key mechanism to reverse migration trends.

The engineering and architectural parameters of buildings are modeled in 3D using BIM. A step further, Digital Twins create a virtual copy of both a single building and an entire village (for example, Agali). This technology, which has been tested in China and European countries (for example, "Digital Twin of the Ocean" or village ecological

monitoring platforms), is an important tool in Azerbaijan for predicting environmental problems, optimal management of resources (water, energy), and involving the population in participatory planning.[14]

Preserving Local Traditions in Modern Parametric Design. Digitalization is not just about engineering solutions; it also ensures the transmission of national-cultural identity into the future through architecture. Different geographical zones of Azerbaijan, such as Sheki-Zagatala, Absheron and Lankaran, have their own vernacular (folk) architectural traditions adapted to their unique climate.[1]

As emphasized in the research conducted by Aydan Agabeyli (2017), the network (a geometric unity of colored glass and wood elements without glue and nails), which is the pearl of Sheki architecture, is based on complex mathematical and geometric calculations.[7] Within the modern concept of "Vernacular digital architecture", these traditions are reinterpreted through Generative Design and algorithmic approaches.

The inner courtyard system and specific facade spaces can be optimized against strong winds (khazri and gilavar) and high solar radiation with parametric coding (e.g. Grasshopper/Rhino).

With digital fabrication and CNC cutting techniques, traditional grid and girix ornaments can be transformed into kinetic facades of modern public buildings and village centers. These facades automatically open and close according to the angle of the sun's rays, regulating the internal thermal comfort of the buildings.

With aerodynamic simulations to ensure cross ventilation, the location and orientation architecture of local houses are adapted to modern energy efficiency standards (Class A).[8]

The Sociological Impact of Cyber-Physical Systems (CPS) and Community Hubs. The power of the proposed IT architecture model to reduce rural-urban migration depends in particular on the functioning of the Social Layer. Cyber-physical systems connect physical buildings with virtual databases, managing the rural living environment proactively rather than reactively.[7] The benefits of these systems to society are delivered through Community Hubs. The former traditional "teahouse" or village center concept is being transformed into digital "Community Hubs".[7] This hubs provides access to co-working, e-commerce (exporting local products to the global market), and remote work opportunities for the population, especially young people. As a result, young people do not have to move to Baku to find work; they can engage in full-fledged economic and social activities within the "Smart Village".[13]

The discussion of large-scale rural digitalization shows that technology is not an end in itself, but a tool for ensuring socio-economic sustainability. In the settlement morphology of Azerbaijan, this approach includes economic profitability (increasing agricultural production thanks to drones and IoT)[12] and improving the quality of social life. Gasimzadeh's (2023) Cost-Benefit Analysis also confirms that, although the initial costs of Agali-type projects are high, they are invaluable in terms of long-term development, energy savings, and social reintegration. However, the main threat to be addressed is the "digital divide". In addition to building advanced infrastructure, increasing the digital literacy of the rural population and investing in human capital are of vital importance.

Table 2. Comparative analysis of approaches to rural construction

Parameter	Traditional Soviet planning	Modern "Smart Village" approach (Agaly)	Perspective approach (2030+)
Settlement structure	Monocentric, rigid hierarchy	Cluster, autonomous	Network, polycentric (Group Systems)
Energetics	Centralized (gas/electricity)	Hybrid (Green Energy + grid)	Distributed (Prosumers), micro-grids
Architecture	Typical, unified	Energy efficient, modern	Parametric, neo-vernacular
Governence	Bureaucratic, paper-based	Electronic (Smart Management)	Predictive (Digital Twin + artificial intelligence)
Economics	Collective Farm / Individual	Agroparks + Processing	Precision farming + E-commerce

4 Conclusion

According to the results, the practical application of digital transformation of rural settlement systems in Azerbaijan is demonstrated by the "Smart Village" pilot project in Aghaly village of Zangilan, which is built on five main pillars: smart infrastructure, governance, energy, education/health, and agriculture. Technologically, buildings and streets are equipped with Internet of Things (IoT) sensors, and energy and road infrastructure are integrated into a smart cloud platform; in agriculture, precision farming is applied using UAVs and multispectral cameras, drastically reducing water and fertilizer consumption. At the same time, the project achieved high energy efficiency by designing all buildings in accordance with the zero emission target and providing energy demand from alternative sources - hydro turbines, solar panels, and geothermal heat pumps. Spatial planning is based on the integration of GIS analytics (resource, topography, and mine hazard zones) at the macro level and BIM/Digital Twins systems at the micro level, serving optimal resource management and prediction of environmental problems. In the field of architecture, local vernacular (folk) traditions, such as grid elements, were synthesized with Generative Design and parametric coding, creating

kinetic facades and orientation architecture that provide energy efficiency, suitable for the winds of Absheron or the humid climate of Lankaran. From a social perspective, the implementation of Cyber-Physical Systems such as ASAN service kiosks, e-health and digital Community Hubs not only increases the digital literacy of the community, but also plays an important buffer role in preventing rural-urban migration by providing young people with access to local coworking, e-commerce and remote work opportunities. Overall, the conclusion of the study is that this IT-integrated architectural model combines historical settlement forms with the modern "Smart Village" concept and is fully consistent with Azerbaijan's "Great Return" strategy.

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